Flexibility for Future Evolution:
Validation and Development of Design Guidelines

by

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Dedication

To my parents for their encouragement and support. This achievement would not have been possible without you.

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August 15, 2008

Abstract

Flexibility for Future Evolution: Validation and Development of Design Guidelines

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The University of Texas at Austin, 2008

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Design flexibility is defined as the ability of a product to be adapted to meet changing or varying design requirements. A list of guidelines for flexibility for future evolution (FFE) was developed to aid designers in the creation of flexible, *mass-produced* products. In this research, the effectiveness of using the guidelines for FFE in the design of flexible, *small-lot* systems is investigated. Furthermore, the current list of guidelines for FFE is expanded to include a more detailed subset of guidelines that suggest including adjustable and tunable features in a design. To meet these objectives, five case-studies of small-lot systems are reverse engineered and their flexibility is measured using Change Modes and Effects Analysis (CMEA). The results of the CMEA are used to verify the effectiveness of the guidelines for FFE and to develop new adjustability enabling guidelines for FFE.

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Chapter 1: Introduction

Product flexibility is defined as the ability of a product to be adapted to changing or varied requirements [1]. There are several subtopics of product flexibility, including mass customization, product platform design, modularity, reconfigurability, and evolvability. Evolvability specifically refers to the ability of a product to be adapted to unforeseen changes in system requirements. There are two goals of this research. The first objective is to investigate the effectiveness of the use of a set evolvability design guidelines in the design and fabrication of small-lot systems. The second objective is to expand the current list of evolvability guidelines to include a detailed subset of guidelines that suggest including adjustable and tunable features into a design.

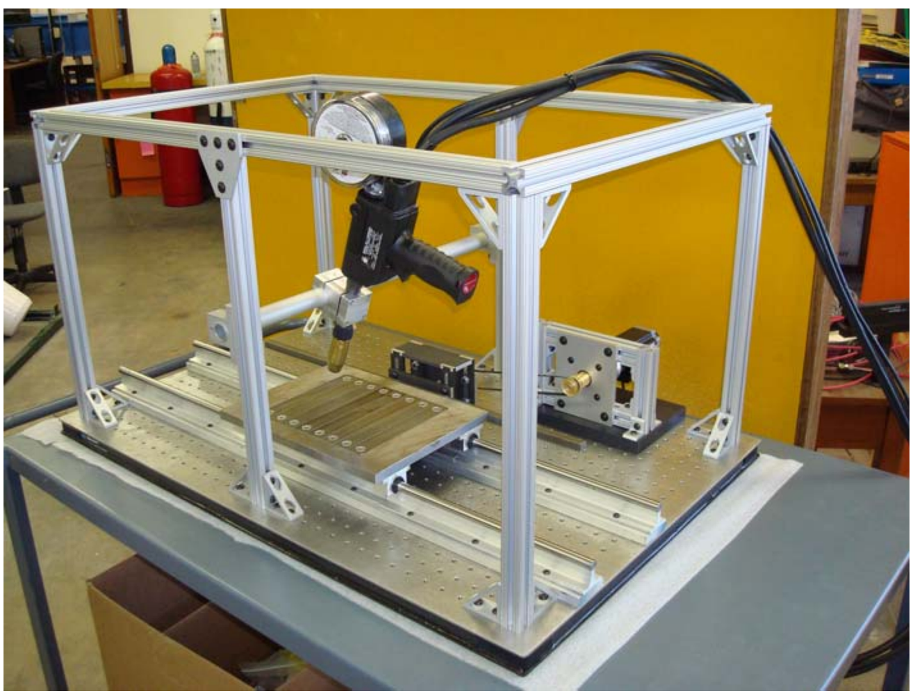

Figure 1.1: Welding test station evolvability case study

To achieve these goals, the evolvability of a series of representative systems is measured using an evolvability metric. The use or nonuse of the guidelines is then correlated to the increased or decreased evolvability of the systems under consideration. The case studies compared are all small-lot, complex engineering systems. One of the case studies, a gas metal arc welding test station (Figure 1.1), was designed by the author with the goal of it being evolvable. It is hypothesized that the implementation of the guidelines in the design of the welding test station resulted in features that make the design more evolvable. It is also hoped that the inclusion or exclusion of adjustable and tunable features in the systems under consideration will yield additional evolvability guidelines.

1.1 MOTIVATION

Complex, small-lot test rigs and manufacturing systems often require significant capital investment from the firms and institutions that purchase them. If the functional requirements of such systems should change, it is of great interest to firms that the changes be met quickly and at low cost. Ideally, changing needs would be met at no cost to the firm. However, this achievement is often impossible when new requirements arise that are outside the range of the current system's tunable parameter range. When such a situation arises, the architecture of the components and system layout has a significant effect on the system's flexibility. There are several strategies for designing flexible products and systems including the following:

- Product platform design
- Mass customization
- Modularity
- Reconfigurability
- Evolvability

Of the five areas listed above, product family design, mass customization, and product modularity have received the most attention to date. Reconfigurability has been studied in the context of reconfigurable manufacturing systems. Evolvability is a fairly new research topic, and refers specifically to the design of products that can be changed to fulfill *unforeseen* needs and requirements.

1.1.1 Product Platform Design

A platform is defined as a collection of assets that are shared by a set of products [2]. Product platform design is executed by architecting products that have changeable components and features around a common platform. The changeable components create the variety that the market demands while the common platform components keep the cost of variety low. It is always a challenge to the designer to maximize commonality while achieving the perceived variety that the market demands [3]. There are many suggested methods for addressing this challenge. For example, deWeck and Suh [4] developed a seven step iterative platform design process, and showed that its implementation results in reduced long term costs. Likewise, Suh, de Weck, Kim and Chang [5] developed design methodology that focuses on the design of the individual system components.

Platform based variety can also be achieved by parametrically scaling design parameters to satisfy different market requirements [6]. For example, slides that are used in linear motion systems are often scaled to different sizes to create a family of similar products that meet different customer needs. In Figure 1.2, a family of ball slides that was designed and manufactured by AG Slides ® is shown.

Figure 1.2: A product family created by scaling components [7]

Another example of successful product family implementation is the Sony Walkman portable cassette player [8]. The Walkman product family features internal components that remained common across each family generation. Sony uses the internals as a common platform on which they could build variety to reach large portions of the market. To achieve variety, Sony changes the look and feel of the product by offering the product with many different styles of external casings. In addition to having a product that can be varied easily, Sony has a solid understanding of the US, Japanese, and European markets. This allows them to fulfill the precise needs of customers rapidly and at low cost.

It is of interest to designers to be able to measure the strength of a given platform design. Martin and Ishii [9] propose a design for variety (DFV) method to minimize the design effort required for future generations of a product. This method uses a QFD matrix to create generational variety (GVI) and coupling (CI) indices. The GVI is an indicator of the redesign effort required for future generations of a product, while the CI indicates change propagation across system components.

When implemented successfully, product families offer a large degree of market perceived variety while keeping a high level of component commonality across the family [10]. This is beneficial to manufacturing firms, because reducing the number of distinct components that must be manufactured greatly reduces production cost. At they same time, they are able to capture a large share of the market since they are able to offer the product variety that is necessary to reach a broad range of tastes and interests.

1.1.2 Mass Customization

Mass customization has emerged as the new paradigm in manufacturing [11]. Mass customization allows customers to select the exact features of a product that they desire during the ordering process, and still pay a competitive price for the item. In this way, firms are able to offer mass produced products that are customized to each *individual* that purchases them [10]. Advances in manufacturing technology have helped the successful execution of mass customization. For example, flexible manufacturing systems (FMSs) and computer integrated manufacturing (CIM) are important tools help firms manufacture mass customized products [12]. The internet greatly facilitates the ordering process, because customers are able to visit company web pages and select product features through interactive menus. Customers can select the features they desire, and preview what the resulting product will look like. For example, the Vicale ®

Corporation of Oxford, CT offers a customizable action figure that can be ordered via their website. The user interface, shown in Figure 1.3, enables customers to choose from multiple options including clothing, hair color, eye color, accessories, and facial expressions. These options create a vast number of possible combinations, giving customers the freedom to create their own customized product.

Figure 1.3: Customized action figure [13]

The nature of the manufacturing process and the architecture of the product have a great effect on the feasibility of mass customization in a given case. To address this issue, Jiao [14] proposes a methodology for developing a product family architecture for mass customization. Feitzinger [15] suggests that mass customization is significantly less costly if product differentiation is postponed until the last possible step in the manufacturing process. In some cases, differentiation can be postponed until the point of sale in a retail store. For example, some grocery stores offer “nut stations” at which customers can select portions of a variety of nuts and combine them into a customized mix. A machine in the store blends and mixes the nuts into a butter or spread for the shopper. This process allows customers to have immediate access to an enormous selection of nut butters. At the same time, the cost of offering this variety is greatly reduced, since the manufacturer does not have to bear the burden of concocting, storing, transporting, and shelving every possible variety of the product.

1.1.3 Modularity

Ulrich [16] defines a modular architecture as one that has a one-to-one mapping of functions to components. With this type of architecture, each function is carried out by a separate module. In contrast, integral designs use single modules to carry out multiple functions. There are several benefits to designing modular products. One benefit of modular design is that changes to one functional feature of a design will not propagate to other functional features [17]. Modular designs can also increase the variety of product line by featuring interchangeable components connected by common interfaces [18]. Such designs make it possible to mix and match parts to create a large number of possible combinations of functionality. Modular designs can also be used to create product families where the product platform itself is interchangeable component [19]. A completely modular architecture is not always achievable. For example, Holtta-Otto and de Weck [20] showed that products that are designed under stringent technical constraints tend to exhibit a more integral architecture.

An example of a modular product and its integral counterpart is the Victorinox Fieldmaster multi-tool and the BCB Mini Work Tool shown in Figure 1.4.

Figure 1.4: Modular vs. Integral Product Architecture [21,22]

The two tools above share many of the same functions such as a bottle opener, cutting blade, and sawing blade. However, the modular architecture of the Victorinox tool allows functional features to be removed and replaced without affecting the others. With the BCB tool, a change to any functional feature results in a change to the entire product.

1.1.4 Reconfigurability

Reconfigurability is a subset of flexibility that refers to the ability of a product or system to be rapidly converted repeatedly and reversibly to perform a predefined set of tasks [23]. Reconfigurability is commonly applied to consumer products and manufacturing systems. In the manufacturing domain, a reconfigurable machine is one that can be reconfigured to manufacture product variants within a specific part family. They are meant to be a compromise between the high cost and high flexibility of flexible manufacturing equipment and low cost and low flexibility of fully dedicated machines [24]. Machines of this type are designed to be switched from one configuration to another quickly and easily after the system has been deployed. Reconfigurability is also important for space systems for reasons of efficiency, extensibility, and mission robustness [25].

An example of a reconfigurable machine is the reconfigurable machine tool (RMT) shown in Figure 1.5. This device is capable of being reconfigured to machine parts at different milling angles. This ability enables a manufacturing firm to fabricate a family of similar parts with this same machinery. This is much more cost effective than having separate, dedicated manufacturing lines for each different part. In Figure 1.6, a pair of different parts that are in the same product family are shown that could be manufactured with a RMT similar to the one shown in Figure 1.5.

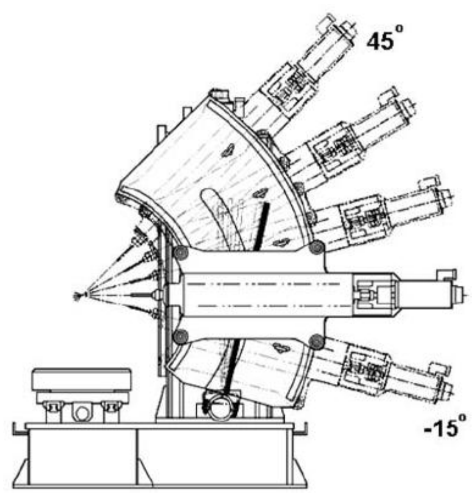

Figure 1.5: Reconfigurable machine tool [26]

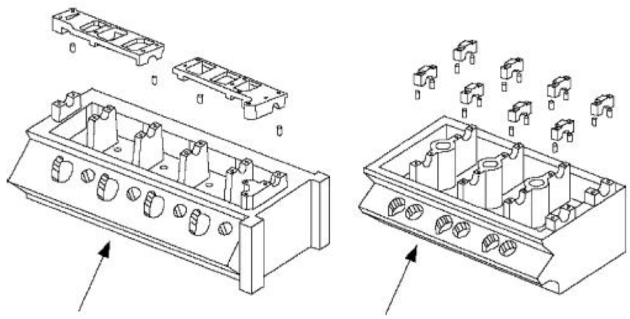

Figure 1.6: Part family produced from a reconfigurable machine tool [26]

A subset of reconfigurability that is commonly applied to the domain of consumer products is transformers. A transformer is defined as a system that exhibits a state change in order to facilitate a new functionality or enhance an existing functionality [27]. Transformers are single devices that can be reconfigured repeatedly and reversibly to perform multiple functions. There can be many benefits to transformer design such as reduced cost, reduced weight, and reduced size [28,29]. An example of a transformer is the Brunton ® Lamplight ™ LED Flashlight and Lantern. This product, shown in Figure 1.7, can be converted from a flashlight into a lantern by pulling out the telescoping head. While configured as a flashlight, the device projects a bright focused beam of light. When converted to a lantern, the light is redirected 360 degrees which is useful for lighting a small area such as a tent or picnic table [30]. This particular design saves the user space, weight, and money since a single device performs two separate functions.

Figure 1.7: Lamplight ™ LED Flashlight and Lantern [30]

Although reconfigurability can increase the capability of a design, there are limitations to its implementation in products, systems, and machines. The specific functional requirements of reconfigurable products and systems are determined at the onset of the design process, and the resulting system is designed to fulfill only a predefined set of needs. Thus, the functionality of a reconfigurable design is constrained to a discreet set of predefined configurations. In some cases, it may be useful to design products or systems that are capable of being adapted to unplanned changes.

1.1.5 Evolvability

Evolvability refers to the ability of a product or system to adapt to unforeseen changes in customer requirements. Designing mass produced, consumer products with evolvability can have significant cost and time saving advantages. There are many cases when the first generation of a product does not satisfy customers in an unforeseen way, and the product must be changed to make it more marketable.

An example of an evolvable product that was easily changed to better meet customer needs is the Black and Decker Lids-Off jar opener. In Figure 1.8, the two generations of the product are shown.

Figure 1.8: The Original Lids-Off and the new Lids-Off Open-It-All Center [31]

The first generation of the product loosened the lids of jars. To better meet the needs of customers, a new generation of the product, the Lids-Off Open-It-All Center, was developed. The Open-It-All Center features the additional capability to open cans and bottles. Because the original Lids-Off opener exhibited characteristics of an evolvable design, the additional functions in the Open-It-All Center were implemented with the reuse of 75% of the original parts [31]. This may have resulted in significant cost savings for Black and Decker, and the advantage of designing an evolvable product is clearly seen in this case.

In addition to the domain of mass produced products such as the Lids-Off opener, evolvability has large potential benefits in the realm of small lot systems. For example, a manufacturer may wish to retrofit a manual cutting or milling machine with a computer numerical control (CNC) system. Applied Robotics, Inc. of Harwood, MD sells a line of CNC retrofit kits that allow customers to retrofit manual manufacturing machines. For example, a Bridgeport mill with a CNC retrofit with an Applied Robotics, Inc. retrofit kit is shown in Figure 1.9.

Figure 1.9: Bridgeport mill with CNC retrofit [32]

Computer numerical controlled machines were invented long after vertical mills like the one shown in Figure 1.9. Therefore, it would have been impossible for the original designers to foresee this particular evolution. Yet, the machine is still inherently capable of accommodating a CNC retrofit. Instances such as these pose an interesting research question: how does one design a machine or product to be evolvable to unforeseen changes? Previous work that was done to help answer this question is described in the next section.

1.2 Research Objectives

1.2.1 Guidelines for Flexibility for Future Evolution

Most of the research in product flexibility has been in the domain of mass produced consumer products. The primary case study presented here, the welding test station, is a small-lot system that was designed and fabricated with the specific goal of being evolvable. To achieve this goal, the list of Flexibility for Future Evolution (FFE) guidelines [31] shown in Figure 1.10 was used throughout the design process of the system with the hope that evolvability would be infused into the final design. The steps that were taken to derive these guidelines are described in Chapter 2.

Modularity Approach

Increase the degree of modularity of a device by…

1 Using separate modules to carry out functions that are not closely related.
2 Confining functions to single modules
3 Confining functions to as few unique components as possible.
4 Dividing modules into multiple smaller, identical modules.
5 Collecting parts which are not anticipated to change in time into separate modules.
6 Collecting parts which perform functions associated with the same energy domain into separate modules.

Parts Reduction Approach

Reduce the number of parts requiring manufacturing changes by…

7 Sharing functions in a module or part if the functions are closely related.
8 Using duplicate parts as much as possible without raising part count.

Spatial Approach

Facilitate the addition of new functionality and rearrangement or scaling of parts by…

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces.
11 Extending the available area on the transmission components of the device.
12 Locating those parts which are anticipated to change near the exterior of the device.
13 Reducing nesting of parts and modules.

Interface Decoupling Approach

Reduce the communications between modules, and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules, by…

14 Standardizing or reducing the number of different connectors used between modules.
15 Reducing the number of fasteners used, or eliminating them entirely.
16 Reducing the number of contact points between modules.
17 Simplifying the geometry of modular interfaces.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need.
19 Creating detachable modules.
20 Using a framework for mounting multiple modules.
21 Using compliant materials.
22 Simplifying the geometry of each component.

Adjustability Approach

Enable the device to respond to minor changes by…

23 Controlling the tuning of design parameters.
24 Providing the capability for excess energy storage or importation.

Figure 1.10: Guidelines for flexibility for future evolution

In this research, the welding test station and a selection of other small-lot testing systems are studied to meet the following two objectives:

1) Investigate the effectiveness of the flexibility for future evolution guidelines on designing small-lot, complex systems.
2) Expand and refine the “Adjustability Approach” guidelines into specific, architectural guidelines that will be more useful to designers.

1.2.2 Objective 1: Efficacy of Evolvability Guidelines

The list of guidelines for FFE was developed from empirical studies of mass produced consumer products. Thus, it is natural to conclude that the list is an effective tool for designing evolvable consumer products. On the contrary, the welding test station is an example artifact of small-lot, moderately complex equipment. Because of this, it is not necessarily clear that the guidelines for FFE will be effective in designing evolvable systems of this type. Thus, the first objective of this research will be to determine if using the guidelines for FFE in the design of the welding test station resulted in a more evolvable system.

1.2.3 Objective 2: Expansion of “Adjustability Approach” Guidelines

Evolutionary changes to small-lot systems are often executed differently than those to mass produced products. Changes to small-lot systems are often made to the units themselves after they have been deployed. In contrast, changes to mass produced products are typically made by making changes to the manufacturing process. Thus, changes to mass produced products are typically made before the units are deployed, rather than after deployment as is often the case with small-lot systems. By studying the evolvability of a selection of small-lot systems, it is hypothesized that the inclusion or exclusion of adjustable and tunable features will respectively increase or decrease the evolvability of a given system.

While the list of guidelines for FFE is very thorough, it is by no means exhaustive. In particular, the guidelines in the final category titled “Adjustability Approach” are very general and are not at the same level of detail as the other guidelines on the list. In this respect, there is an opportunity to refine and expand Guidelines 23 & 24 to a higher level of detail so that they are more similar to the others on the list. A study on the evolvability of small-lot systems provides a unique opportunity to achieve this objective. Thus, the second objective of this research is to gather and categorize adjustable and tunable features that increase evolvability and generalize them into a set of design guidelines.

1.3 OVERVIEW OF THESIS

This thesis contains six chapters. In Chapter 2, an overview of current research in the adaptability of small-lot systems is provided. In chapter 3, the approach that will be used to meet the research objectives that are posed in this chapter will be presented. In Chapter 4, the case study of the welding test station that was designed with evolvability as a project deliverable will be introduced and explained in detail. In Chapter 5, four additional case studies of small-lot systems that are analyzed for evolvability are introduced. In Chapter 6, the evolvability of the case studies is evaluated with an evolvability metric. In Chapter 7, the effectiveness of using the guidelines for FFE to design small-lot systems is determined. In addition, adjustable features of the case studies are gathered and studied to expand the current set of “Adjustability Approach” guidelines. Lastly, in Chapter 8, closing remarks and recommendations for future work are made.

Chapter 2: Review of Flexibility Research

The objectives presented in this research rely on two entities in flexibility research. The first of these entities is the set of guidelines for flexibility for future evolution (FFE). The second entity is a methodology for measuring the evolvability of a design, known as Change Modes and Effects Analysis (CMEA).

A handful of approaches were taken spanning several years to derive the current list of guidelines for FFE. In this chapter, a detailed history of the work that was done to derive this list of guidelines is discussed. In addition, the development of the CMEA evolvability measurement method is thoroughly explained. By providing a detailed review of the works that provide the foundation for current flexibility research, the need and appropriate direction for further development are motivated.

2.1 GUIDELINES AND PRINCIPLES FOR GOAL ORIENTED DESIGN

There are a number of design guidelines in existence that are used to design toward specific goals. If a resulting design is desired to exemplify certain characteristics, design principles and guidelines can be used to aid designers in reaching those goals. A review of these guidelines was crucial for this research because it was important to understand how design guidelines should be developed, phrased, categorized, and used in practiced.

Perhaps the most famous set of design principles are those that are associated with the theory of inventive problem solving (TIPS or TRIZ). The theory was developed by Genrikh S. Altshuller beginning the late 1940's. The basis of the theory is that patterns exist in patent claims that are based on the same working principles [33]. Altshuller discovered that a large portion of solutions are ones that resulted from identifying conflicts and solving them with known physical principles. To solve such engineering conflicts, Altshuller developed the 40 TIPS design principles. These principles are meant to be used during the concept generation phase of the design process to help designers create innovative solutions to design problems.

There are several sets of Design for Manufacture and Assembly (DFMA) guidelines which are intended to help designers reduce the manufacturing time and cost of products by making them easy to assemble. Incorporating DFMA into a design not only reduces manufacturing time, but has also been shown to increase reliability [34]. Boothroyd and Dewhurst [35] provide a comprehensive overview of DFMA methods and guidelines and cover many of the issues associated with implementing DMFA in all of the most common manufacturing processes. A set of DFMA guidelines which was adapted from several sources is given by Otto and Wood [33].

Design for Environment (DFE) principles are meant to help designers and engineers create products that have a minimal impact on the environment. Telenko et al. [36] complies an extensive list of DFE principles from a large number of sources. Otto and Wood also give several Design for Environment (DFE) guidelines [33]which are intended to help designers develop products that have a minimal impact on the environment. The guidelines are split into four categories: product structure, material selection, labeling and finishing, and fastening. Design for Environment guidelines should be consulted after concept development, during embodiment and detailed design to check all design decisions for improvement towards minimal environmental impact.

Fricke and Shultz [37] published a list of principles of Design for Changeability (DfC). They stated that there are four aspects of changeability: robustness, flexibility, agility, and adaptability. Robustness characterizes a system’s ability to be insensitive to changing environments. Flexibility characterizes a system’s ability to be changed easily.

Agility characterizes a system's ability to be changed rapidly. Lastly, adaptability characterizes a system's ability to adapt itself towards changing environments. The DfC principles can be viewed as having a broader purpose than then guidelines for flexibility for future evolution that were introduced in Chapter 1. The DfC principles include the four aspects listed above, while the guidelines for FFE deal specifically with a design's ability to be changed to meet unforeseen changes in design requirements. Another key difference between the DfC principles and the guidelines for FFE is the manner in which they are stated. The DfC principles are posed as theoretical ideas that should be merely taken into consideration when designing changeable products (e.g., [Principle of] Modularity/Encapsulation; [Principle of] Ideality/Simplicity, etc.). The guidelines for FFE are more practical and are stated in a way that guides designers towards flexible solutions (e.g., #2: Confining functions to single modules; #22 Simplifying the geometry of each component).

Katz [24] introduced a list of design principles for reconfigurable machines. Katz defines a reconfigurable machine (RM) as one that is specifically designed to manufacture product variants within a specific part family. The RM design principles are worded in such a way so that they provide definitions of what RMs are, rather than providing guidance during the design process. For example, the first phrase in most of them is "A reconfigurable machine is…" which does not follow the *verb noun* format that is typical for most design principles and guidelines.

Singh et al. [28,27] provide a list of transformation *principles* and supporting *facilitators* to aid in the design of transforming products. They define a transforming product as one that possesses a broader functional repertoire by transforming into different configurations.

The guidelines discussed in this section are used to design towards specific goals. Some of them, namely the principles for reconfigurable machines and the transformation principles, are used to increase the flexibility of a resulting design. However, none of these principles address the need to design products that are flexible to unforeseen changes in design requirements. The guidelines for flexibility for future evolution, which are discussed in the next section, were developed to fill this void.

2.2 GUIDELINES FOR FLEXIBILITY FOR FUTURE EVOLUTION

2.2.1 Development of the Guidelines for Flexibility for Future Evolution

The current list of guidelines for flexibility for future evolution is the result of several years of cumulative research. Palani Rajan et al. [38] derive a set of 6 guidelines for improving the flexibility of a product's design. This early attempt at a set of flexibility guidelines introduces some of the main features of a flexible product that would eventually become key themes in the current set of guidelines. For example, they suggest making designs modular, and using standardized components and interfaces.

Pinyopusarerk [39] continues this research and proposes a set of 6 principles that are derived by studying a selection of U.S. patents. There is some similarity between the work of Pinyopusarerk and Palani Rajan et al. For example, Pinyopusarerk finds that increasing the modularity of the design increases the overall flexibility of a product. In addition to making designs modular, Pinyopusarerk suggests using external interfaces and modules for added user functionality. While this list of principles provides useful guidance towards the design of flexible products, some of the principles are better suited to other topics in product variety such as platform design and transformer design.

Furthermore, the author admits that the list fails to provide a comprehensive overview of product flexibility principles.

Schaefer [40] develops a set of product flexibility design principles by studying patents that have either been specifically designed for flexibility or have been modified to meet changing customer needs. The set is combined with those that are derived from Pinyopusarerk [39], resulting in a list of 13 principles.

Kuchinsky [41] further develops the list of design flexibility principles by following a similar patent study methodology. By studying patents that display flexibility, he develops new flexibility principles and combines them with the previous lists. This research results in a combined total of 21 design flexibility principles.

Qureshi [42,43] also uses a patent study methodology to develop a set of 12 flexibility principles. Qureshi notices that many of the principles in Kuchinsky's list are restatements of the categories into which the list is divided. For example, the first principle under the "Modularity Related" section is "Make the device modular." He also observes that some of them are redundant. He eliminates such principles from the list and combines his own list with the remaining principles from Kuchinsky into a concise list of 17 flexibility principles.

As a parallel effort to the work of Qureshi, Keese [44,31] develops a list of 16 guidelines for flexibility for future evolution (FFE) by performing an empirical study of actual products. Of the 33 principles developed between Qureshi and Keese, 9 were common to both lists. Thus, the combination of the two lists results in a set of 24 guidelines for flexibility for future evolution. The list presented by Keese, shown in Figure 2.1, is the most current set of flexibility guidelines.

Modularity Approach

Increase the degree of modularity of a device by…

1 Using separate modules to carry out functions that are not closely related.
2 Confining functions to single modules
3 Confining functions to as few unique components as possible.
4 Dividing modules into multiple smaller, identical modules.
5 Collecting parts which are not anticipated to change in time into separate modules.
6 Collecting parts which perform functions associated with the same energy domain into separate modules.

Parts Reduction Approach

Reduce the number of parts requiring manufacturing changes by…

7 Sharing functions in a module or part if the functions are closely related.
8 Using duplicate parts as much as possible without raising part count.

Spatial Approach

Facilitate the addition of new functionality and rearrangement or scaling of parts by…

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces.
11 Extending the available area on the transmission components of the device.
12 Locating those parts which are anticipated to change near the exterior of the device.
13 Reducing nesting of parts and modules.

Interface Decoupling Approach

Reduce the communications between modules, and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules, by…

14 Standardizing or reducing the number of different connectors used between modules.
15 Reducing the number of fasteners used, or eliminating them entirely.
16 Reducing the number of contact points between modules.
17 Simplifying the geometry of modular interfaces.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need.
19 Creating detachable modules.
20 Using a framework for mounting multiple modules.
21 Using compliant materials.
22 Simplifying the geometry of each component.

Adjustability Approach

Enable the device to respond to minor changes by…

23 Controlling the tuning of design parameters.
24 Providing the capability for excess energy storage or importation.

Figure 2.1: Guidelines for flexibility for future evolution

Tilstra [45] effectively shows that the guidelines for flexibility for future evolution are a unique contribution to the field of flexibility research. By comparing the types of guidelines and principles introduced and their respective contexts, he demonstrates that most of the flexibility research to date addresses the planning and management level of design. The guidelines for FFE are different than previously published guidelines and principles because they offer suggestions that help designers and engineers build flexibility into their designs at the detailed design level.

2.2.2 Need for Improvement

There is evidence that suggests that there are still opportunities to improve the list of guidelines for FFE. Parallel approaches in previous research to derive guidelines yielded different results, which implies that they may not have been exhaustive in their searches. Also, a previous author makes specific suggestions about potential avenues for improving the guidelines. Lastly, some of the guidelines, namely those in the Adjustability category, are broader in scope than the other guidelines in the list.

In the works of Qureshi et al. [43] and Keese et al. [31], two distinct and parallel approaches were taken to derive separate lists of guidelines for FFE (as discussed in Section 2.2.1). There was some overlap between the results (9 out of 33 guidelines) but most of the guidelines that were derived were distinct. This discrepancy suggests that neither approach completely captured all of the guidelines that could be yielded and further study is needed.

In his master's thesis literature review, Tilstra [45] identified scaling, robustness, and using of off-the-shelf components as concepts that are commonly accepted in the flexibility research community but are missing from the list of guidelines for FFE. Many authors agree that these are concepts that can improve the flexibility of a design, so it makes sense that they should have a place in the guidelines for FFE.

The two guidelines that exist in Adjustability Approach category of the guidelines for FFE are broader in scope than the other guidelines in the list. They do not guide designers towards specific design solutions. Rather, they provide abstract ideas that are good practice to follow but are general and nonspecific. Therefore, the Adjustability Approach guidelines could be split into several guidelines that are narrower in scope with the intention of making their application more practical for designers and engineers. Rather than having fewer guidelines that are broader in scope, the nature of the guidelines in the list would be more consistent if there were more numerous guidelines that are narrower in scope.

2.3 MEASURING PRODUCT FLEXIBILITY

There are several methods in existence that measure product flexibility. Unfortunately, the methods differ drastically due to inconsistencies in how people define product flexibility. Shewchuk [46] suggests a generic flexibility measure that allows designers to measure flexibility based on their own view of what flexibility is. This method may be effective for an individual, but the results are likely to vary from user to user due to the subjectivity of the process.

Component commonality [47-50] across a product family is often used as an indicator of product flexibility. Martin and Ishii [9] propose a generational variety index (GVI) for measuring variety across generation of products, and a commonality index (CI) for measuring commonality across the current generation of a product family.

While commonality indices can be used to provide a measure of flexibility, they can only be used after more than one generation of a product has been realized. Change

Modes and Effects Analysis (CMEA) [51] was developed to address this issue. Change Modes and Effects Analysis aims to measure the flexibility for future evolution of a design before future generations are developed.

2.3.1 Change Modes and Effects Analysis (CMEA)

Change Modes and Effects Analysis (CMEA) was developed as a method to evaluate the flexibility for future evolution of a design. The first version of CMEA, which is shown in Table 2.1, was introduced by Palani Rajan et al. [51] and was intended to be analogous to Failure Modes and Effects Analysis (FMEA) [52].

CHANGE MODE AND EFFECTS ANALYSIS FOR POTENTIAL CHANGES IN PRODUCT DESIGN							
Modules / Parts	Potential change Mode	Potential Effects of change	Design Flexibility	Potential Cause(s) of Change	Occurrence	Readiness	Change Potential Number

Table 2.1: Original CMEA [51]

The method is designed to evaluate the severity of the impact on a firm of implementing potential future changes to a design. The method is executed by rating the flexibility of the design, F_i, likelihood of occurrence of a change mode, O_i, and readiness of a firm to implement the change mode, R_i, on a scale of 1-10. These metrics are then used to calculate the change potential number (CPN) based on the following formula:

$$CPN = \frac{1}{N}\sum_{i=1}^{N}\frac{[(R_i + F_i) - O_i + 8]}{27}$$

where N is the maximum among the number of potential change modes, number of potential effects of change, and the number of potential causes of change. The CPN is intended to be an indicator of the overall flexibility of a product to any future change. It can be any value between 0 and 1, with 0 indicating a completely inflexible design, and 1 indicating a completely flexible design. This formula for the CPN is notably different than the formula for the risk number (RN) that is associated with FMEA. The RN can be any value between 1 and 1000, and is simply the product of the three FMEA table metrics (occurrence *O*, significance *S*, and detection *D*).

While the method proposed by Palani Rajan et al. provides an excellent foundation for measuring product flexibility, there are some aspects of it that could benefit from further development. The ratings for the readiness, flexibility, and occurrence are very subjective, and are likely to change depending on the person performing the analysis.

2.3.2 Enhancements to CMEA

Keese et al. [44,1] propose an "enhanced" version of CMEA that aims to be more intuitive to users that are familiar with FMEA and to provide more repeatable measures of flexibility for future evolution. There are two key changes to this new CMEA method. First, the rating scales of the Flexibility, Occurrence, and Readiness and the subsequent calculation of the CPN are revised so that they more closely resemble those of FMEA. The rating scales of the individual metrics are changed so that high numbers correspond to undesirable scenarios. The scales are still bound from 1 - 10. The CPN for each change mode is simply the product of the three metrics. In this way, the resulting CPN must be on a scale from 1 - 1000, with 1 being a completely flexible design and 1000 being completely inflexible. These rating methods are more similar to FMEA than the previous technique, and should be more intuitive to users who are already familiar with FMEA. Second, an objective process is developed for calculating the flexibility rating so that it is more consistent across different users.

While the CMEA method that is proposed by Keese et al. is a clear improvement to the previous method, it is best suited for application to mass produced consumer products. This is because the flexibility metric is heavily influenced by considerations in the manufacturing process.

In her MS Thesis, Takawale [53] develops a method for determining a readiness metric that was specifically tailored for injection molding manufacturing processes. The proposed method is very systematic and significantly reduces the effects of subjectivity in the assignment of the readiness rating. This method is intended specifically for use with injection molded parts, and is not used in the research presented here.

In the next section, a CMEA method is introduced that is suitable for the design of small-lot products and systems, which are the focus of this research.

2.3.3 CMEA for Small-lot Designs

Tilstra [45] introduces a CMEA method that is specifically tailored for use with small-lot systems. Because the focus of the research presented in this thesis is on the evolvability of small-lot systems, this method is used to evaluate the evolvability of the case studies that are presented in Chapter 4. This method of performing CMEA will be explained in the most detail of the current and previous versions. In Table 2.2, a blank CMEA table for analysis of small-lot systems is shown.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Design Flexibility (F)	Occurrence (O)	Readiness (R)	CPN	Description

Table 2.2: Blank CMEA table for small-lot systems [45]

This CMEA method preserves the features that are proposed by Keese et al. [44,1] that make the method intuitive to users that are familiar with FMEA. The Flexibility, *F*, Occurrence, *O*, and Readiness, *R*, metrics are all computed or assigned on a 1-10 scale and the CPN is the product of the three. The major differences in the method are with respect to the manner in which the Flexibility and Readiness metrics are determined. In the following subsections, the details of how the Flexibility, Occurrence, and Readiness ratings are determined are explained in detail. Lastly, a flowchart of the overall process is presented.

Flexibility Rating

The flexibility metric is calculated by counting the number of unique parts that are reusable for the implementation of a given change mode. This quantity is then taken as a percentage of the total number of unique parts in the original design. This calculation will result in the percentage of readily reusable parts, *%RR,* as given by Equation 2.1.

$$\%RR = \frac{\text{\# of readily reusable parts}}{\text{Total \# of parts}} * 100\% \qquad (2.1)$$

Once the *%RR* is determined, this figure is used to calculate the Flexibility rating that will be an input to the CMEA table. Recall that the Flexibility rating must be an integer between 1 and 10, and that a lower rating implies a more flexible design. In order to meet these requirements, Equation 2.2 can be used to calculate the Flexibility rating by using the percentage of readily reusable parts.

$$F = \text{int}(10 - 9 * \%RR) \tag{2.2}$$

There are a few points to consider when using this approach to determining the Flexibility rating. First, only the number of unique parts needs to be considered. The reason for this is that the flexibility rating for small-lot systems is a measure of the redesign effort that is required to implement a change. Counting the total number of parts would result in flexibility ratings that are erroneously high since duplicate parts would be counted more than once when they only need to be redesigned once. Second, fasteners need not be considered in the analysis. Fasteners are neglected because they are selected in conjunction of the two parts that they are joining. Therefore, the redesign effort that is required for a fastener is captured in the effort of redesigning the joined components [45]. Third, if there is any uncertainty as to whether a part is reusable, it should not be considered reusable. The reason for this is that there could be some parts that require further analysis after a change mode has been implemented. In this case, the part's reusability would depend on the results of the analysis. Even if this part were found to be reusable, the analysis still needed to be performed to determine the suitability of the part. Therefore, this effort must be captured and considered as redesign effort, even if no change resulted from the analysis.

This method of calculating the Flexibility rating is appropriate for small-lot systems because it places emphasis on the redesign and selection of the individual components in the system, rather than on the manufacturing process. The "enhanced" CMEA method proposed by Keese et al. [1] added categories that specifically measured the propagation of a change through various elements of the manufacturing process. For example, this method features columns in the CMEA table that measure manufacturing process changes and assembly sequences and methods. These columns are not necessary for evaluating changes in small-lot products because changing the manufacturing and assembly processes does not significantly contribute to the cost of implementing the change. With regard to small-lot products, most of the cost of implementing a change is associated with the redesign of the individual components. Therefore, the method for calculating the flexibility rating explained here is best for small-lot products and systems.

Occurrence Rating

The occurrence rating is an indicator of the likelihood that a particular change mode will occur. When used in the CMEA table, it provides a metric to lessen the severity of extreme but unlikely change modes. For example, certain change modes may be determined to be very difficult to implement but are extremely unlikely to occur. The occurrence rating will keep the CPN for such change modes at a reasonable level. The Occurrence rating is assigned by the user and is determined by using the rubric shown in Table 2.3.

Probability of Occurrence	Occurrence Rating (O)
Very high and almost inevitable	9-10
High	7-8
Moderate	5-6
Low	3-4
Unlikely to Occur	1-2

Table 2.3: Occurrence rating rubric [45]

Readiness Rating

The readiness rating is intended to account for the level of a firm's preparedness to implement a given change mode. The readiness rating is selected by using the rubric that is shown in Table 2.4.

Readiness	Ranking	Interpretation
Completely unprepared	9-10	Low chance of finding a vendor
Very low preparedness	7-8	Current vendor cannot produce component; will require a highly specialized vendor
Moderate	5-6	Current vendor can implement change with significant effort
High	3-4	Current vendor can implement change; exceeds in-house capabilities
Completely prepared	1-2	Change can be implemented using in-house capabilities
Remove	Blank	Part in its current form will not be adapted to redesign

Table 2.4 Readiness rating rubric [45]

The rubric shown in Table 2.4 is similar to that which is proposed by Palani Rajan et al. [51] with a few key differences. First, the ranking system is inverted so that higher numbers correspond to undesirable situations. Second, a third "Interpretation" column has been added that helps users pair specific scenarios with appropriate ratings. The scenarios listed in the "Interpretation" column are meant to be typical situations that are encountered when firms implement changes to small-lot products.

CMEA Process Overview

Performing Change Modes and Effects Analysis for small-lot systems is a ten step process that results in several deliverables. A flowchart of the CMEA process is shown in Figure 2.2.

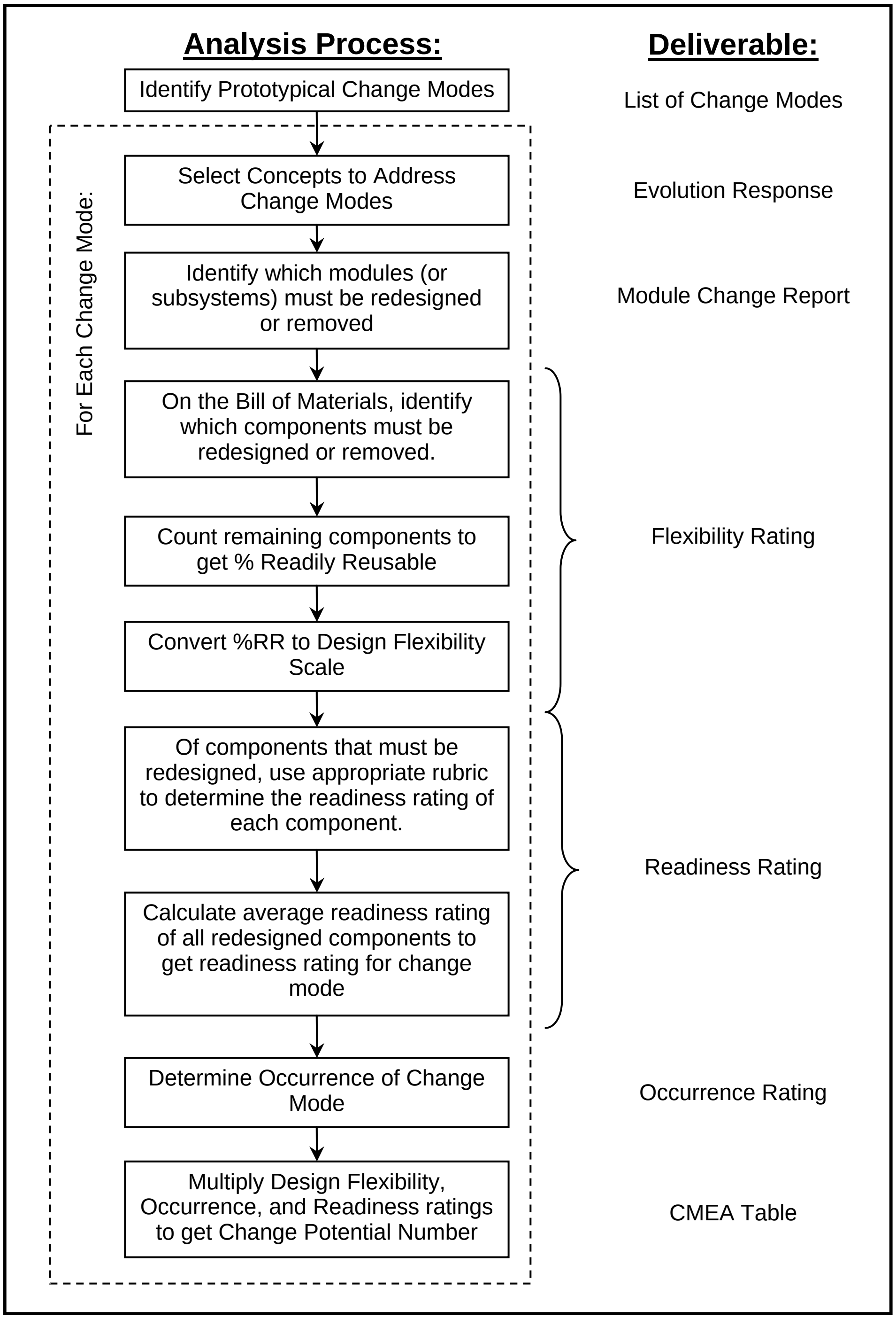

Figure 2.2: CMEA process flowchart [54]

The first step in the CMEA process is to identify the potential change modes of a design. These are gathered from a variety of sources, but the primary sources are customer statements and designer intuition. During the initial phase of a design project, a customer or project leaders may state overly ambitious design requirements for the project. Due to immediate time or financial constraints, many of the early requirements may not be incorporated into the final design of a project. The unused requirements, if they are still considered relevant, may be considered to be potential change modes. Customers may also express additional needs as the project progress. If such needs can not be implemented before the first generation of the project result is complete, they can also be listed as change modes. Once the change modes for a project have been identified, steps two through ten in Figure 2.2 are performed for each of the listed change modes.

The second step in the CMEA process is to develop and select concepts that address the listed change modes. A detailed design of each concept need not be developed for the CMEA process, but the concepts must be developed to the point where the basic architecture of each concept is well understood.

The third step in the CMEA process is to identify which modules will be affected by the implementation of each change mode. This step will be necessary to develop the Flexibility rating for the final CMEA table. Whether or not a module needs to be changed to accommodate a given change mode will depend on the concept that was generated to address that change mode in step two. If there is any uncertainty as to whether the concept will affect a certain module, it should be assumed that the concept does affect it so that the results are conservative and represent a worst case scenario. Steps four, five, and six of the CMEA process are taken to determine the Flexibility rating, as explained in the *Flexibility Rating* section.

Steps seven and eight of the CMEA process result in the Readiness rating that goes into the CMEA table. In step seven, the Readiness rubric that is explained in the *Readiness Rating* section is used to determine the Readiness rating of each individual component. In step eight, the average Readiness rating of all of the redesigned components is computed. This figure represents the final Readiness rating for a given change mode and will be placed directly into the CMEA table.

The ninth step in the CMEA process is to determine the occurrence ratings for the change modes that were listed in step one. The occurrence ratings are assigned according to the rubric that is discussed in the *Occurrence Rating* section.

The final step in the CMEA process is to multiply the Flexibility, *F*, Readiness, *R*, and Occurrence, *O*, ratings in the CMEA table. Once all ten of the steps outlined in Figure 2.2 are complete, the change potential number (CPN) for each change mode is obtained.

2.4 SUMMARY OF REVIEW

In this chapter, the state of the art of the guidelines and measurement methods for flexibility for future evolution is reviewed. Several years of cumulative research have resulted in a list of guidelines for flexibility for future evolution that can be used to help designers develop products and systems that are flexible to unforeseen changes in design requirements.

While the current list of guidelines for FFE is an effective tool for the development of evolvable products and systems, an opportunity to improve its utility is identified. The two guidelines that use the “Adjustability Approach” are found to be too general, and do not connote the same semantics as the other guidelines in the list. It was also suggested by a previous author that the current list of guidelines fails to include the use of off-the-shelf components, the concept of robustness, and the concept of scalability. Lastly, previous research methods that aimed to develop guidelines for FFE exhibited minimal overlap in their results. This discrepancy suggests that neither method fully captured all of the possible guidelines that could be listed. The research that is presented in the remainder of this thesis will further develop and expand the guidelines for flexibility for future evolution with the goal of improving the aforementioned areas of need.

Several methods for measuring the flexibility of a design are discussed. Change Modes and Effects Analysis (CMEA) is a method that was developed to measure the flexibility for future evolution of a design. The development of this method is discussed, and a version of it that is specifically tailored for use on small-lot designs in explained in detail.

In the following chapter, the research approach that is used to meet the two objectives of this research is presented.

Chapter 3: Research Approach

To meet the research objectives listed in Chapter 1, a selection of small-lot complex testing systems that are similar to the welding test station are analyzed for evolvability using Change Modes and Effects Analysis. As noted in Chapter 1, the first objective of this research is to verify the effectiveness of using the Guidelines for Flexibility for Future Evolution for designing evolvable, small-lot systems. The second objective is to further develop the current list of guidelines to include a more detailed subset of "Adjustability Approach" guidelines.

The general steps in the approach to satisfying Objectives 1 and 2 are outlined in Figure 3.1. While the first five steps for Objectives 1 and 2 are identical, the final steps differ significantly for each objective. In the sections that follow, the details of each step are explained.

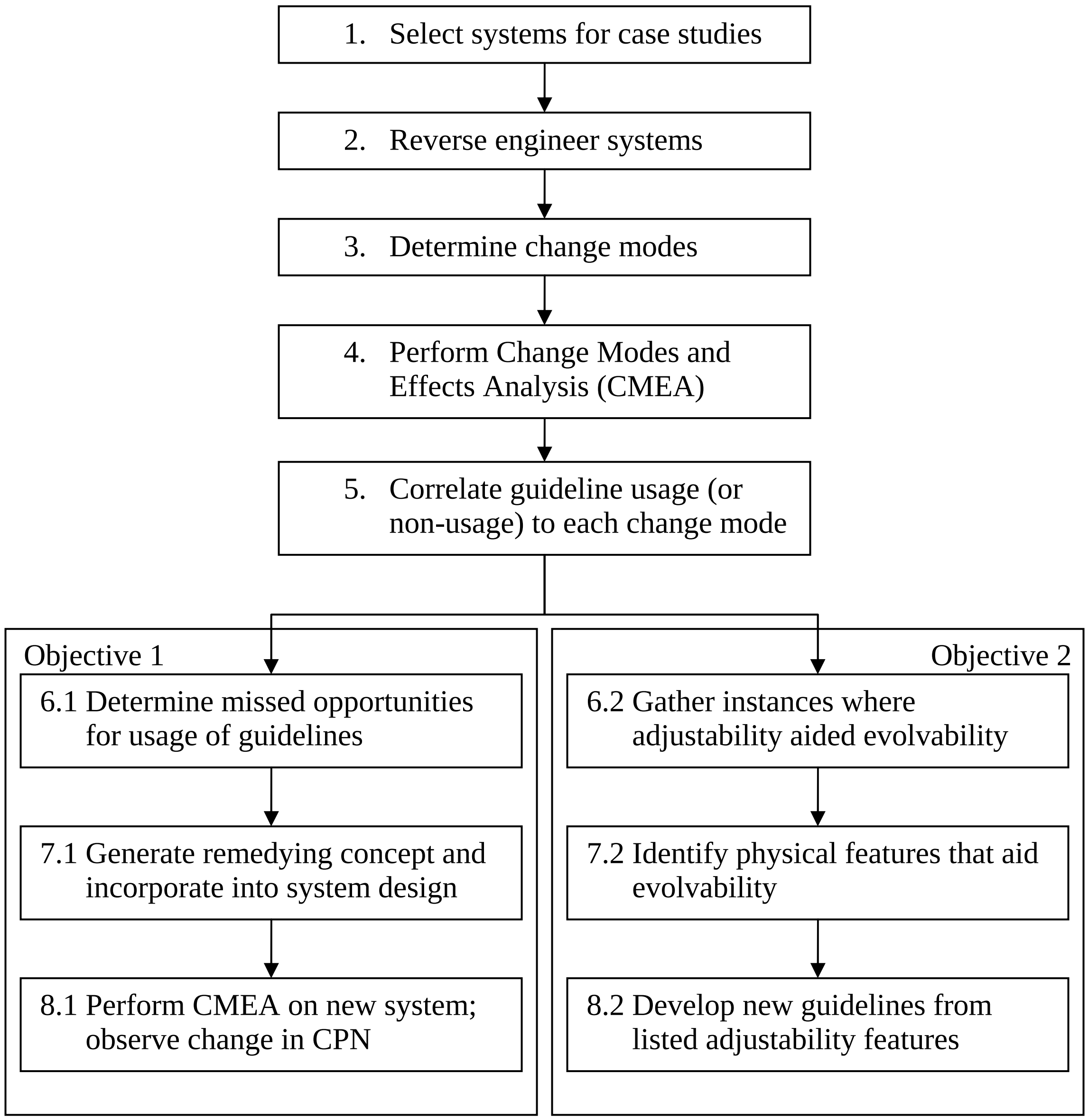

Figure 3.1: Research Approach

3.1 CASE STUDY SELECTION

The first step in the approach is to select a set of systems that will serve as case studies. To ensure the production of valid results and useful insights, the systems will be selected based on the following criteria:

1) Each system must not be mass produced and must be designed and fabricated for a specific application.
2) Each system must have more than two and fewer than ten subsystems that interact with each other on some level.

The reasoning behind the first requirement is that any potential evolutions to each system are to be done to the currently deployed units, rather than to future units that have not yet been fabricated. The current set of guidelines for FFE was developed using mass produced consumer products, in which the cost of implementing a given change mode is strongly related to the cost of changing the manufacturing process. In this situation, the changes are implemented on future realizations of the product, rather than on units that are currently in use. On the other hand, the cost of changes to small-lot systems is primarily associated with the redesign effort and the reusability of system components. Thus, it is important that all of the systems under consideration for this study not be mass produced.

The second requirement is in place to ensure a uniform level of complexity across all of the systems that are being studied. The CMEA results are heavily influenced by the percentage of parts that are reusable for a given change mode. If a system is studied that has dozens of subsystems and thousands of components, a significant change to one of the subsystems may result in a very flexible CMEA rating due to the high number of total system components. Systems such as these may require a different approach that involves decomposing them and investigating one subsystem at a time. Thus, it is important that all of the systems used in this study be of similar size and complexity.

3.2 Reverse Engineering

The second step of the research approach is to reverse engineer the systems. Due to time constraints, a full reverse engineering process such as that which is suggested by Otto and Wood [55] will not be possible. Since many of the systems are currently in operation, it is also not practical to disassemble the systems because this could potentially interrupt the testing schedules and programs of those who use them. However, some reverse engineering is necessary in order to analyze the systems for evolvability. Thus, an abbreviated reverse engineering process will be implemented using the following three steps.

The first step of the reverse engineering process is to create or obtain graphical representations of the systems so that the overall system architectures can be documented. If these documents are unavailable, they are constructed either in the form of solid models or photographs. The second part of the reverse engineering process is to identify system modules. This step helps identify the major sub-functions of the system, and provides a convenient way to categorize the individual components of the system. The third part of the reverse engineering process is to obtain a bill of materials for each system. If a bill of materials is unavailable, one is constructed. A bill of materials for each system is necessary to perform the evolvability analysis, which is explained in Chapter 2.

3.3 Change Mode Determination

The third step in the research approach is to determine change modes for each system. A change mode represents one possible way in which the test station is anticipated to change. For the welding station, change modes are gathered by investigating the requirements list generated during the early steps of the design process.

For the other systems, current users are interviewed and asked to identify useful changes for their system.

Some system users may suggest change modes that are inappropriate for this analysis, and therefore must be neglected. Primarily, the change modes considered in this study must not be too simple. A change mode that only requires replacement of a single part will unfairly reduce the change potential number (CPN), which is the resulting metric of the CMEA. For example, the replacement of a single OEM component, such as a valve or motor, cannot be considered as a change mode for this analysis because any number of individual parts can be replaced with high readiness and low likelihood of occurrence. Thus, including single component change modes in this analysis will unfairly result in low CPN, and will not be considered in this analysis.

Ideal change modes for this analysis are ones that demand significant changes to at least one of the system modules. In this case, a significant change is one that adds a new function or replaces and existing function of the system. The addition or replacement of a function is likely to affect several of the components in a given module and may even propagate to other system modules. Therefore, these types of changes are not so simple that only one part is affected, and they will not drastic enough to warrant complete redesign of the system.

Another type of acceptable change mode is one that requires a change to a major design parameter, such a size dimension or range of motion. These types of changes have the potential to provide valuable insights towards meeting the second objective of this research, which focuses on adjustability. As was the case with the function changing or replacing change modes, these types of change modes must affect several of the system components to be considered for this study.

3.4 EVOLVABILITY ANALYSIS

After the change modes have been gathered, Step 4 of the research approach is to measure the evolvabilities of each respective system. This step will be completed using Change Modes and Effects Analysis (CMEA), which is described in detail in Chapter 2. The result of the CMEA is the change potential number (CPN), which is an indicator of the evolvability of each system to each change mode. The change mode specific CPNs for each system can also be averaged to provide an overall evolvability measurement for each system.

3.5 CORRELATING GUIDELINES USAGE TO CHANGE MODES

To correlate the usage of each guideline with the evolvable features of each system, a Use of Guidelines report is generated for each system as performed by Tilstra [45]. In Table 3.1, a blank use of guidelines report is shown. To conserve space, only a partial report is shown. A full use of guidelines report has one row for each guideline (24 total), and three columns for each change mode.

	Used	Helpful	Change Mode 1:	Used	Helpful	Change Mode 2:
Modularity			Explanation			Explanation
1 Using separate modules to carry out functions that are not closely related						
2 Confining functions to single modules						
3 Confining functions to as few unique components as possible						
4 Dividing modules into multiple smaller, identical modules						
5 Collecting parts which are not anticipated to change in time into separate modules						
6 Collecting parts which perform functions associated with the same energy domain into separate modules						
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related						
8 Using duplicate parts as much as possible without raising part count						

Table 3.1: Partial use of guidelines report [45]

In the first column for each change mode, the user inserts either a "Y" or "N" to indicate whether the guideline was used in relation to that change mode. In the second column, the user inserts either a "Y" or "N" to indicate whether the guideline was (or would have been) helpful in reducing the CPN of that change mode. The third column is reserved for any explanation that is necessary for the user to record how the guidelines were used, not used, helpful, or not helpful.

The use of guidelines report contains valuable information that is used to meet both of the objectives of this research. The report allows a user to see how the use or nonuse of the guidelines influences each change mode. Because the report also contains explanations of how the use or nonuse of guidelines were or were not helpful, the user gains insights about how the physical features of the system influence the evolvability of the system for each change mode.

3.6 FINAL STEPS: OBJECTIVE 1

Recall from Figure 3.1 that the first five steps taken to meet the two objectives of this research are identical, while the final three steps for each object vary significantly. The first objective of this research is to investigate the effectiveness of using the guidelines for FFE on the design of evolvable products and systems. To complete this task, three additional steps are taken after the first five.

First, the use of guidelines report is reviewed and any missed opportunities for guideline usage are listed. A missed opportunity is one in which a guideline was not used for a relevant change mode ("N" in the first column), but its usage would have been helpful in improving the evolvability of a design ("Y" in the second column).

The second step of the final three steps for the first objective is to generate concepts that use the guidelines listed in step one as missed opportunities. The concepts do not need to be developed in complete detail, but they must be clear enough for CMEA to be performed with their hypothetical implementation into the design.

The third and final step is to perform CMEA with the new concepts incorporated in the design of each system. It is hypothesized that the CPN for each change mode will be reduced for the conceptual design with the guidelines incorporated. A reduction in the CPN will confirm the hypothesis that using the guidelines in the design of small-lot systems is effective in creating a more evolvable design.

It is also hypothesized that there will be significantly less room for improvement with the welding test station, because it was designed using the guidelines for FFE and should already be very evolvable. A percent decrease in average CPN for the welding station that is less than that for all of the other systems under consideration is an additional indicator of the effectiveness of using the guidelines for FFE to design evolvable small-lot systems.

3.7 FINAL STEPS: OBJECTIVE 2

The second objective is to further develop the "Adjustability" FFE guidelines. Currently, there are two guidelines in the "Adjustability" section of the guidelines (Guidelines 23 and 24). As discussed in Chapter 1, there is a need to expand these two guidelines, so that they are more effective in guiding designers towards specific design solutions that improve the evolvability of their design.

There are three basic steps specific to the second objective of this research. First, any instances where either of Guidelines 23 or 24 are utilized to aid evolvability are gathered. The use of guidelines report is utilized to achieve this task. Any instances for Guidelines 23 and 24 where there is a "Y" in both of the first two columns of a given change mode is an indicator that a guideline was successfully utilized.

Next, the physical features of the systems that relate to these instances are listed. The “Explanation” columns in the use of guidelines report are used to gather these features.

Lastly, the third step in meeting the second objective of this research is to use the features that were gathered in the second step to develop more specific “Adjustability” guidelines. It is hypothesized that useful new guidelines can be developed by studying physical features that improve the evolvability of a system by means of adjustability.

3.8 CHAPTER SUMMARY

In this chapter, the research approach for meeting the two objectives of this research is explained. The approach uses a known method of measuring evolvability (CMEA) and a tool for correlating the usage of guidelines to physical system features.

A selection of case studies of fully deployed small-lot systems is needed for analysis to successfully meet the objectives of this research. In Chapter 4, a welding test station that was designed by the author using the guidelines for flexibility for future evolution is presented. In Chapter 5, the other systems studied for this research are introduced, and their major functions and features are explained.

Chapter 4: Design of an Evolvable Welding Test Station

A welding station was designed and built for a national laboratory that wants to perform gas metal arc welds on laboratory test specimens. The overall purpose of the project is to investigate the effects of welding process parameters on the quality and characteristics of the resulting joint. To ensure consistent data points, there is a need to perform well characterized welds repeatedly and reliably. It is practically impossible to perform consistent welds by hand, and a typical welding robot would have been too costly. To meet this need within budget, a semi-automated welding station was designed and built by graduate and undergraduate students.

As the project progressed, it was found that many of the design requirements were not well defined and were subject to unknown future changes. The guidelines for flexibility for future evolution (FFE) were used throughout the design process with the hope that the resulting test station would be able to accommodate foreseen and unforeseen future changes.

4.1 RELEVANCE TO RESEARCH OBJECTIVES

There are two objectives to the research presented in this thesis. Objective 1 is to determine the effectiveness of using the guidelines for FFE in the design of new products and systems. Objective 2 is to expand the guidelines for FFE to include more detailed guidelines in the "Adjustability Approach" category.

The welding test station that is described in this chapter presented an opportunity to investigate the effectiveness of using these guidelines in the design of new products and systems. The guidelines for FFE were used during certain steps in the design process to ensure that the resulting system contained several evolvable features.

To meet the first objective of this research, the evolvability of the design is evaluated using the methods described in Chapter 2, and compared to the evolvability of similar products that were not designed using the guidelines for FFE. It is hypothesized that the utilization of the guidelines for FFE in the design of the welding test station produces a more evolvable system.

The welding test station is also an excellent case study for meeting the second objective of this research. The design has several adjustable features that add to the evolvability of the resulting system, which are extracted as new guidelines for FFE under the "Adjustability Approach" subsection. In the next section, an explanation of how the guidelines for FFE were used in the design of the welding test station is given.

4.2 DESIGN PROCESS

The design of the welding test station was an open ended problem with many possible solutions. A structured design process was utilized to ensure the development of the best possible design. In order to infuse evolvability into the design, the guidelines for FFE were used at key steps throughout the design process. The design process with the steps where evolvability was used is shown in Figure 4.1. The shaded blocks in the figure represent the steps where the flexibility for FFE guidelines were used during the design process.

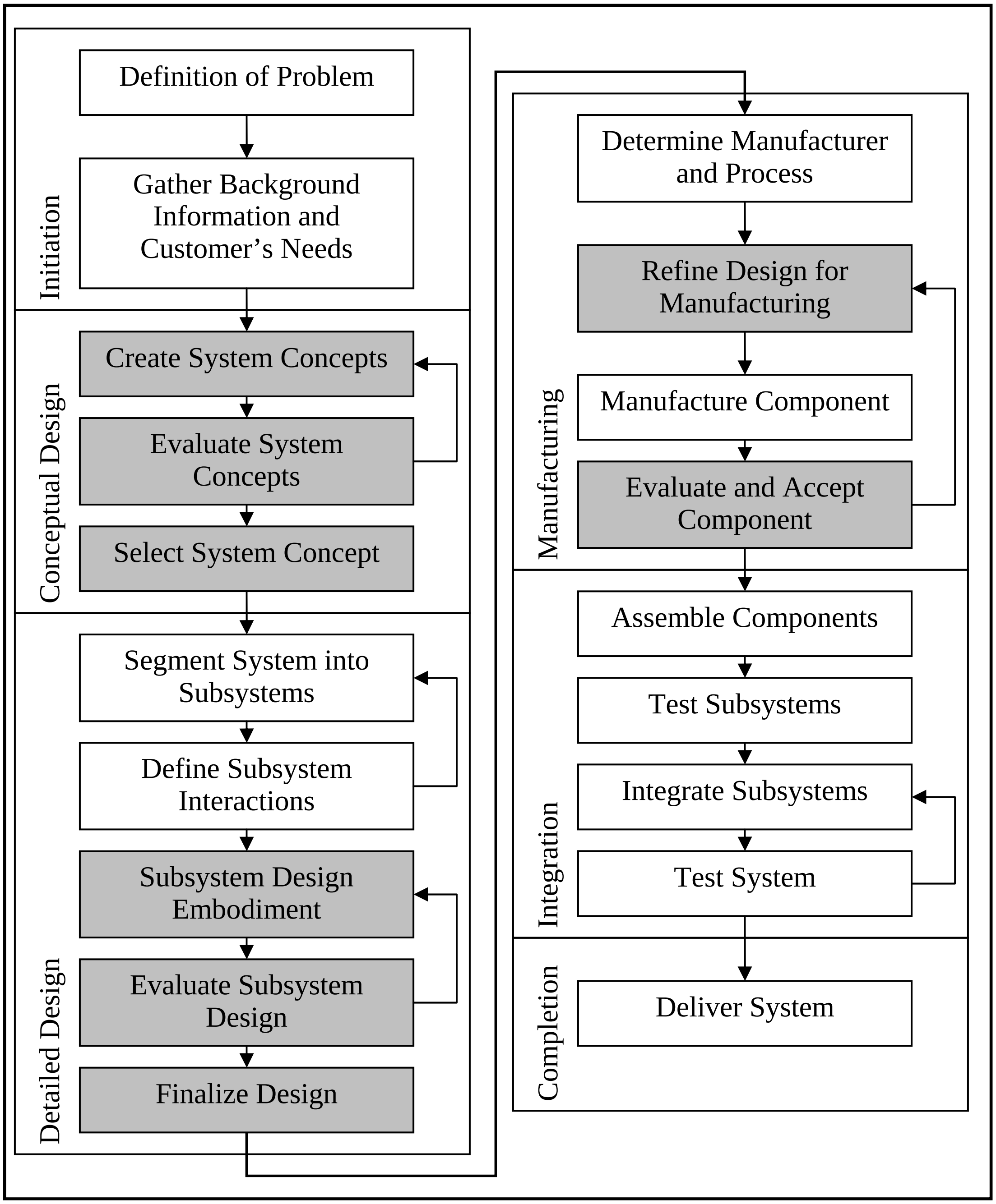

Figure 4.1: Welding station design process

In the *Initiation* phase of the process, the requirements the design must meet were gathered and organized. This was completed by interviewing welding experts at LANL and by conducting a literature review of common welding parameters and their effects on weld quality. In the *Conceptual Design* phase, a large set of concepts that could be implemented to meet the identified design requirements was generated. A group sketching method which is described in Section 4.4 was implemented to complete this task. The finishing step of the *Conceptual Design* phase was to select the best features of the concepts and combine them into a set of refined concept variants. In the *Detailed Design* phase, the subsystems of the selected concept were refined and embodied into a preliminary layout. The next step in this phase was to finalize the design based on the preliminary design. Once the final design was created, the *Manufacturing Phase* could begin. In this phase, the components and materials that were to be used were selected and purchased. Next, the parts were fabricated from the stock materials. In the *Integration* phase, the machined parts were assembled with the other components and subsystems into the final assembly. Finally, the system was tested and debugged and prepared for final delivery. A detailed explanation of how the guidelines for FFE were used throughout each of these steps is given in Section 4.6. In the following chapter sections, the steps of the design process that is described above are explained in detail.

4.3 GATHERING AND ORGANIZING DESIGN REQUIREMENTS

The first step of the design process of the welding test station was to gather and organize design requirements. There were two main approaches taken to complete this task. First, welding experts at the LANL were contacted and interviewed via telephone. Second, a literature review of technical publication was conducted. Information from these two sources was combined with the engineering knowledge of the designers and organized into a requirements list.

4.3.1 Customer Interview

The first step taken to identify the required functions of the welding test station was to consult with welding experts at the Los Alamos National Lab. A question and answer session was conducted via telephone, so that the test station designers could gain a general understanding of how the beryllium is welded at Los Alamos. The notes from the teleconference are shown in Table 4.1:

<table>
<tr><td colspan="2">Meeting Notes: UT-LANL Teleconference, Initial welding process discussion / Q&A</td></tr>
<tr><td>Date: November 20, 2006</td><td>Attendees:
UT: Dr. C. Seepersad, Dr. E. Taleff, Pete Backlund
LANL: Dr. Mike Prime, Paul Burgardt</td></tr>
<tr><td colspan="2">Notes:
1. What is the filler metal composition?
    a. Al-Si Eutectic,   Type 4047 Filler
2. What is the wire diameter and feed rate?
    a. d = 0.030 in
    b. Feed rate: 735 in/min
3. What is the base metal (Be) composition?
    a. Pure Be, S-200F grade, Structural grade Be-Oxide
    b. A powder metallurgy product
4. What is the weld geometry (base metal thickness, gap size, joint type, joint shape, etc…)?
    a. Cylindrical Shape, single piece
    b. See diagram for dimensions
5. What is the traverse speed?
    a. 95 in/min – Fast to reduce heat input to the Be
6. What current and voltage are used?
    a. 21.8V – Constant DCEP
    b. Current set by feed rate ~ 150 A
7. What type of shielding gas is used? Flow rate?
    a. Mixture He-Ar fed separately
    b. 50 CFH He + 9 CFH Ar
8. What are the preheat conditions and cooling rates?
    a. Natural, Air cooling
    b. 127 C Preheat with electrical heaters
9. What is the general welding environment (atmosphere, fixtures, chills, etc…)?
    a. Atmosphere is Argon
    b. 3 pass weld, third layer is machined away
10. Why GMA braze-welding and not some other technique?
    a. Had to be a process that would put appropriate filler metal in place
    b. Wanted to minimize heating of the structure around the weld
11. Are fluxes typically used? What type?
    a. No fluxes used</td></tr>
</table>

Table 4.1: Initial welding discussion meeting notes

The most insightful points gained from the teleconference were the general characteristics of LANL's braze-welding process. The following is a list of useful insights:

1. The welding station needs to perform radial and linear welds.
2. A constant voltage power supply with feed rate dependent current is acceptable.
3. The work piece may need to be preheated.
4. The welding station needs to perform multi-pass welds.

It is important to note that it was not the goal of the designers to duplicate LANL's beryllium braze-welding process. The finer details of the process, such as the exact values of traverse speed and welding voltage, are not of interest. The parameter values will be recorded only as benchmark values. This is because beryllium cannot be welded by UT due to its hazardous nature. In its place, thermal and mechanical surrogate materials were selected for processing at UT. It is expected that the welding process parameters for the surrogate materials will be different than the ones that are used to weld beryllium at LANL. The primary purpose of the telephone interview was to gain an understanding of the general characteristics of the welding process used at LANL so that a similar process can be created.

4.3.2 A Review of Common Welding Parameters and Effects

To augment the list of station requirements obtained from the teleconference, a review of technical publications was conducted. The goal of the review was to determine which process parameters can be varied to affect weld quality. The weld voltage, welding speed, feed rate/current, pulse parameters, preheat conditions, and shielding gas type were determined to be significant parameters. What follows is the review that was conducted to gather these process parameters.

The GMA welding machines at the University of Texas and at the Los Alamos National Lab are both of the constant voltage type. When operating machines of this type, the voltage is set before welding begins, and it stays constant throughout the welding process. Karadeniz et al. [56] argue that the welding voltage has an effect on the depth of penetration. Kim et al [57] also found that the welding voltage plays a key role in obtaining a desired back bead width, which is the width of the bead on the underside of the workpiece.

The welding speed refers to the relative motion between the welding torch and the work metal. The welding speed has significant effects on weld quality. Siddique et al. [58] found that decreasing the welding speed in circumferential welds can significantly increase residual stresses. Likewise, Teng and Lin [59] conclude that decreasing the weld speed significantly increases the heat affected zone and the residual stress. Kim et al. [60] found that welding speed has an effect on the width of the bead, and a lesser but still significant effect on height and penetration.

The welding current and feed rate are also important parameters that affect weld quality. With constant voltage welding machines, the welding current is dependent on the feed rate that is set by the user. Thus, they were considered jointly for this review. Karadinez et al. [56] found that the depth of penetration increases linearly with welding current. Furthermore, Kim et al. [61] have suggested that increasing the arc current (and the feed rate) will increase the width of the weld bead.

Although it was indicated by LANL that they use a pulsed GMAW process, the literature showed that pulsed parameters can have an effect on weld quality. Palani and Murugan [62] showed that pulsed GMAW is better for welding thin sheets of metal, since there is a cooling off period between pulses. They also suggested that the best weld quality is achieved when there is one droplet per pulse (ODPP) spray transfer. Ghosh and Ghosh [63] showed that properly selecting pulse parameters drastically reduces the residual stress in a welded joint. The pulse parameters that can be controlled are the peak current I_p, base current I_b, peak duration T_p, and the base duration T_b.

Preheating is a common practice that is well known to improve the appearance and consistency of welds. Teng and Lin [59] also showed that residual stresses are significantly decreased when the work piece is preheated.

The shielding gas used in a gas metal arc welding process also has drastic effects on the quality of the weld. Typically, pure Argon is used for welding non-ferrous metals. It is also common to use a mix of inert gases in place of pure argon. For ferrous metals the shielding gas is usually pure CO_2 or a mix of CO_2 and other inert gases. The effects of shielding gas composition, as suggested by Iordachescu et al. [64], can include process stability, bead appearance, and heat input.

In Table 4.2, the findings of the above literature review are summarized. It is a list of all of the important parameters that were determined to affect resulting welds, and the corresponding effects of the parameters.

Parameters	Effects
Weld Voltage	-Penetration -Back bead width
Welding Speed	-Residual Stress -Heat affected zone -Bead geometry
Feed Rate/Current	-Penetration depth -Bead width
Pulse Parameters	-Weldability of thin sheets -Residual Stress
Preheat Conditions	-Bead appearance -Residual stress
Shielding Gas	-Process stability -Bead appearance -Heat input

Table 4.2: Process parameters and corresponding effects

It should be noted that the listed parameters are likely to have effects other than those listed here. At this point, the designers were only concerned with which parameters to vary so the test station could be designed to accommodate these requirements.

4.3.3 Test Station Requirements List

Once the needs of the welding test station are well understood, they need to be organized and consolidated. The information gained from the interviews and the literature review is combined to create a requirements list. A requirements list is a single document that summarizes all of the needs that a final product must meet [52]. The requirements list for the welding station is shown in Table 4.3.

The requirements list features three columns. The first column, titled “D W,” identifies whether the listed requirement is a Demand or a Wish. It was observed that some of the requirements needed to be met immediately by the first version of the welding station. Other needs were ones that potentially needed to be met in the future. To distinguish these Immediate and Future needs, a second column, titled “I F,” was created. The third column, titled “Requirements,” lists the identified requirements of the welding station.

P. Backlund A. Browning	**Requirements List** Automated Weld Test Station	Issued on 8/15/07

D *W*	*I* *F*	*Requirements*
		1. Geometry
D	I	• Overall System Fits in elevator, can be in multiple parts
W	F	• Cylindrical Test Specimen: ~1” wide, 6.5” OD, 6.1” ID (LANL)
W	I	• U-Groove: ~0.1” Wide, 0.12” Deep, 12° Sidewall angle (LANL)
W	I	• Filler Wire: d = 0.030” (LANL)
D	I	• Flat Specimen: Various lengths and widths
D	F	• Various weld joint types (butt, lap, groove etc…)
D	F	• Various specimen geometry
		2. Kinematics
W	F	• Specimen moves with rotational motion
D	I	• Specimen moves with relative linear motion
D	I	• Speed: Variable (95 in/min @ LANL)
D	I	• Feed Rate: Variable (735 in/min @ LANL)
D	I	• Weld in 3 passes
D	I	• Variable tip angle
D	I	• Variable nozzle distance/free wire length
W	F	• Weld gun can move with relative motion
		3. Forces
D	I	• Tightly secure and constrain test specimen
W	F	• Allow various means to secure and constrain test specimen
		4. Energy
D	I	• Ground wire (output)
W	F	• Preheating temperature control
W	F	• Cooling rate control
W	I	• Variable Weld Voltage (LANL: Constant Voltage – 21.8 V, 150 A)
D	I	• Variable Weld Current
D	I	• Variable weld speed
W	F	• Tunable arc pulse parameters
		5. Material
D	I	• Shielding gas (Argon)
D	I	• Work surface must be electrically conductive
D	I	• Commercial Bronze 22000 Surrogate Metal
D	I	• Appropriate filler wire for the surrogate work metal.
		6. Signals
D	I	• Start/Stop
D	I	• Real-time measurements of temperature with IR camera / thermocouples
W	I	• Photographs of weld
W	I	• Convenient parameter tuning

W	I	• Weld time, path, and distance
W	F	• Shielding gas flow rate
		7. Ergonomics
D	I	• Emergency shut-off
D	I	• Ventilation
W	I	• Accessible arrangement of controls
W	I	• Safety shield – Possible molten projectiles from spinning specimen
W	F	• Tinted glass to safely view process
		8. Production
D	I	• All parts can be either purchased "off the shelf" or machined in-house
		9. Quality Control
D	I	• Repeatability
D	I	• Accuracy of measurements
		10. Assembly
W	I	• Can be assembled in-house
		11. Transport
D	I	• Mobile, can be transported in an elevator
		12. Operation
D	I	• Base metal must be kept free of contaminants
D	I	• Surface Preparation: Normal, detergent clean is adequate
D	I	• Can be stored in upstairs lab, and operated in the basement
		13. Maintenance
W	I	• Maintenance needy parts accessible for adjustment, tuning, lubrication etc.
		14. Cost
D	I	• Costs no more than $20,000
		15. Schedules
D	I	• Deliverables on 90 day intervals (see proposal)
		16. Flexibility
D	I	• Can accommodate foreseen and unforeseen change modes

Table 4.3: Welding station requirements list

Most of the needs listed in the requirements list came from contacts at LANL or from the literature review. However, several of them were the inspiration of the experience and intuition of the designers. For example, it was known that the device needed to be transported from storage in a 6th floor lab to the 1st floor shop for usage.

From this observation, it was stated that the device must be mobile and compact enough to fit in an elevator as a design requirement.

Throughout the design of the welding test station, the Requirements List served as a working document that was continuously updated as project requirement evolved. When it came time to build a functioning prototype of the welding station, the engineering metrics in the Requirements List served as a reference to ensure the station met all of the immediate needs of the project.

4.4 PRELIMINARY DESIGN

The first step in the design of the welding test station was to identify what the device must do. This step was accomplished with the creation of the requirements list. The next step was to generate concepts for a device that will meet the needs that were listed in the requirements list. This was accomplished sequentially by generating a set of concepts, selecting a design from the set, and then refining the selected design into a preliminary layout.

4.4.1 Concept Generation

There are many techniques for generating design concepts, most of which are a group effort. A particularly effective one that generates many concepts in a relatively short period of time is the 6-3-5 method [33]:

- Six (“6”) designers sit around a table, each with a large, clean sheet of paper.
- Each designer divides the paper into three (“3”) sections and draws three concepts that satisfy a specific set of functions.

- After a set period of time, the sketches are passed to the right and the designers add ideas to the previous sketches.
- One full rotation of the sketches is considered to be one round, and the process is repeated for five ("5") rounds.

There are several advantages of this technique as compared to other concept generating methods. First, 6-3-5 combines both words and pictures to effectively convey ideas. Second, there is no talking allowed; so, it is impossible for group members with dominant personalities to prevent others from contributing. Lastly, participants tend to springboard off of each other's ideas as the sketches are exchanged.

For the welding station, a group of mechanical engineering design graduate students were asked to generate concepts for a GMAW setup that can perform both linear and radial welds. Several good ideas came from the session. The students were given the functional requirements of the system, but were not shown the evolvability guidelines for flexibility for future evolution. The best ideas were taken, combined, and then converted into a cleaned up concept, forming a set of concepts from which we could choose. These concepts are shown in Figure 4.2 through Figure 4.6.

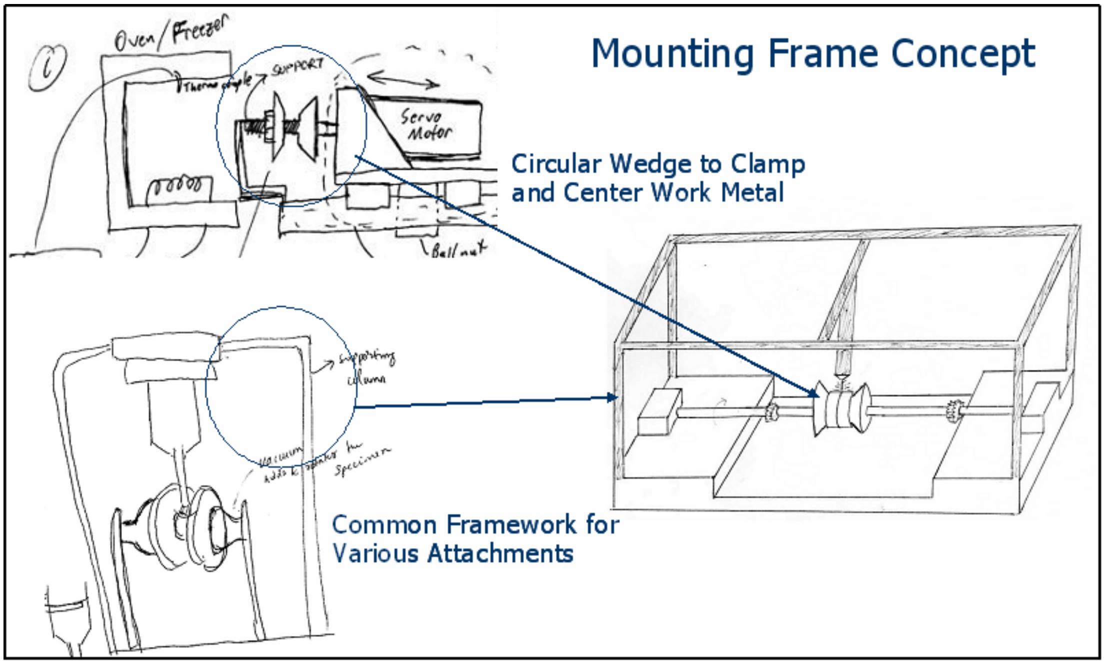

Figure 4.2: 6-3-5 Mounting frame concept

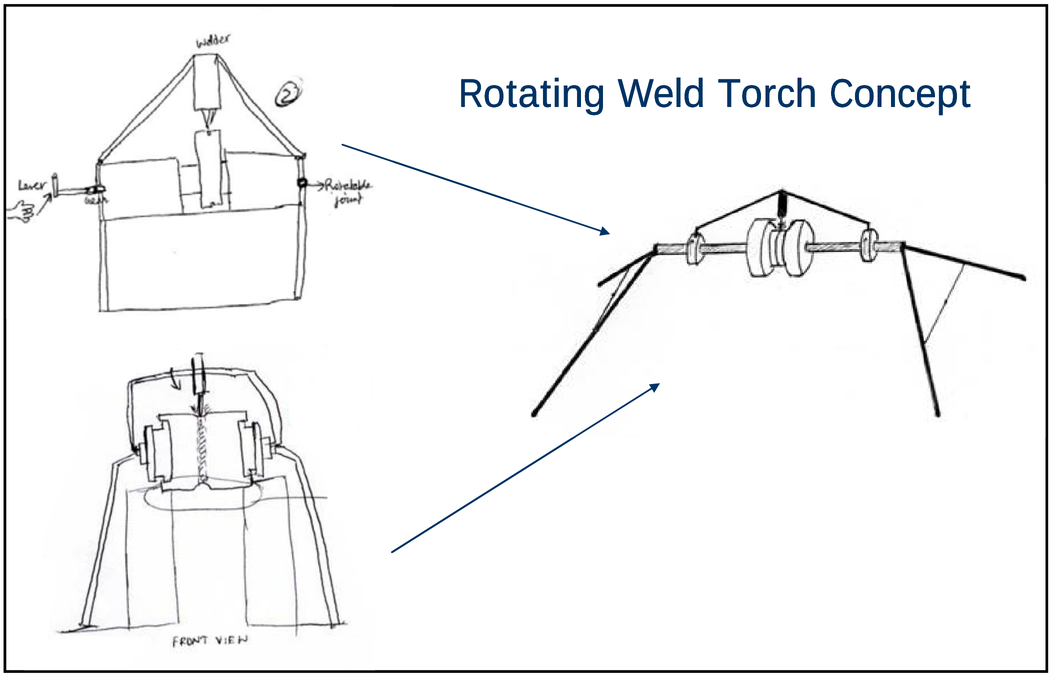

Figure 4.3: 6-3-5 Rotating weld torch concept

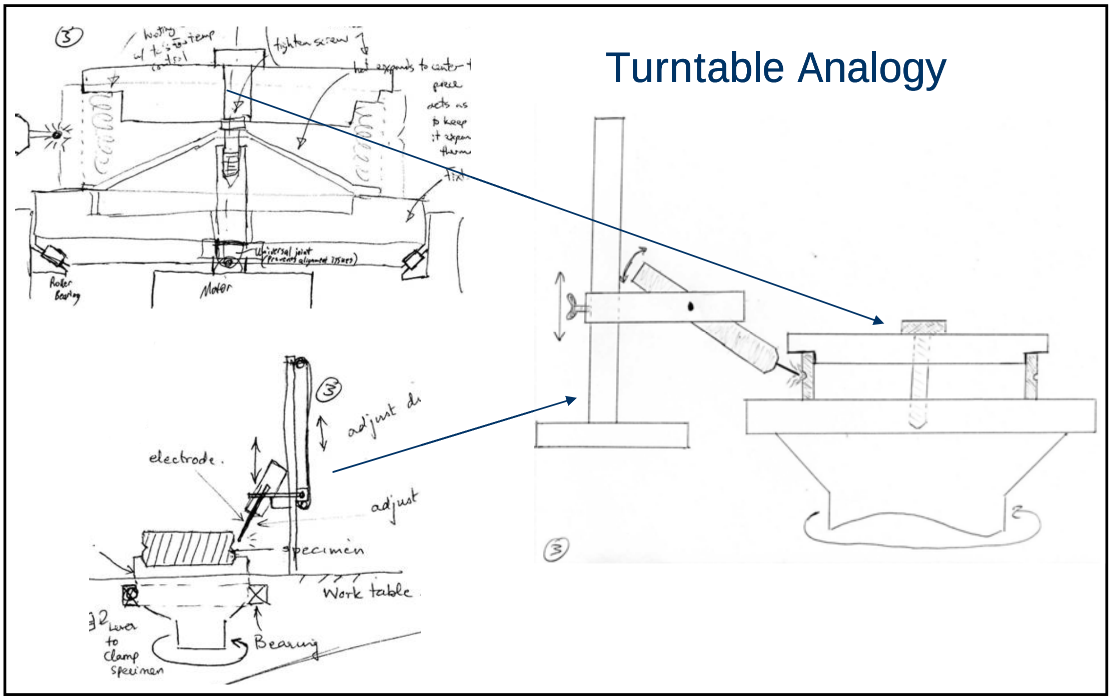

Figure 4.4: 6-3-5 Turntable analogy

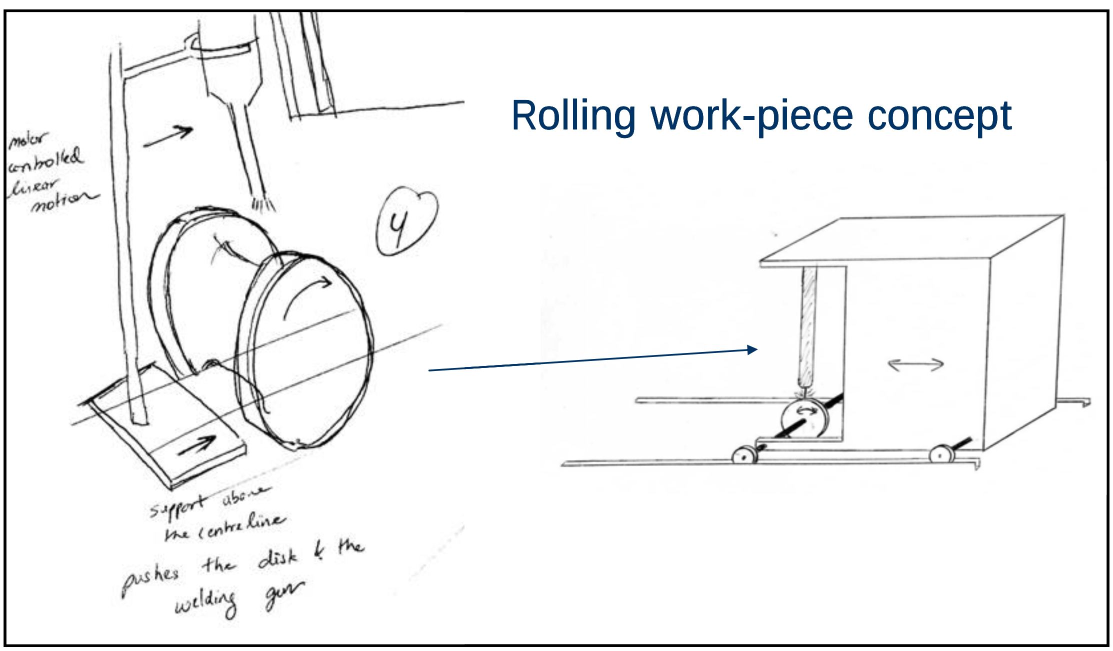

Figure 4.5: 6-3-5 Rolling work-piece concept

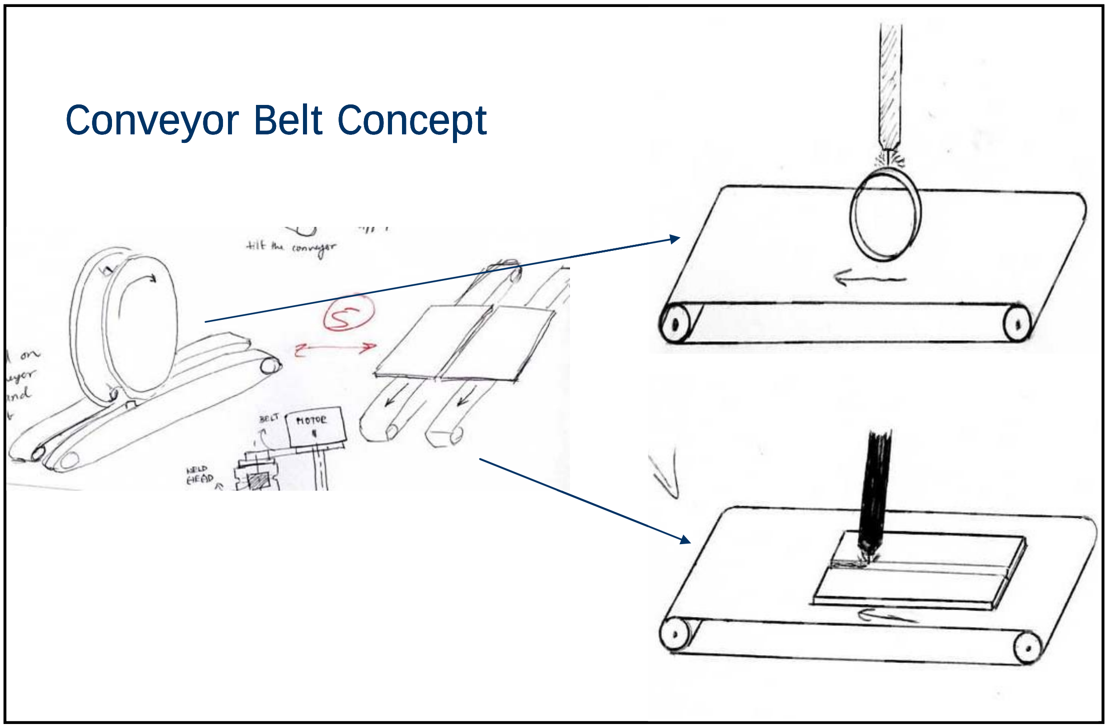

Figure 4.6: 6-3-5 Conveyor concept

The session resulted in a set of five unique concepts. To refine this set, the guidelines for flexibility for future evolution were used to select evolvable features from the concepts. These evolvable features were then combined to create the final concept. For example, the concept shown in Figure 4.2 features a framework that surrounds the work envelope. Using a framework for mounting multiple modules is one of the guidelines for FFE, so this feature was incorporated into the final concept.

4.4.2 Conceptual Design

The selected concept was a combination of three main ideas. The first idea was to use a common framework to create a work envelope. The second idea was to use a turntable for performing radial welds. The third idea was to use a rack and pinion style motion table for performing linear welds. A simple sketch of the selected concept is shown in Figure 4.7.

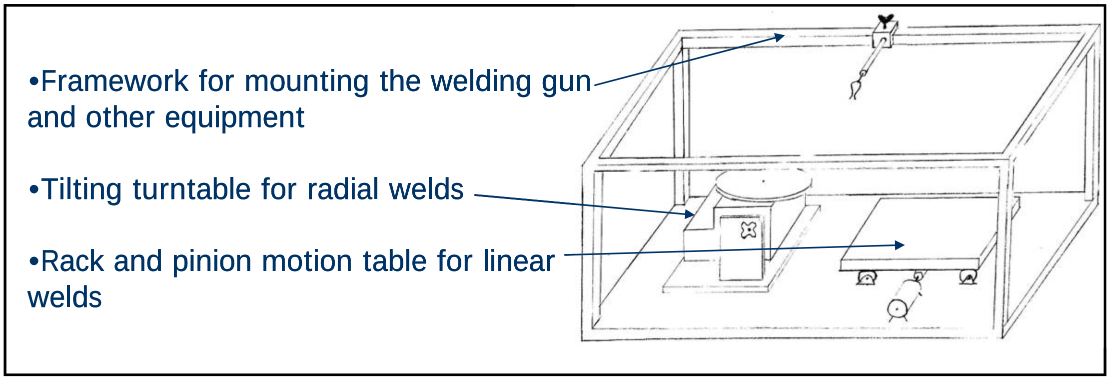

Figure 4.7: Selected concept

A commercially available off-the-shelf turntable could be used for performing radial welds, as shown in Figure 4.8. To save money and design time, the motor in the turntable could be used to drive a rack and pinion linear motion table for performing linear welds. A standard chuck is often available as an accessory for such a turntable so a shaft with a pinion gear can be easily integrated into the assembly. A preliminary solid model of the test station in this configuration is shown in Figure 4.9.

Figure 4.8: MK Products *AirCrafter T-200* rotary table

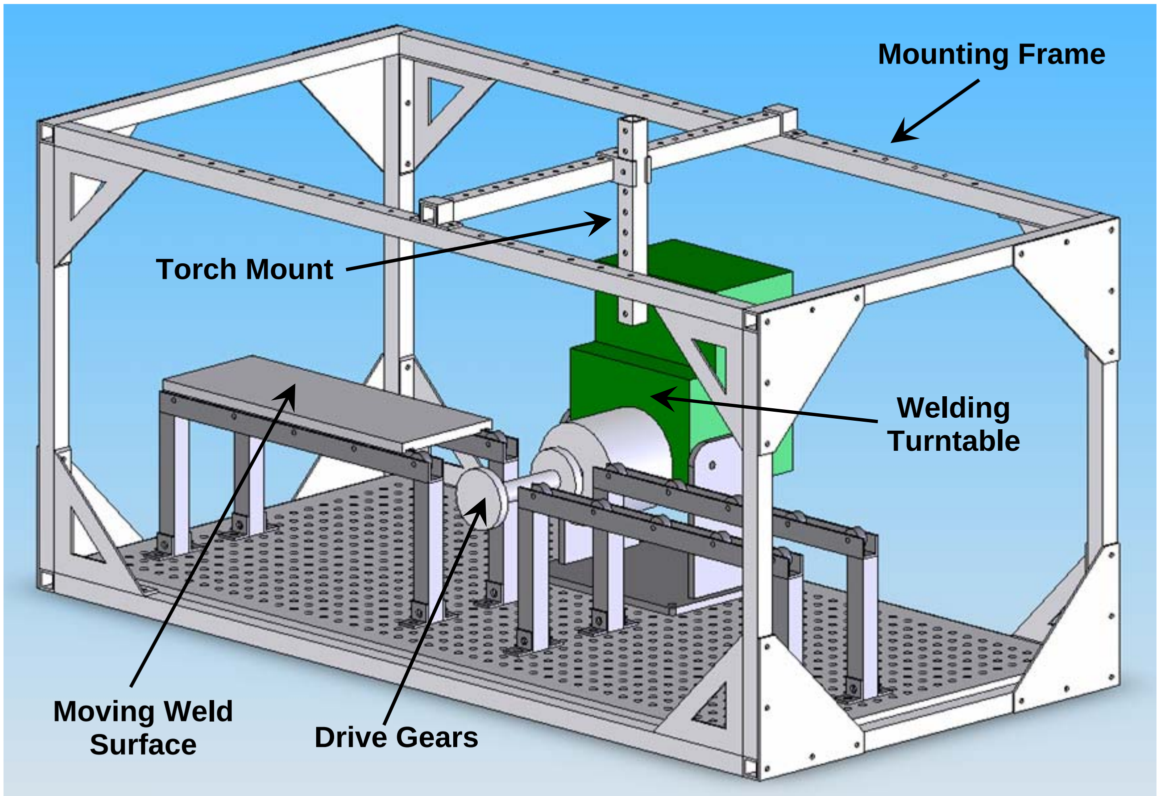

Figure 4.9: Preliminary design

The design in Figure 4.9 was meant to portray the basic concept of the final design. It did not yet represent the final product. The components and materials that were to be implemented in the final design were yet to be selected and sized. In addition, the cost, availability, and manufacturability of the final components also needed to be considered.

4.5 FINAL DESIGN

In this section, detailed solid models of the individual modules and the overall layout of the final design are presented and explained. The final design of the test station is a detailed version of the concept that was generated and refined in Section 4.3 with only one major functional difference. The off-the-shelf rotary table is replaced with a stepper motor system that can drive a rack and pinion linear motion table. This decision was made because the turntable concept only allowed for single pass, constant speed motion. With a LabVIEW controlled stepper motor system, it is possible to program motion sequences such as a rapid return for multi-pass welds. Furthermore, it is much easier to couple the motion control with the data acquisition if both are controlled with a common platform such as LabVIEW. Lastly, it was indicated by LANL personnel that radial welds were not a critical capability at this point in the project.

4.5.1 Final Layout

The final layout of the test station, as illustrated in Figure 4.10, is composed of five separate modules that carry out the main functions of the system. The frame assembly is the common platform that all other modules connect to. It is used for mounting any other equipment that must be interfaced with the system such as an infrared camera. The linear weld surface holds the test specimen and moves laterally to provide the desired process motion. The drive-shaft assembly, which is connected to the motor with a belt pulley system, drives the linear weld surface. The torch mount holds the welding torch in a specified position during the welding process. Lastly, the motor assembly holds the motor in place, and isolates it from the electrical current that is present during the welding process.

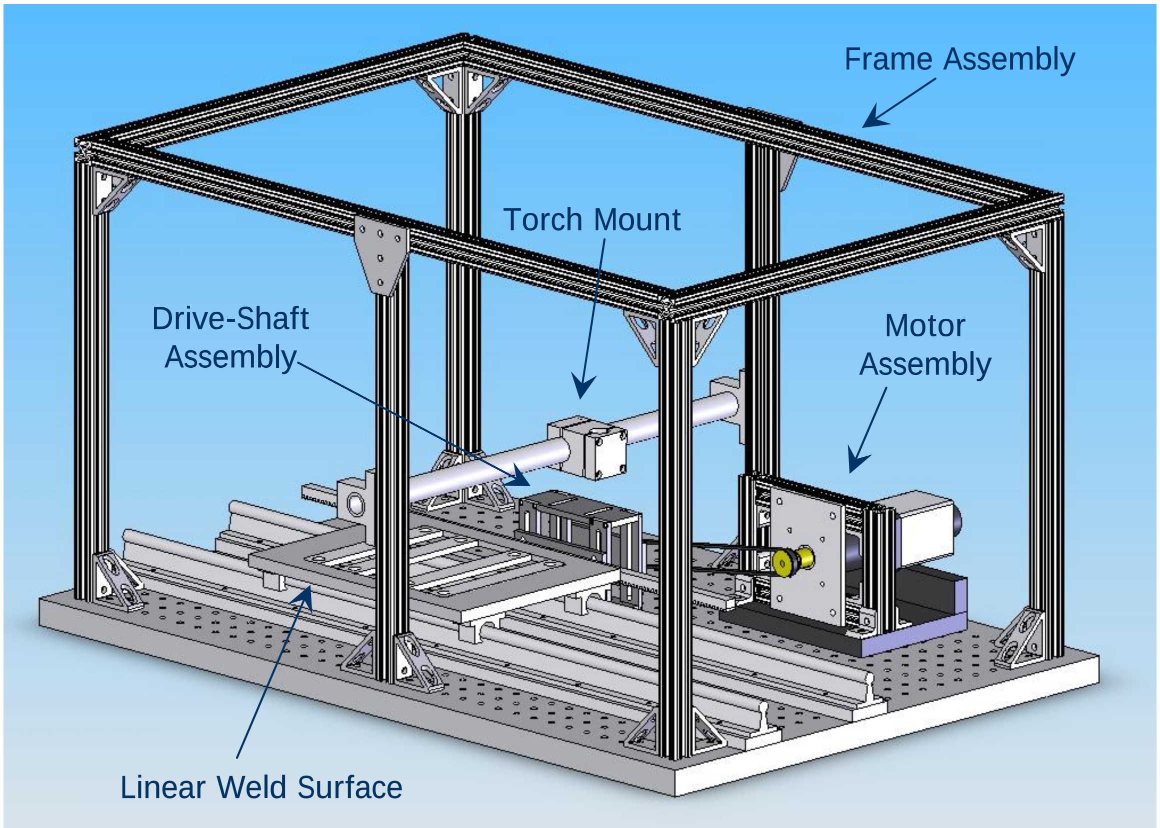

Figure 4.10: Final test station layout

In the following subsections, the solid model of each module is presented, and the details of each module's functions are explained.

4.5.2 Frame/Base Assembly

The frame/base assembly, shown in Figure 4.11, has two main features. The first feature is the optical breadboard that functions as the base of the system. The outer dimensions are 2 ft. x 3 ft., and it features an array of 1” spaced ¼-20 threaded holes. Although it is more costly than other solutions, the use of the breadboard increases the flexibility of the system. The pattern of threaded holes makes it very easy to add or subtract modules and components if the needs and functions of the system change in the future.

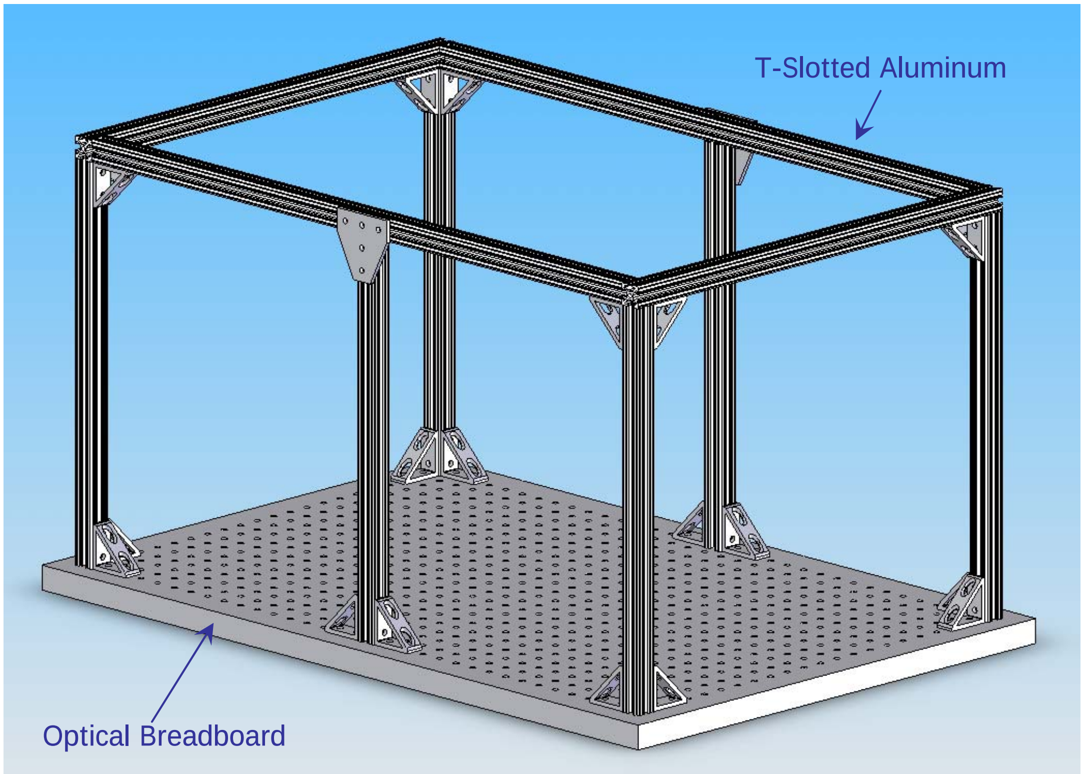

Figure 4.11: Frame assembly

The second feature of the frame/base assembly is the structural mounting frame. The frame can be used to mount various components and modules and is constructed of 8020 brand T-Slotted aluminum. Due to the nature of the T-Slotted members, anything that is mounted to the frame can be secured in any desired position. This functionality is very important since the positions of the welding torch and the infrared camera are be critical process parameters.

4.5.3 Linear Motion Table

The linear motion table, shown in Figure 4.12, provides a moving surface to which the test specimens can be mounted. One of the requirements of the welding surface is that it must accommodate a large range of specimen shapes and sizes. Also, it must be able to physically constrain and secure the specimens in various ways. A simple, solid rectangular plate would not accommodate these needs. If the test piece is too long, it would extend beyond the edges of the surface. If the test piece is too short, it may not be able to be constrained in the desired fashion with standard C-clamps. To meet this challenge, the welding surface has removable sections on the interior. This way, any test piece that is between 1 inch and 12 inches can be constrained from both ends. Furthermore, it may be desirable to take temperature measurements from underneath the test piece. The option of an open section in the middle of the welding surface meets this need.

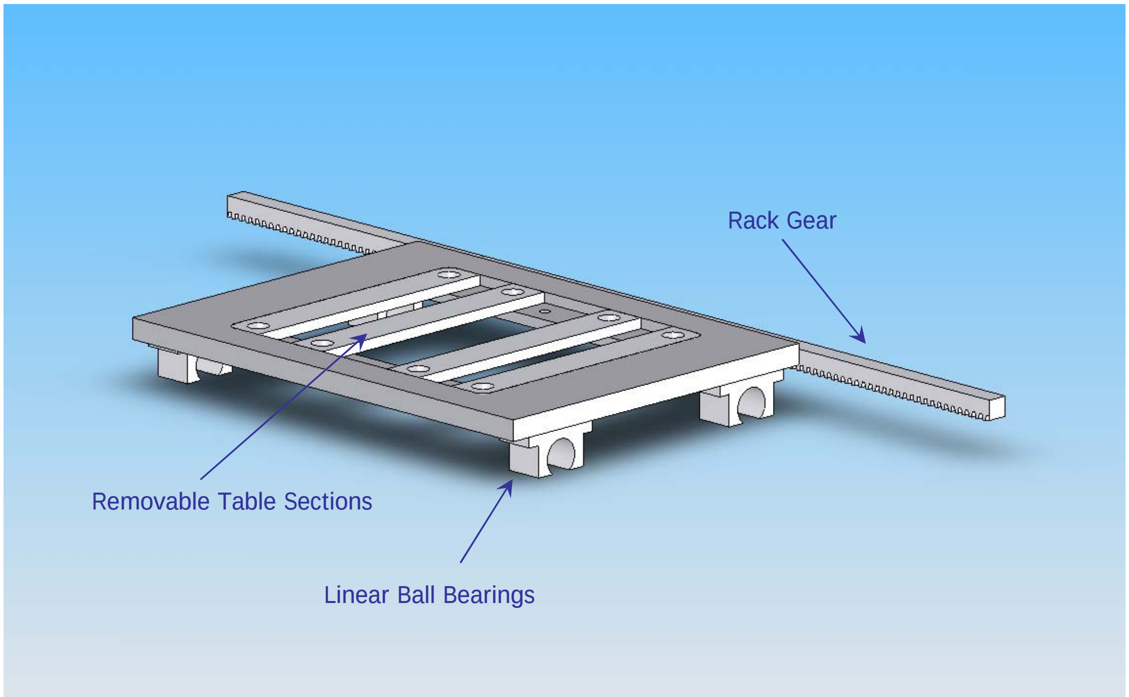

Figure 4.12: Linear motion table

To allow the necessary lateral motion, the rectangular surface sits on four pillow blocks that house linear ball bearing elements. These elements slide on two parallel rails that sit on the optical breadboard. These rails are bolted to two parallel risers which screw in to the breadboard. It may become necessary to view the test specimen from underneath with the IR camera, so these risers can be raised to achieve the necessary angle of view. The assembly has a 24 inch rack mounted along the back edge. This is driven by a pinion gear in the shaft mount assembly to provide the desired motion.

4.5.4 Torch Mount

The torch mount is used to hold the welding torch in a preset position during the welding process. The torch height and the torch angle are both important process parameters, so it is important that the torch mount assembly accommodate the adjustability of both.

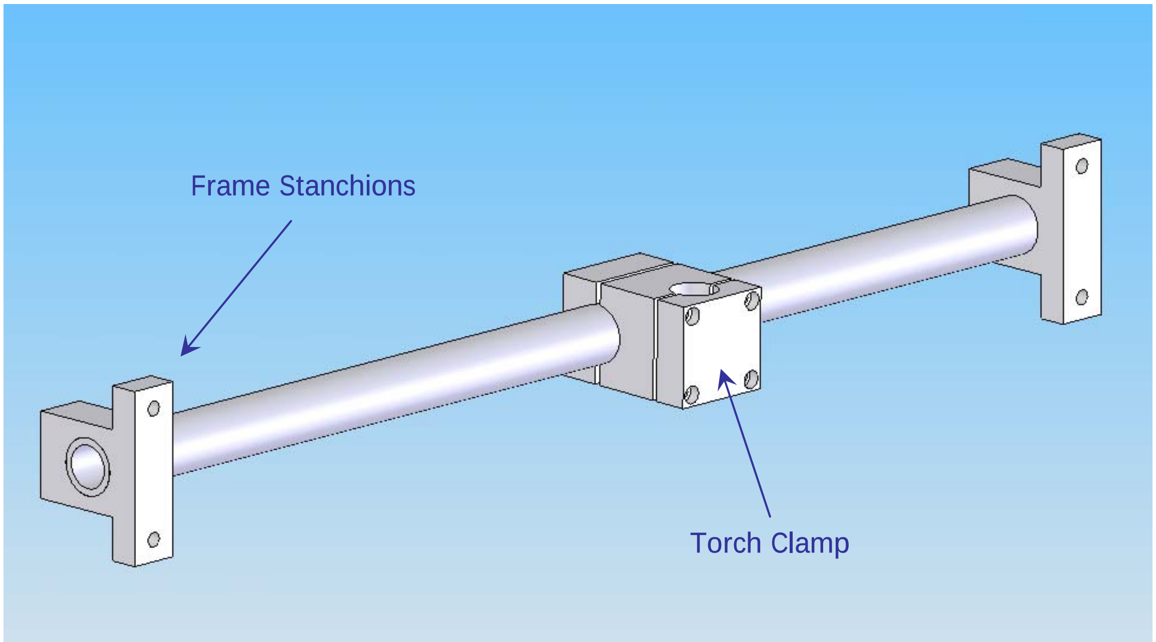

Figure 4.13: Torch mount assembly

In Figure 4.13, the design of the torch mount assembly is shown. It consists of a circular beam that is supported by stanchions at each end. The stanchions mount to the frame assembly and can be mounted at any height, thus providing the necessary height adjustment. The torch clamp is a three piece assembly with two orthogonal holes bored at each end. The larger hole is used to wrap around the circular beam. It can be rotated to any angle, thus providing the necessary angle adjustment. The smaller hole is used to secure the welding torch.

4.5.5 Drive Shaft Assembly

The drive shaft assembly shown in Figure 4.14 and Figure 4.15 interfaces with the linear motion table and drives the sliding weld surface in a pre-programmed sequence. The drive shaft in the module is driven by a belt pulley system that connects directly to the motor. The front of the assembly, shown in Figure 4.14, shows the pinion gear that drives the motion table.

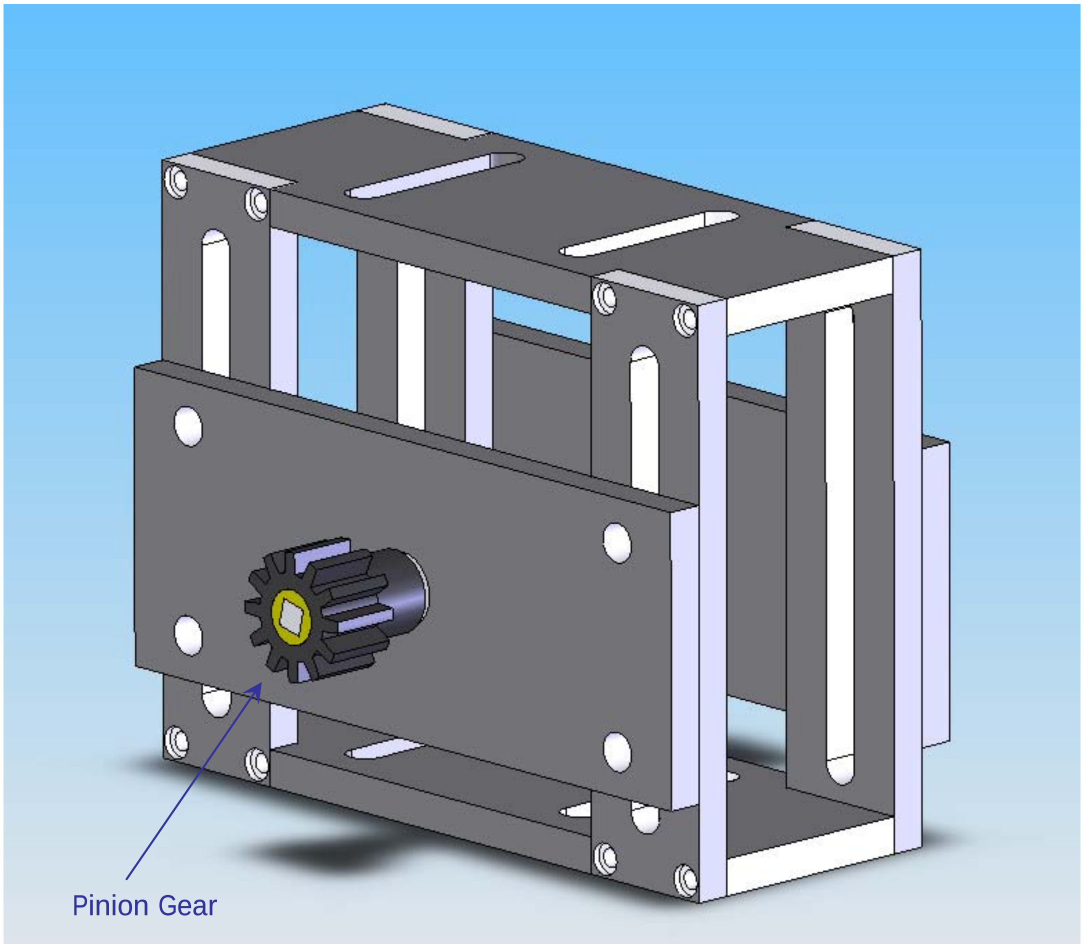

Figure 4.14: Drive shaft assembly - front view

The pinion gear is connected to one end of a double ended shaft which runs from the front to the rear of the module. The rear view of the assembly is shown in Figure 4.15. On the other end of the drive shaft, there is a belt pulley. The pulley system is used as a way to insulate the motor from the electrical current that comes from the welding torch.

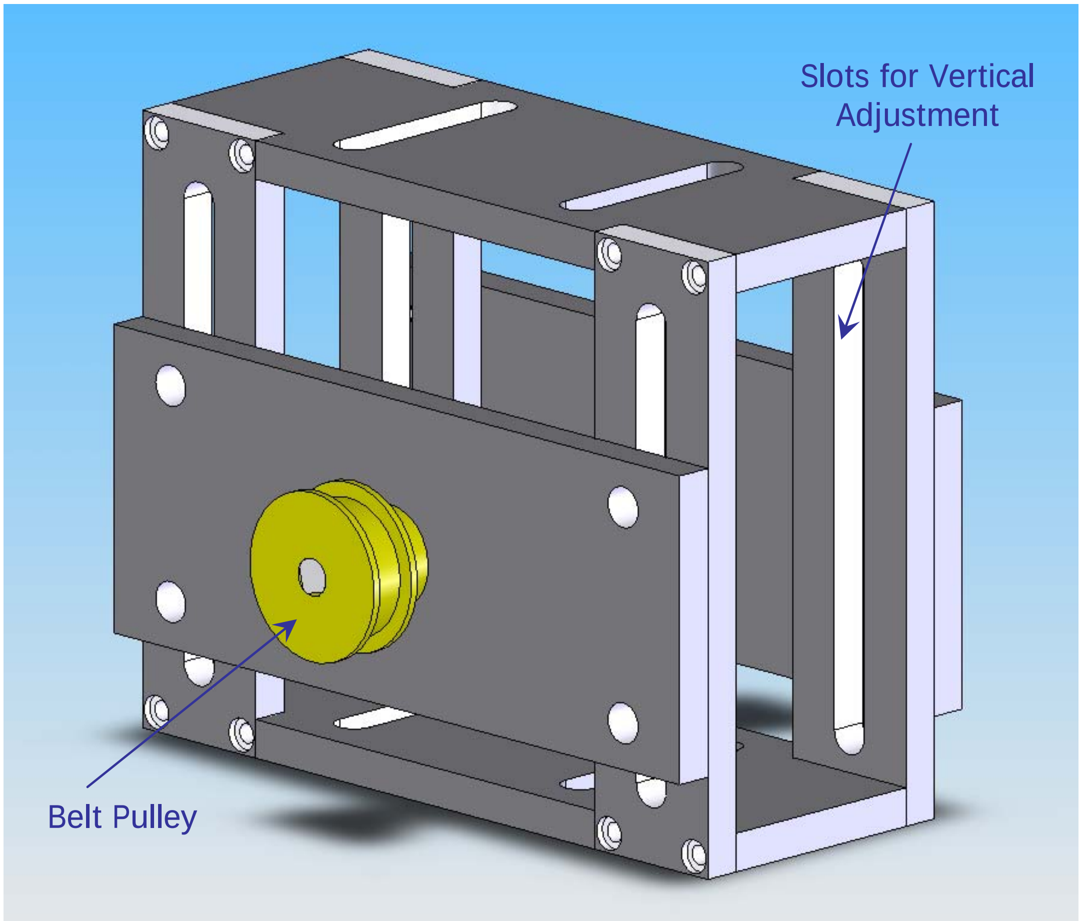

Figure 4.15: Drive shaft assembly - rear view

4.5.6 Motor Mount

The motion of the sliding table is driven by a stepper motor that is controlled with LabVIEW motion control software and hardware. The final design of the motor mount is shown in Figure 4.16. This motor subsystem has two major design requirements. First, it must completely isolate the motor from the welding current. This is achieved by using a plastic, electrically insulating base to connect the motor to the frame base. Second, it must allow the motor to be adjusted horizontally, so that the drive belt can be tensioned. This is achieved by mounting the motor in slotted frame members.

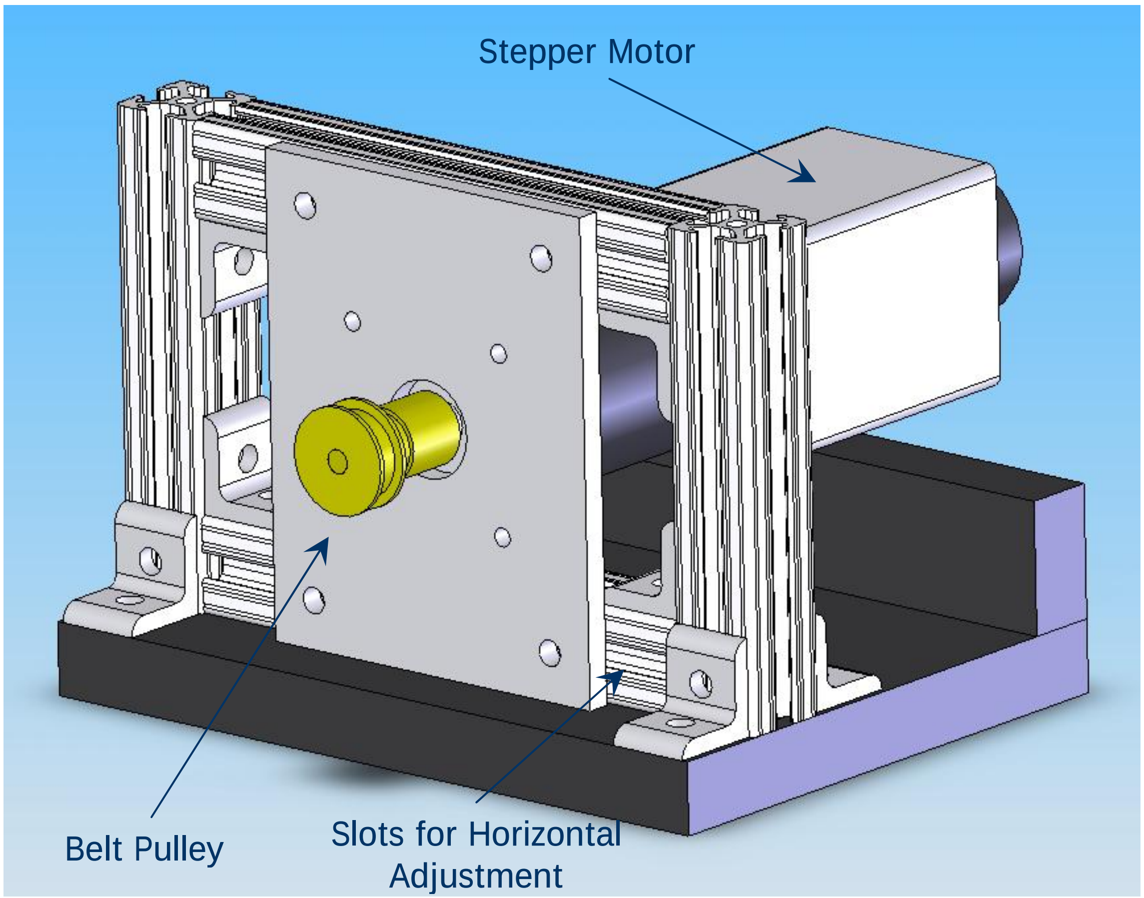

Figure 4.16: Motor assembly

The figures and models described in this section are meant to be a general overview of how the modules are designed and arranged. A detailed bill of materials for all of the test station parts and components is listed in Appendix A.

The welding station that resulted from the design process described above is truly unique and is a valuable contribution to welding research. It has several features that are not found on typical automated welding systems. For example, most automated welding systems have an integrated welding torch that is custom designed and manufactured to match the welding system. The welding test station in Figure 4.10 has a universal torch mount that can hold most standard welding torches. This feature allows users to perform automated or manual welds with the same welding power supply.

Another unique feature of the welding station is that the welding torch remains stationary throughout the welding process. This feature enables the user to record the vents that occur in the weld zone with a video or infrared camera without having to also move the camera. Conversely, most automated welding systems move the welding torch and hold the work-piece in a fixed position. One motivation for holding the work piece in a fixed position is that it is difficult to provide an electrical ground for a moving weld fixture. The design features that isolate the motor from the welding current solve this problem and allow the weld zone to be viewed with a stationary camera during the welding process.

Lastly, the motion control system on the welding station is synchronized with eight thermocouple input modules. This feature allows researchers to take valuable temperature measurements with known relative torch position. This data is important for understanding critical research issues that are related to temperature of the work piece during and after the welding process.

4.6 DESIGN FOR EVOLVABILITY

A major challenge that the designers faced when designing the welding test station was that many of the requirements listed in the requirements list were not precisely defined. For example, it was known that it may be necessary to perform various weld joint types (butt, lap, etc.) or have various test specimen shapes and sizes. Also, many of the requirements were anticipated to change in the future. This was first addressed in the requirements list when a column was added that identified each need as an immediate or a future need. These challenges were met in full by using the flexibility for future evolution guidelines that are discussed in Chapter 1. Since the welding test station was anticipated to change, the flexibility principles were implemented during certain steps in the design process. A flowchart of this process was first presented in Section 4.2, and is given again here (Figure 4.17) for convenience. The shaded blocks in Figure 4.17 represent the steps in which the guidelines for FFE were used.

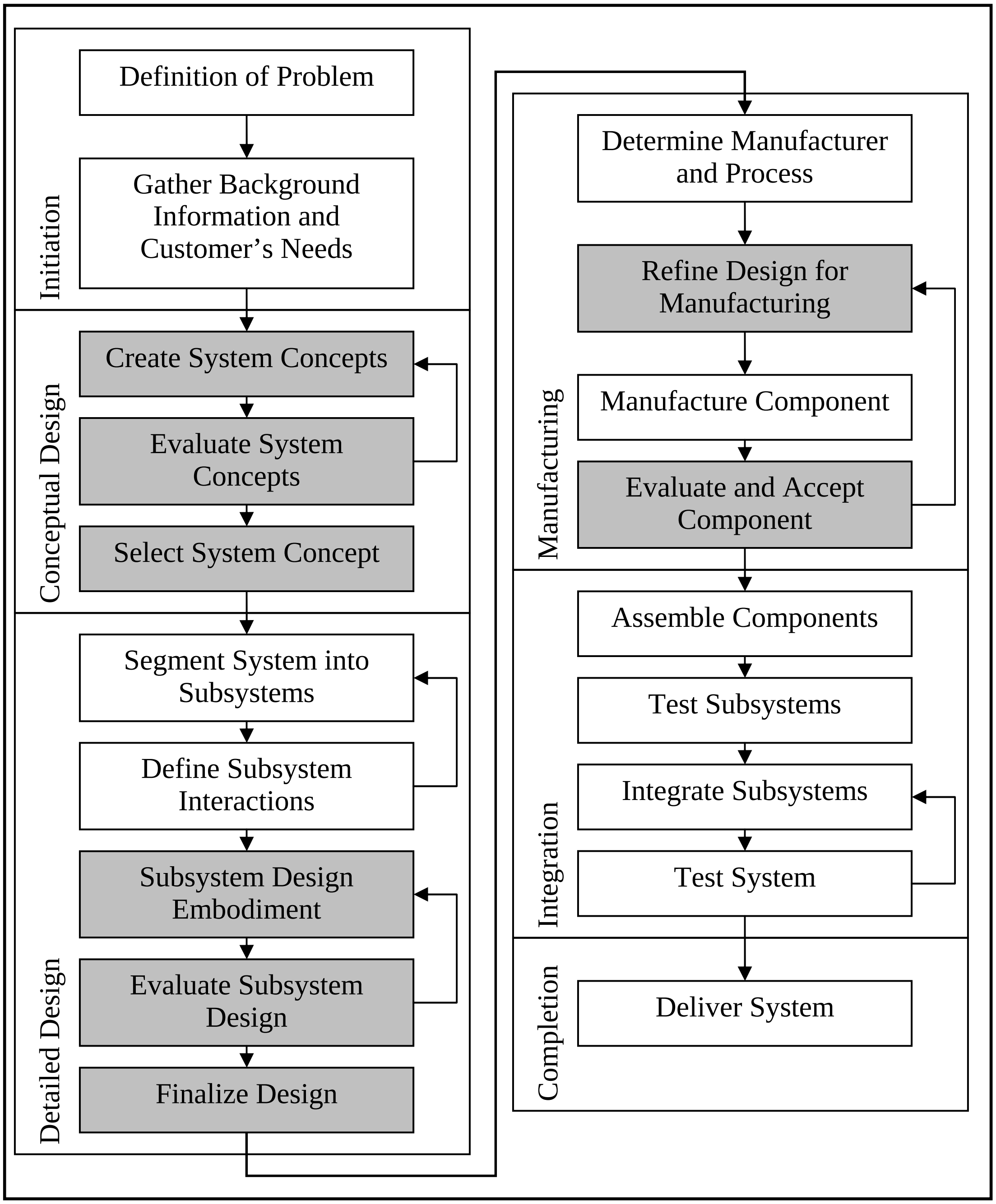

Figure 4.17: Design process with steps where guidelines for FFE were used shaded

During the concept selection phase, guidelines were used to select evolvable features from the concepts. These evolvable features were then combined to create the final concept. For example, one concept featured a framework that surrounded the work envelope. Using a framework for mounting multiple modules is Guideline 20, so this feature was incorporated into the final concept.

During the detailed design phase, the flexibility guidelines were used when making decisions about the overall system layout, and the architecture and specific features of each module. First, the main functions of the system were clearly listed and efforts were made to ensure that they were separated into separate modules, as suggested by Guidelines 1 and 2. Once the separate modules were identified, the guidelines were used "on-the-fly" to influence the architectural and embodiment design decisions. For example, when designing the welding surface to which the test specimens are affixed, an important consideration was that the size of the specimen was unknown and subject to variety. To accommodate this potential change, the surface was split into multiple, smaller pieces that are removable, as suggested by Guideline 4.

During the manufacturing phase, efforts were made to preserve the evolvable features of each part and module when selecting components and refining the designs for manufacturability. For example, Guideline 19 suggests creating detachable modules. In order to ensure the detachability of all modules, an optical breadboard was used for the base that features an array of evenly spaced threaded holes. Since all modules are attached to this base or to the framework with removable fasteners, all of them can be moved or removed easily.

The use of the flexibility for future evolution guidelines during the design of the welding test station resulted in features that make the design notably more evolvable. In Figure 4.18, the overall layout of the system is shown with its evolvable features and corresponding guidelines labeled.

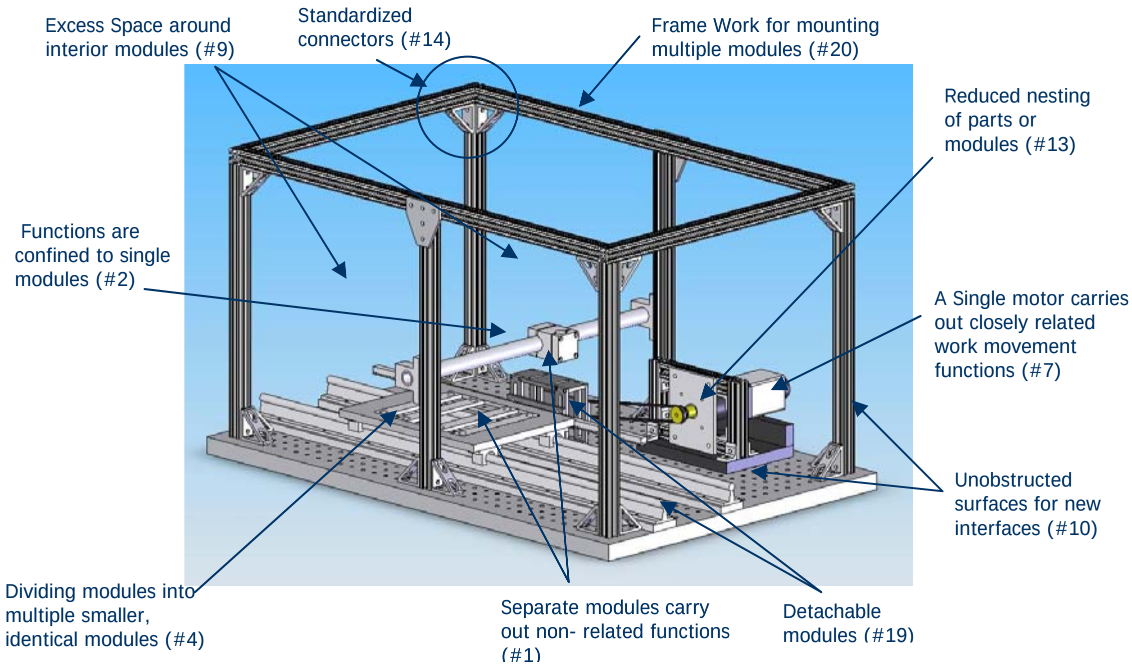

Figure 4.18: Welding test station with evolvable features and corresponding guidelines

The frame/base assembly has five features that make it evolvable. The first is the optical breadboard that functions as the base of the system. The breadboard features an array of threaded holes so that multiple modules can be easily attached and removed, as suggested by Guideline 19. The second evolvable feature of the frame-base assembly is the implementation of the structural mounting frame, as suggested by Guideline 20. The third evolvable feature of the frame is that it is constructed of T-Slotted aluminum. This enables the use of standardized connectors on all surfaces of the frame, as suggested by Guideline 14. The slots in the frame also allow for easy adjustment of any components that are mounted to it, as suggests by Guideline 23. The fourth evolvable feature of the frame/base assembly is the incorporation of several unobstructed surfaces as suggested by Guideline 10. This leaves space for additional module interfaces should the need arise. Lastly, the interior volume of the frame is intentionally larger than the necessary work envelope of the current setup. This creates excess space around interior modules as suggested by Guideline 9. Because there is excess space, additional or larger modules can be added without affecting the frame.

The linear motion table, shown in Figure 4.12, provides a moving to which the specimens can be mounted. One of the challenges faced when designing the welding surface is that it has to accommodate various specimen shapes and sizes. Also, the specimens need to be constrained in various ways. A simple, solid rectangular plate would not meet these needs. If a test piece is too long, it would extend beyond the edges of the surface. If a test piece is too short, it may not be possible to constrain it in the desired fashion with standard C-clamps. To meet this challenge, the interior of the welding surface was segmented into multiple, small sections as suggested by Guideline 4. This way, any test piece that is between 1 inch and 12 inches can be constrained from both ends.

The discussion here is meant to provide only a few examples of the evolvable features of the welding test station. More examples will be provided when the test station is analyzed for evolvability in Chapters 6 and 7.

Implementation of the guidelines for FFE in the design of the welding test station resulted in a system that is unique and valuable to the field of flexibility research. It is the first small-lot system of its type to be designed with the guidelines for FFE and is therefore an excellent case study for this field of research. As was shown above, the usage of the guidelines resulted in several features that facilitate evolution and enable users to implement changes more easily. This fact plays a key role in meeting Objective 1 of this research, which is to investigate the effectiveness of using the guidelines for FFE in the design of small-lot systems.

4.7 CHAPTER SUMMARY

In this chapter, a welding test station that was designed using the guidelines for flexibility for future evolution (FFE) is introduced. The design is a major contribution to the study of flexibility for future evolution because it provides an opportunity to validate the effectiveness of using the guidelines for FFE on the design of new products and systems.

When the welding station was designed, it was hypothesized that the use of the guidelines would result in a more evolvable system. In the next chapter, a selection of small-lot case studies that are similar in complexity to the welding test station are introduced. In later chapters, the evolvability of each case study is measured using Change Modes ad Effects Analysis and the results are used to determine the effectiveness of using the guidelines for FFE on the design of small-lot systems.

Chapter 5: Evolvability Case Studies

In this chapter, the additional case studies that will be analyzed for evolvability are presented. Recall that the first objective of this research is to investigate the effectiveness of using the guidelines for flexibility for future evolution (FFE) in the design of small-lot systems. The welding station in Chapter 4 was designed with the specific goal of it being evolvable, and the guidelines for FFE were infused in the design process to achieve this goal. There are four case studies that are presented in this chapter, each of which was designed without the use or knowledge of the guidelines for FFE. In future chapters, the evolvabilities of the welding station and of the cases presented in this chapter are measured using Change Modes and Effects Analysis. It is hypothesized that there are fewer opportunities to improve the evolvability of the welding test station than the other four case studies because the guidelines for FFE were used to design the welding test station.

The second objective of this research is to expand the guidelines for FFE in the "Adjustability Approach" category. The case studies presented in this chapter play a crucial role in meeting this objective. By performing Change Modes and Effects Analysis, it is hoped that features that enable evolvability by means of adjustability can be identified and used to identify additional "Adjustability Approach" guidelines.

The first case study is a scaled seal testing system that was designed to test oil well drilling seals. The second case study is a gas pressure blow forming system for forming dome shaped shells from thin metal plates. The third case study is a device for measuring constant temperature curves on the pressure – volume – temperature diagram of ethyl alcohol. The fourth and final case study is a beam pattern measuring system for acoustics research.

The purpose of this chapter is to introduce each system in enough detail so that the reader gains a general understanding of how each system is laid out. Detailed technical information is not presented because it is outside the necessary scope of this work. The reader is referred to documentation that contains this information whenever it is available.

5.1 SCALED SEAL TESTING SYSTEM

The first case study is a scaled seal testing system for testing high pressure seals. The system was originally designed by students and faculty at the University of Texas at Austin for a local industrial partner. Detailed technical information of the design is documented by Tilstra in his Master's Thesis [45].

The system is designed to test a scaled high pressure seal. In real operation, the tested seal is used to retain pressurized drilling mud while allowing a drill pipe to pass through its orifice. The tested seal must retain pressure and structural integrity while a pipe with sections of varying diameter is moved through it. A photograph of the seal testing system is shown in Figure 5.1.

Figure 5.1: Scaled seal testing system [45]

In Figure 5.2, the overall layout of the seal testing system is shown in schematic form. There are three main modules to the overall system. The first module is a pressure vessel that is centrally located between two identical linear motion systems, which compose the second and third modules. The seal being tested is installed on one side of the pressure vessel and the backside of the pressure vessel is sealed using a similar seal. The tested seal is subjected to varying pipe diameters during operation, which is a more demanding condition than that which the untested seal is exposed to. Thus, it is expected that the seal being tested will fail before the untested seal.

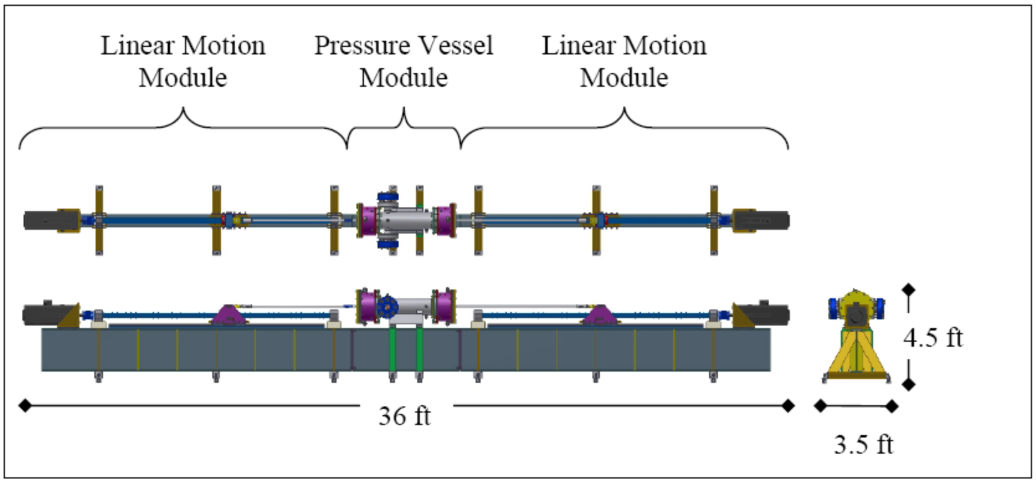

Figure 5.2: Overall layout of the scaled seal testing system [45]

The linear motion systems use motors, ball screws, and linear guide rails to alternately pull the pipe back and forth through the pressure vessel. In Figure 5.3, a detailed schematic of one side of the seal testing system is shown with the major components labeled.

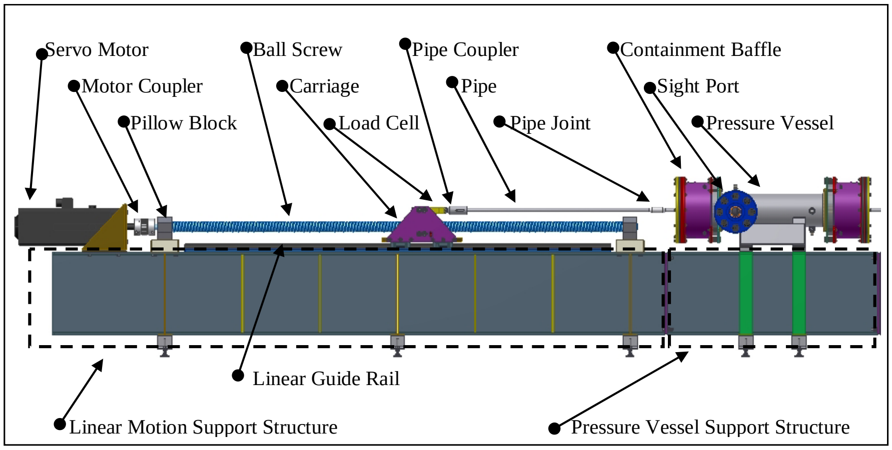

Figure 5.3: Schematic of left side of scaled seal testing system [45]

In field operation, the seals are used to contain an opaque fluid, but for the purposes of testing, plain water was used so that direct visual inspection of the seal would be possible during testing. The pressure vessel contains two sight ports that are on either side of the seal being tested. This feature allows one port to be used to light the inside of the vessel and the other port to be used for visual inspection via a machine vision camera. The vessel also contains two ports for plug heaters that are used to maintain the water in the vessel at the operating temperature [45,54].

The coordination of the linear motion and data acquisition systems, including the camera, is handled by a personal computer. The computer allows the technician to change the speed of the pipe in each direction independently and also allows different stroke patterns to be used. The high-speed camera can be used to capture video of the seal under test or can be used to take still shots [45,54]. A bill of materials for the scaled seal testing system is given as a part of the details of the evolvability analysis in Appendix C.

5.2 GAS PRESSURE BLOW FORMING SYSTEM

The second case study is a gas-pressure blow-forming (GPBF) system that is used to form dome shaped shells from thin metal discs. The system was originally designed by a graduate student for research purposes in the Mechanical Engineering Department of the University of Texas at Austin. Detailed technical information of the design is documented by Moller in his Master's Thesis [65].

The GPBF process is summarized in Figure 5.4. In its initial state, the test specimen is in the shape of a thin circular disc (Figure 5.4a). It is pressed between two die-rings throughout the entire process. Before the GPBF process can begin, a "draw-bead" must be formed around the periphery of the disc to form a seal between the disc and the die-rings. To perform this task, the die-rings and the blank are heated to a high temperature with a furnace that surrounds the entire assembly. Once the disc is at the appropriate temperature, compressive force is applied to the die-rings to form the draw-bead (Figure 5.4b). Once the draw-bead is formed, the bulge-forming process can begin. At this point, pressurized gas is admitted into the chamber from above. Because the aluminum disc is already at a high temperature, plastic deformation occurs relatively easily as a result of the pressurized gas. This step of the process and the resulting specimen geometry are illustrated in Figure 5.4c.

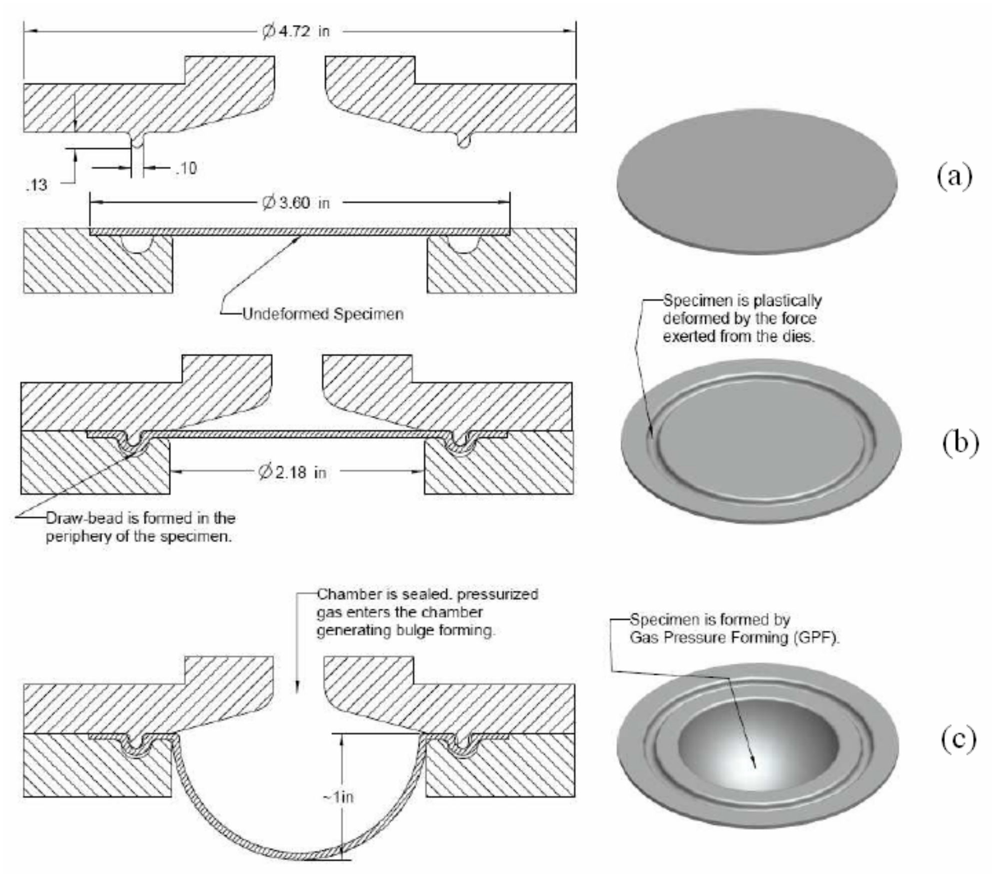

Figure 5.4: (a) Blank test specimen, (b) forming of the draw-bead by the clamping of die-rings, (c) forming of dome by gas-pressure blow-forming [65]

The overall GPBF system layout is shown in Figure 5.5. To provide the compressive force that is required for the forming process, the die-rings are mounted on two columns in a servo-hydraulic unit. The furnace is mounted to the frame of the servo-hydraulic unit and attached to a swinging hinge so that it can be opened for access to the test specimen and die-rings. The heat applied to the die-rings conducts to the load columns and must eventually be removed from the system. To perform this task, copper cooling coils are wrapped around the load columns at the top and bottom of the assembly. These coils are directly connected to the building's chilled water supply, which provides a constant flow of chilled water for effective heat removal.

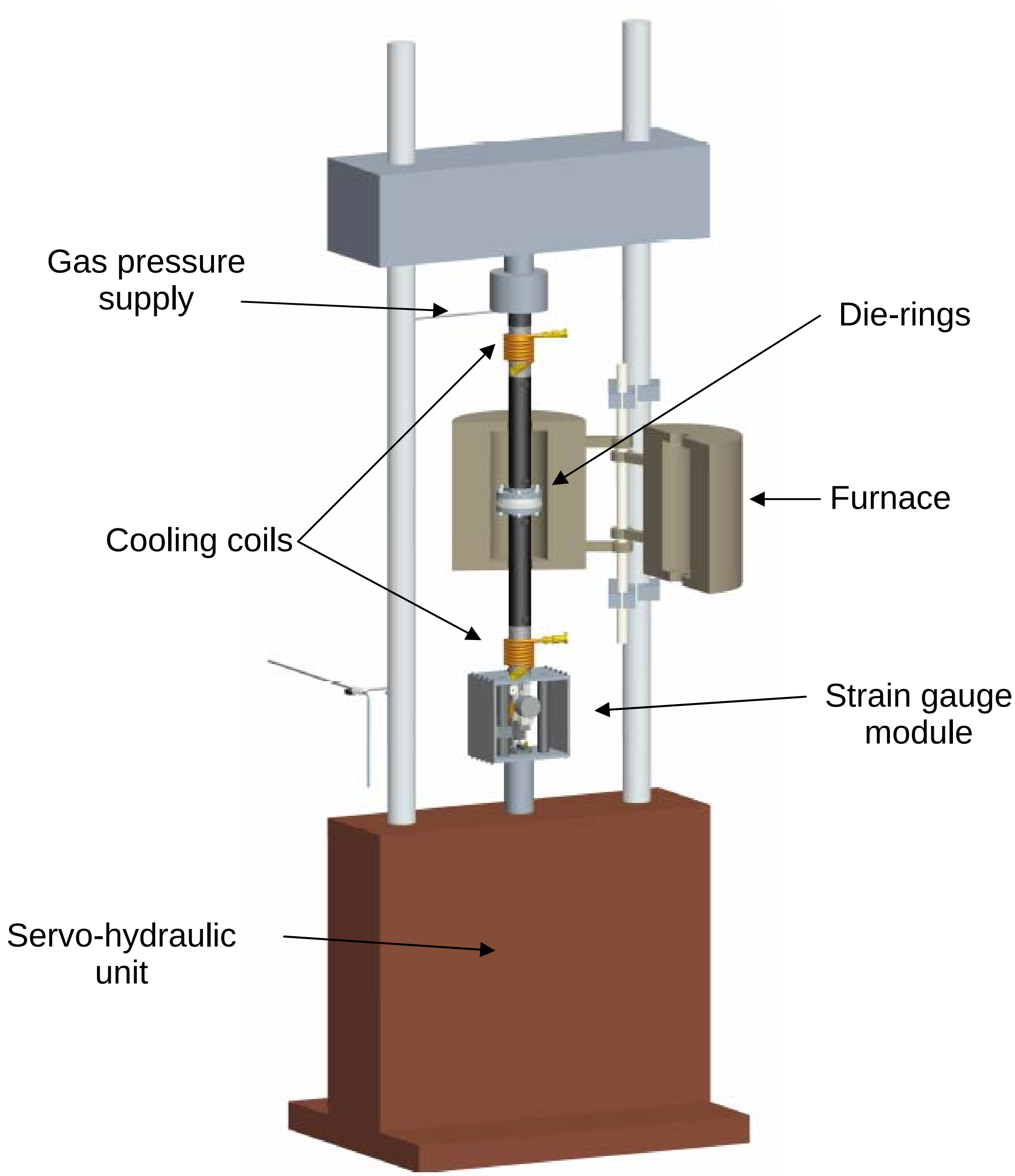

Figure 5.5: Gas-pressure blow-forming overall system layout [65]

One of the design requirements of the system is that it needs to measure the distortion of the material as it is being formed. To perform this task, a strain gauge module is included at the base of the lower load column (Figure 5.6). A long pin extends from the strain gauge, through the inside of the load column, and into the test chamber where it rests very gently against the underside of the test piece. As the bulge is forming, the strain gauge provides precision reading of the deformation that is occurring.

Figure 5.6: Strain gauge module [65]

Although the heat is effectively removed from the system with the cooling coils, thermal expansion in the load columns is significant and cannot be neglected. To compensate for this expansion and to avoid overloading the specimen and the load columns, the load is controlled with a closed loop control circuit. There is a load cell on top of the upper column that measures force throughout the entire process, and feeds that information to a computer control system. The computer control program automatically adjusts the servo-hydraulic unit to maintain constant pressure on the test specimen, regardless of how much the load columns expand from temperature change. A bill of materials for the gas-pressure blow-forming system is given as a part of the details of the evolvability analysis in Appendix D.

5.3 THERMODYNAMIC IN-CLASS DEMO DEVICE

The third case-study for this research is a device that is used for in-class demonstrations in an introductory thermodynamics class. The device is used to measure points along an isothermal curve on a pressure vs. volume graph (Figure 5.7) of a pure substance. The device was designed and constructed by an undergraduate student working under Dr. John Howell at the University of Texas at Austin.

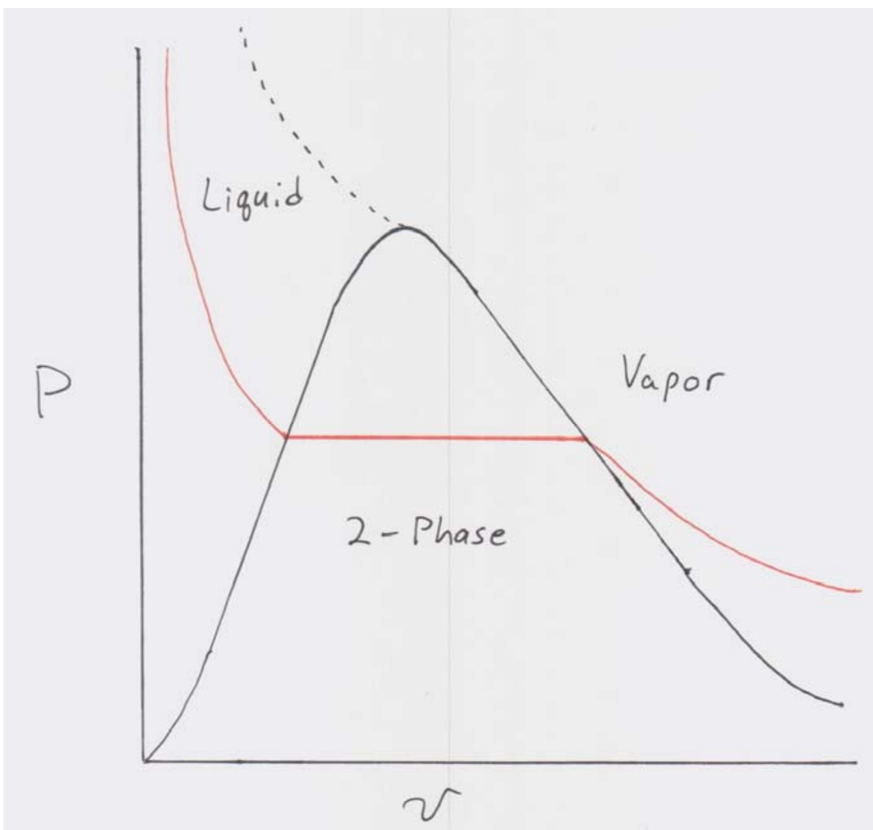

Figure 5.7: Pressure vs. volume graph

The device, as shown in Figure 5.8, is composed of five main modules which carry out the major functions of the design. The cylinder base acts as a support for all of the other components of the system. It features a copper plate in its center, which adds heat capacity to the interior chamber and helps keep temperature constant during the test process. The pressure gauge is used to take pressure measurements throughout the test process, and it features a valve that can be opened and closed so that excess air can be expelled from the system if necessary.

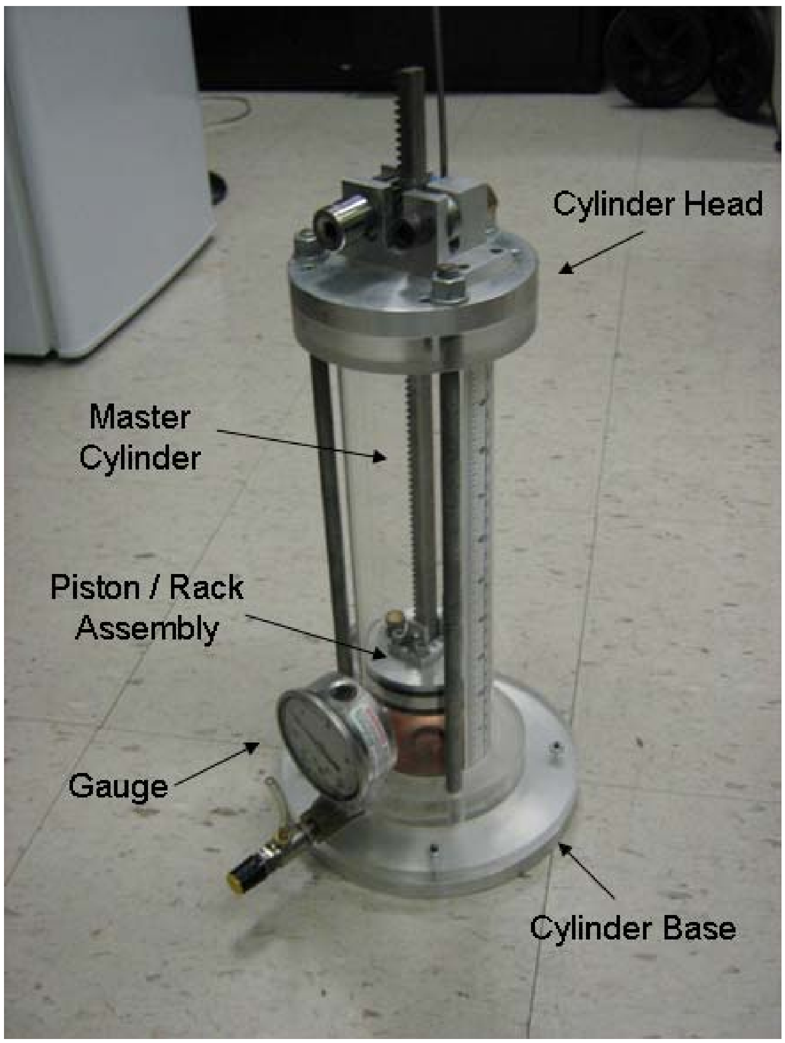

Figure 5.8: P-V-T measurement system

The master cylinder creates a test chamber, where the substance under study is confined and expanded during testing. It features a measurement scale on the exterior, so that the height of the piston can be measured. It is necessary to know the height of the piston in order to calculate the volume of the chamber during testing. The piston / rack assembly is forced upward during the process, thus reducing the interior pressure of the device and forcing the substance to undergo phase change from liquid to vapor. The piston also has a thermocouple probe for verifying the temperature of the interior chamber. Lastly, the cylinder head that is attached to the top of the master cylinder holds the pinion gear that is manually turned to move the rack that is attached to the piston. It is connected to the base with fully threaded rods that serve to provide additional support for the forces that are involved with expanding the fluid inside the chamber. A bill of materials for the P-V-T measurement system is given as a part of the details of the evolvability analysis in Appendix E.

5.4 BEAM PATTERN MEASUREMENT SYSTEM

The fourth evolvability case study is a beam pattern measurement system for acoustics research. The system uses transducers that send and receive sound waves for beam-pattern measurement. The system was designed and built by students and faculty in the Mechanical Engineering Department at the University of Texas at Austin. A thorough discussion of the design and layout of the system can be found in James Alan Ten Cate's Ph.D. Dissertation [66].

The beam-pattern measurement (BPM) system used in this study is shown in Figure 5.9. It is composed of three subsystems that work together to carry out the major functions of the design. The positioning system is used to position and move the transducers which hang from it into the water tank. The support frame supports the positioning system and holds it at an appropriate height above the water tank. Underneath the positioning system is the water tank, which is filled with distilled, degassed water during operation.

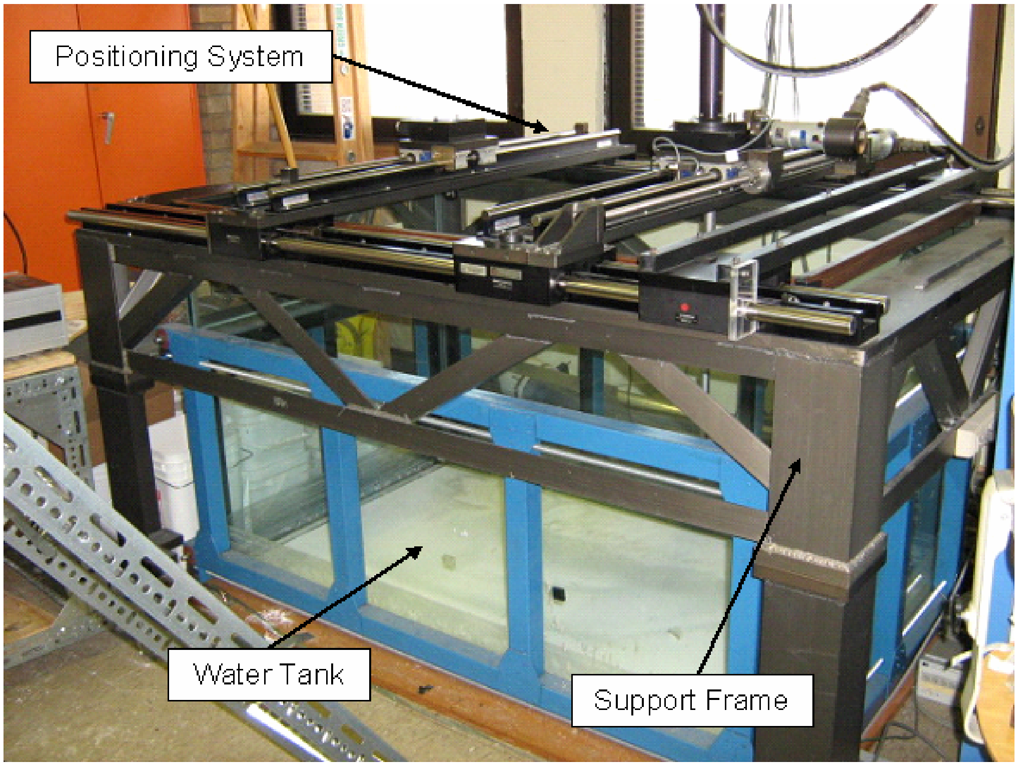

Figure 5.9: Beam-pattern measurement system

The BPM system works by suspending two transducers in 3-dimensional space in a tank of distilled, degassed water. The transducers are capable of both sending and receiving ultrasonic sound waves. In order to measure a full beam pattern, the motion of at least one of the transducers must be precisely controlled during testing.

A close up view of the positioning system is shown in Figure 5.10. In its current configuration, only one of the transducer mounts is controlled with motors. The other transducer mount is fully adjustable, but all adjustments must be done manually. Both of the transducer mounts have length (x-axis), width (y-axis) and height (z-axis) adjustment. In addition, they can both be rotated about the vertical (z) axis.

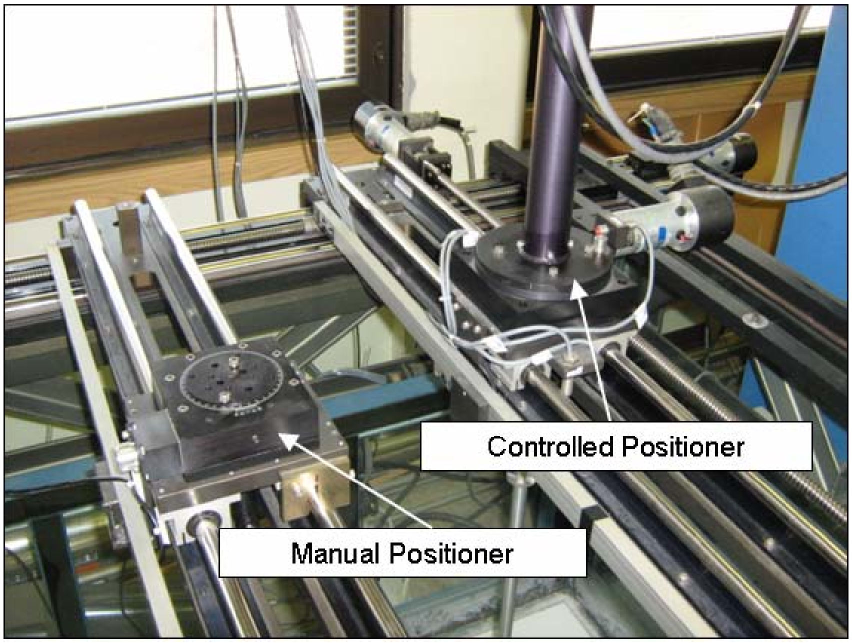

Figure 5.10: Positioning system

The support frame (Figure 5.11) has three important features that are worth mentioning here. First, the uppermost members of the frame compose a precision surface for mounting the positioning system components. The second important feature of the support frame is its removable legs. According to Cate, [66], the legs were made removable so that the support frame would be able to fit through the door of the laboratory in which it was to be used. Lastly, it should be noted that all of the members of the frame have welded joints and have been anodized after assembly.

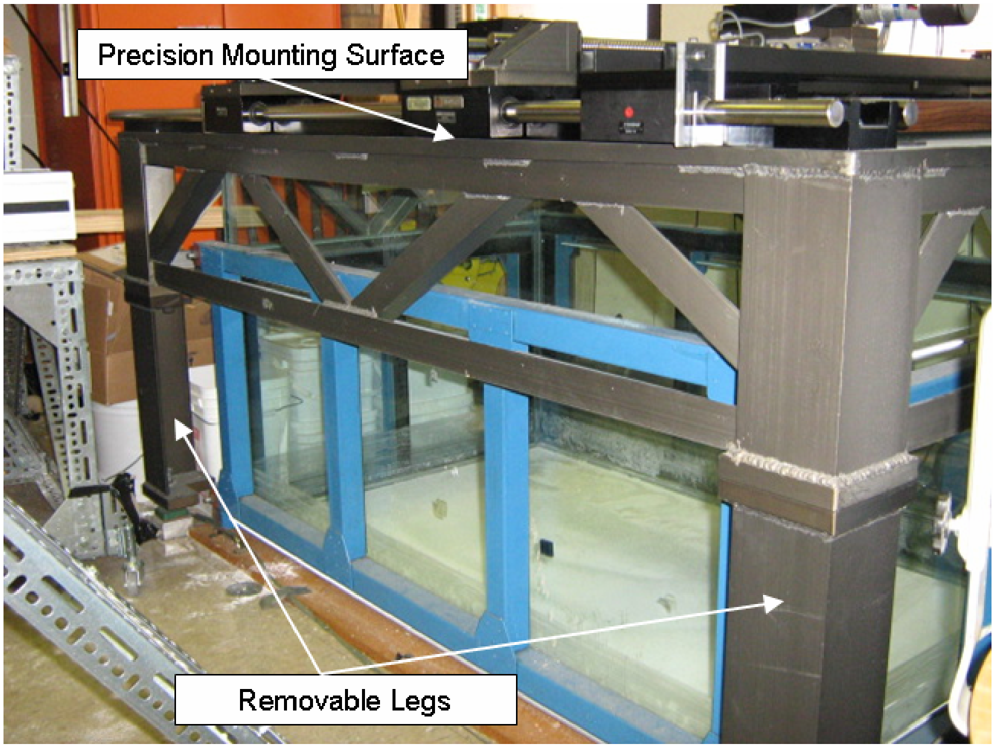

Figure 5.11: Support frame

The water tank of the BPM system holds the distilled, degassed water through which the ultrasonic sound waves are sent during testing. The half inch thick glass is sealed on the inside corners with RTV Silicone Sealant and then reinforced with glass strips and more sealant [66]. The external tank support frame is made up of varying lengths of square tubes all of identical cross sections. All of the members are fastened together with removable mechanical fasteners. A bill of materials for the beam pattern measurement system is given as a part of the details of the evolvability analysis in Appendix F.

5.5 CHAPTER SUMMARY

In this chapter, four case studies were introduced that are used in later chapters to meet the goals of this research. None of the case studies presented in this chapter were designed with the use or knowledge of the guidelines for flexibility for future evolution. On the contrary, the welding test station that is presented in Chapter 4 was designed with the goal of it being evolvable, and the guidelines for FFE were infused in the design process to achieve this goal. In the next chapter, the evolvabilities of the four systems in this chapter and the welding station are measured and compared using Change Modes and Effects Analysis.

Chapter 6: Evolvability Analysis

In this chapter, the evolvabilities of the five case-studies introduced in Chapters 4 and 5 are measured with Change Modes and Effects Analysis (CMEA). For each case study, the change modes are explained along with their proposed evolution responses. Each evolution response represents a design concept that successfully implements its respective change mode. Once the change modes are described in detail, the results of the CMEA are presented. For each system, the details of the evolvability analysis, including the module change reports, BOM / reusability matrices, and use of guidelines reports are listed in the appendices.

The focus of this research is strictly on use of the guidelines for flexibility for future evolution in the design of small-lot systems. Using the guidelines has no effect on the likelihood that a change mode is to occur (Occurrence Rating O), and only secondary effects on the readiness of a firm to implement a given change mode (Readiness Rating R). The use of the guidelines has the most significant effect on the Design Flexibility Rating F of each change mode. Thus, after the CMEA results are presented, only the Flexibility Ratings F are discussed.

Recall from Chapter 3 that the first five steps taken to meet the two objectives of this research are identical, and the final three steps for each object vary significantly. The research approach is shown again in Figure 6.1, with the steps that are completed in this chapter shaded in gray. The final four steps for each objective shown in Figure 6.1 are completed in Chapter 7.

In the remainder of this chapter, the results of the efforts of the first four steps of the research approach are presented. Each case study is presented in its own section which is divided into two parts. In the first part of each section, the change modes for the given case study are explained in detail along with their proposed evolution responses. In the second part of each section, the results of the Change Modes and Effects Analysis are presented and discusses.

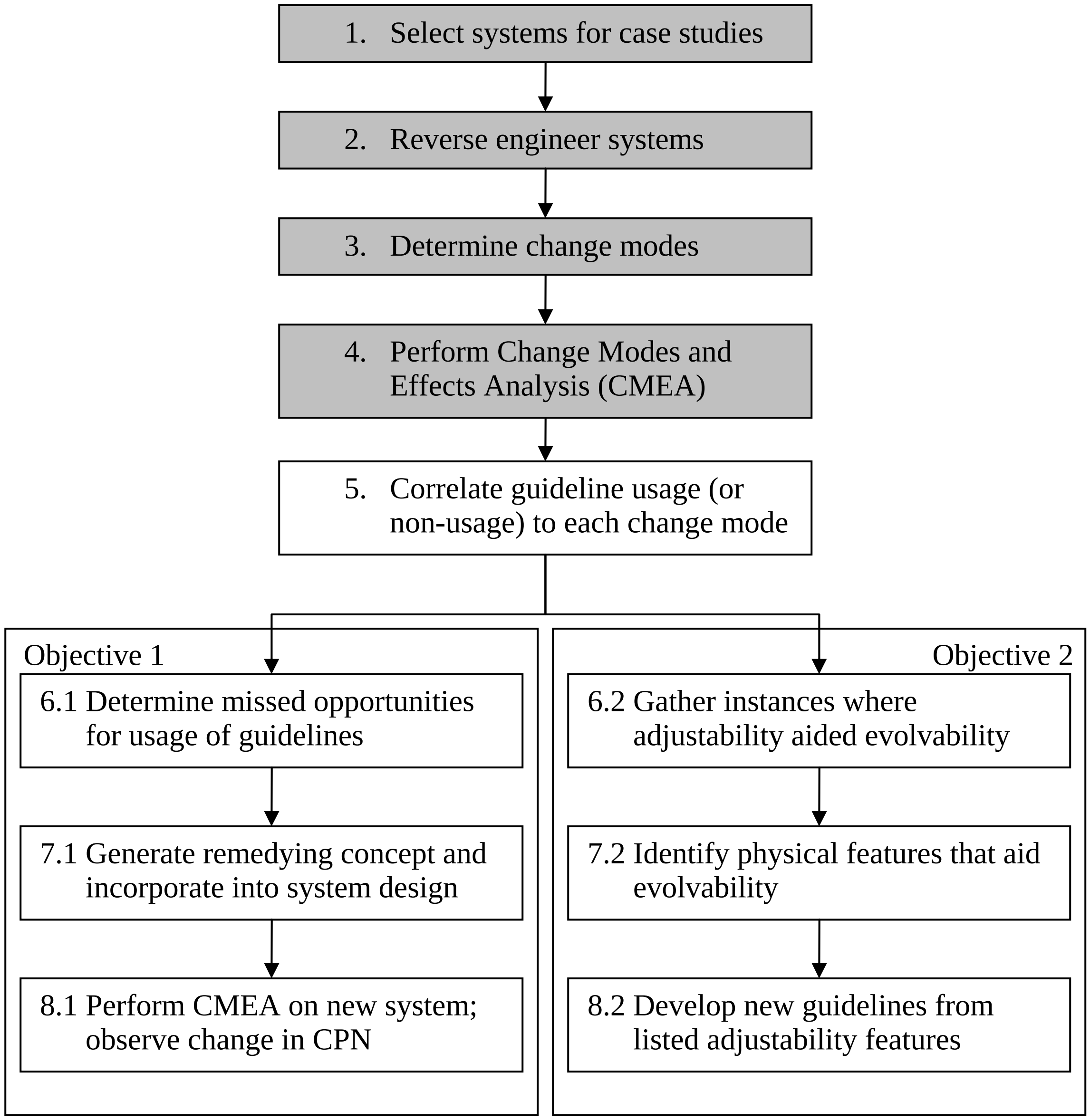

Figure 6.1: Research approach

6.1 WELDING TEST STATION

The first case-study analyzed in this chapter is the welding test station described in detail in Chapter 4. The welding station was designed using the guidelines for flexibility for future evolution (FFE), and it is hypothesized that it is more evolvable than the other case-studies presented in this research.

Change Mode		Evolution Response	Readiness
1	Perform radial welds on circular specimens	The linear weld surface and bearing rails will be completely removed and replaced with a radial weld fixture. The radial module will be driven with the same motor and mechanical belt drive.	The radial motion module will need to be completely designed. The current vendor can supply necessary materials and the design can be manufactured in-house.
2	Increase the weld pass length	The overall device will need to lengthened, resulting in a longer breadboard, frame, and linear motion components.	Parts with longer dimensions will need to be fabricated. The current vendor can supply the necessary materials, and they can be assembled in-house.
3	Increase the possible weld speed range	The pinion gear diameter will be increased. This change will propagate to other components in the drive shaft assembly module.	Some new materials will need to be ordered from the current vendor. All of the parts can be fabricated in-house.
4	Raise the sliding weld surface	The rail supports may need to be modified to sit on stilts and the drive shaft will need to be raised.	Some new materials will need to be ordered from the current vendor. All of the parts can be fabricated in-house.
5	Add a protective glass shield	The joining plates on the outside of the frame will need to be replaced with inside corner brackets, so the shield can sit flat on the outside of the frame.	A vendor will need to be located for the shield materials. It can be cut, drilled, and attached in-house.
6	Perform other types of welds (GTAW, Laser, etc.)	A new bracket will need to be designed and machined for different torch geometry. An auto-feed module will need to be mounted adjacent to the GTAW torch. Beam may not be reusable.	Stock materials can be purchased for the new bracket. A vendor will need to be located for the auto-feed components. A compatible OEM assembly may not be obtainable.
7	Integrate an IR camera	Additional frame support members shall be added to the upper horizontal beams of the frame. A mounting bracket will need to be designed and machined. A shield will need to be fashioned to block the angle of view from the arc.	Raw materials need to be purchased for the additional beams and the bracket. The same vendor can be used as was used for the rest of the frame.
8	Include torch motion	Horizontal torch mount bar will need to be replaced with a motorized carriage on a track.	A vendor for the motorized carriage will need to be located. If no OEM assembly is available, a solution will need to be designed from scratch.

Table 6.1: Welding station evolution response table

There are eight change modes that are used for the analysis of the welding test station. In Table 6.1, these change modes and their respective responses are summarized in an Evolution Response Table. In addition, the calculation of the "Readiness Rating" in the CMEA table is described briefly.

6.1.1 Change Modes

Change Mode 1: Perform Radial Welds on Circular Specimens

The first change mode that is listed in Table 6.1 is to Perform Radial Welds on Circular Specimens. The welding station is currently capable of performing linear welds on flat test pieces. However, the original specimen geometry requested by the customer was a circular hoop with a weld groove around the outer perimeter. Early design concepts aimed to accommodate both radial and linear welds. During the design process, the customer indicated that the radial weld was not an immediate project need, due to the high cost-to-benefit ratio of obtaining specimens of that geometry. Eventually, it may be of interest to weld the originally suggested radial geometry. The welding station will have to be modified to hold and rotate the radial specimens, since it is currently only capable of performing linear welds on flat plates.

The evolution response to this change mode is to completely remove the linear motion components. These include the linear motion table and linear bearing guide rails. The linear motion components are replaced with a fixture for performing radial welds. This fixture needs to hold the radial test specimens and rotate when driven by the existing pinion gear. All of the other system modules remain unchanged, including the frame, drive shaft, motor, and torch mount.

Change Mode 2: Increase the Weld Pass Length

The second change mode that is listed in Table 6.1 is to Increase the Weld Pass Length. The welding station was designed to perform welds that are up to 12” in length. For the current project needs, this stroke length is adequate because only small test pieces are being welded for analysis. The usefulness of the welding station could be drastically improved by enabling it to perform longer welds on longer pieces.

To achieve this task, all of the linear motion components are lengthened. This includes the linear bearing guide rails and the rack gear on the linear motion table. In addition, the entire frame and base assembly are lengthened, because the rails cannot extend beyond the end of the table.

Change Mode 3: Increase the Possible Weld Speed Range

The third change mode that is listed in Table 6.1 is to Increase the Possible Weld Speed Range. The speed range of the linear motion table is dependent on the speed range of the motor and the gear ratio of the belt pulleys and the pinion drive gear. The table can be moved at speeds ranging from 0-120 inches per minute. It may become necessary to move the table at higher speeds for research purposes.

To implement this change mode, the pinion gear that drives the rack on the linear motion table is replaced with one that has a larger diameter. A larger gear provides a higher top speed with the rotational speed range of the current motor. Because a larger gear transfers a higher torque to the current drive shaft, the shaft is analyzed for failure and is not considered reusable.

Change Mode 4: Raise the Sliding Weld Surface

The fourth change mode that is listed in Table 6.1 is to Raise the Sliding Weld Surface. In the current configuration, there is approximately 2.25” of clearance between the underside of the moving weld surface and the upper surface of the breadboard that serves as the base of the system. There are several reasons that this clearance may need to be increased. One possible motivation is that it is very difficult to mount thermocouples on the underside of a test specimen with only 2.25” of clearance. Another benefit of raising the welding surface is that it may be of interest to view the underside of a test piece with an infrared camera. In the current configuration, it is nearly impossible to obtain the necessary angle of view to achieve this goal.

To implement this change mode, most of the linear motion components remain unchanged. The linear bearing guide rails rest on two support bars, which are raised up on columns to provide the necessary clearance. The support bars are modified to interface with the columns, depending on how the columns are designed.

Change Mode 5: Add a Protective Glass Shield

The fifth change mode that is listed in Table 6.1 is to Add a Protective Glass Shield. There are serious hazards associated with gas metal arc welding, and it is dangerous to humans if proper precautions are not taken. The arc is extremely bright, which damages the human retina and causes “sun burn” type symptoms to the skin. Also, molten droplets of the filler wire known as spatter are projected from the weld zone during welding. Spatter burns human skin and ignites flammable materials. The welding station operator wears a mask with dark tinted lenses, thick leather gloves and a jacket, and removes nearby flammable materials to prevent accidents. However, the addition of a protective glass shield to the welding station protects people who wish to observe the testing process.

This change mode is very easy implement because of the framework that surrounds the work area. The only potential change to the existing system is that the 5-hole T-brackets that join the upper lengthwise frame members to the middle support columns are replaced with inside corner brackets. Using inside corner brackets creates a completely flat exterior surface on the outer faces of all of the frame members, making it very easy to affix a protective glass shield

Change Mode 6: Perform Other Types of Welds

The sixth change mode that is listed in Table 6.1 is to Perform Other Types of Welds. The welding station is only configured to perform gas metal arc welds (GMAW). Research objective may eventually demand the use of other types of weld process such as Laser-beam welding (LBW) or gas tungsten arc welding (GTAW).

The torch mounting bracket is designed to hold a specific GMAW torch, and it is unlikely that it can hold a different welding heat source. To implement this change mode, a new bracket is designed for different torch geometry. Also, GTAW requires the filler metal to be fed in from the arc separately, and a motorized feed module is designed or purchased and mounted to the horizontal mounting tube.

Change Mode 7: Integrate an Infrared Camera

The seventh change mode that is listed in table 6.1 is to Integrate an Infrared Camera. Currently, the welding station is only set up to take temperature measurements with up to eight thermocouples. While thermocouples are very good for taking measurements of specific points, an infrared (IR) camera may be necessary to measure temperatures on a two-dimensional surface.

To implement this change mode, the camera is mounted on additional frame members that span the upper horizontal frame members. Special mounting hardware is custom designed and machined for the camera. Lastly, the camera lens is shielded from the brightness of the welding arc to avoid damage. To meet this need, an opaque shield is placed over the torch head to block the angle of view from the camera.

Change Mode 8: Include Torch Motion

The eighth change mode that is listed in Table 6.1 is to Include Torch Motion. Currently, there is a single axis of motion on the welding test station. It may eventually be of interest to perform computer-controlled two-dimensional weld paths on flat surfaces for research interests.

Implementation of this change mode requires the design of a motorized carriage on a track that moves the torch laterally above the test specimen. The current torch mount and horizontal mounting beam are not reusable.

6.1.2 Change Modes and Effects Analysis

The CMEA results for the welding station are shown in Table 6.2. The average CPN for all eight of the change modes is 22, which is very good considering that a CPN of 1000 represents the least evolvable design. More importantly, the highest Design Flexibility Rating *F* is 4, which is also good considering it is on a 1-10 scale.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	**Design Flexibility (F)**	**Occurrence (O)**	**Readiness (R)**	**CPN**	**Description**
CM #1	12	34	65%	4	8	2	64	Radial Welds
CM #2	6	34	82%	2	4	2	16	Weld Pass Length
CM #3	5	34	85%	2	5	2	20	Weld Speed Range
CM #4	2	34	94%	1	10	2	20	Raise Weld Surface
CM #5	1	34	97%	1	4	1	4	Glass Shield
CM #6	4	34	88%	2	4	2	16	Other weld types
CM #7	1	34	97%	1	9	2	18	Mount IR camera
CM #8	5	34	85%	2	2	5	20	Torch motion
				1.9			22	Average

Table 6.2: Welding station CMEA results

Recall from the discussion in Chapter 2 that the Design Flexibility rating *F* is determined from the percentage of components that are reusable when a given change mode is implemented. Change Mode 1 has the worst *F* rating of the eight change modes considered. This poor rating stems from the fact that none of the linear motion components are reusable when the change mode is implemented. However, the modular architecture of the system improves the *F* rating for Change Mode 1 because the drive gear and motor are reusable for a radial fixture. An integral architecture would have precluded the reuse of these modules.

Change Mode 4 has one of the best *F* ratings of all of the change modes. This strong rating is the result of several system features that enable a high percentage of component reusability. For example, the mounting frame is taller than necessary for immediate project needs. This feature creates excess space inside the work envelope, and raising the weld surface does not have an effect on the size of the mounting frame components.

Change Mode 7 is another change mode with a very good *F* rating. The decision to use a common framework around the workspace has a direct effect on the flexibility of the system to accommodate this change mode. The existence of the frame makes it very easy to mount an infrared camera for thermal data acquisition. The frame members are stronger and stiffer than necessary for the current project needs, and they are all reusable for the implementation of this change mode. Only one part (torch mount) is redesigned for this change mode because it has to include a feature to shield the camera lens from the welding arc.

The three cases above are just a few examples of how the system features affect the Design Flexibility ratings of the system. For all of the details of the evolvability analysis of the welding station, refer to the tables in Appendix B.

6.2 SCALED SEAL TESTING SYSTEM

There are ten change modes that are used in the Change Modes and Effects Analysis of the scaled seal testing system. In Table 6.3, these change modes and their respective evolution responses are summarized in an Evolution Response Table. In addition, the calculation of the "Readiness Rating" in the CMEA table is described briefly.

Change Mode		Evolution Response	Readiness
1	Increase pipe stroke length	The current ball screw cannot be extended in length. A new linear motion module must be designed that uses a cable winch system.	New vendors must be sought to supply the cable and winch system. Although the frame must be redesigned, the current vendor can accommodate the changes.
2	Increase number of tool joints	The pipe design must be changed to include more, shorter sections. The pressure vessel design must be changed to accommodate pipe joints passing through both ends. The rest of the components can be used as previously designed.	The new parts can be manufactured in-house.
3	Increase field of view	A larger pressure vessel must be redesigned that has a studded outlet.	The current vendor can implement the change, but significant effort will be required of them to redesign the pressure vessel.
4	Increase pipe speed through seal	The motor and ball screw cannot be operated at a higher speed. A new linear motion system module must be designed that uses hydraulic cylinders.	New vendors must be sought to supply hydraulic components and control systems. Although the frame must be redesigned, the current vendor can accommodate the changes.
5	Use drilling mud instead of water	The vision system could no longer be used and therefore sightglass flanges are not needed. Transfer barrier accumulator would need to be mounted onto PV Support Weldment. Current hose from pressure circuit would attach to transfer barrier accumulator.	Pressure circuit mounting plate would need to be modified. This could be done by the in-house machinist.
6	Increase stripper rubber size for static calibration	The pressure vessel would have to be redesigned to accommodate full scale stripper rubbers. Current linear motion system is adequate for static testing.	Current vendor can implement the change, but significant effort will be required of them to redesign the pressure vessel.
7	Increase scaling factor	Increasing the scaling factor will increase the size of the system and also the parameters of testing. Therefore, the current linear motion modules, pressure vessel, and frame must be redesigned. The evolved concept would require a larger pressure vessel and a cable and winch motion system.	New vendor must be sought to supply the cable and winch systems. The current vendor of the pressure vessel may not be able to accommodate the required design change. Although the frame must be redesigned, the current vendor can accommodate the changes.
8	Change test environment	The motors and ball screws used on the current system are not suitable for outdoor use. Therefore a new linear motion system module must be designed that uses hydraulic cylinders. The control and data acquisition system must either be redesigned using more rugged components or changed so that it can be operated remotely.	New vendors must be sought to supply hydraulic components and control systems. Although the frame must be redesigned, the current vendor can accommodate the changes.

9	Quicker test setup	The current pressure vessel design uses large flanges that bolt onto the vessel. A significant portion of test setup time is spent turning on all the nuts. It also requires an overhead crane to move the flanges in and out of place. A hinged flange system with a cam lock may be able to be designed that would make access to the stripper rubber much quicker and easier.	Pressure vessel flanges will need to be redesigned with hinges and cam lock. Current vendor can perform this task but with significant effort.
10	Decrease scaling factor	If the scaling is found to be accurate at smaller scales, the current system design could be used with very small modification. A decrease in scaling factor would also effectively lengthen the stroke since pipe length scales with the stripper rubber diameter.	Drill pipes and stripper rubber support shims would need to be redesigned for smaller seals. All changes can be performed using in-house capabilities.

Table 6.3: Scaled seal testing system evolution response table [45]

6.2.1 Change Modes

After the scaled seal testing system was designed and fully deployed, Tilstra determined change modes for the system and performed change modes and effects analysis. The change modes and their respective evolution responses are summarized in Table 6.3. The following discussion is taken directly from his Master of Science Thesis [45].

Change Mode 1: Increase Pipe Stroke Length

> Drilling rigs are classified by height in terms of how many drill pipe segments can be pulled out at a time. A double stand drilling rig can strip up to 60 feet at one time. The stand is then disconnected from the drill string remaining down-hole and moved to the pipe rack. A triple stand drilling rig can strip up to 90 feet at one time. The capability to remove multiple segments from the hole at once reduces the time and effort to perform maintenance on the down-hole equipment and drill bit if needed. The current test stroke for the quarter scale test system is 7.5 feet which relates to a single 30 foot segment of drill pipe. It may be necessary for a future scaled testing machine to simulate the stripping of two or three segments of drill pipe on each cycle. [45]
>
> The ball screw system used on the current design will not be able to adapt to this change. The ball screw is currently at its limit in terms of buckling strength and also whip-speed so its length cannot be extended. Therefore the current linear

motion system would need to be radically redesigned. A promising solution would be to use a cable winch system. This is analogous to the block and tackle systems used on the actual drilling rigs. A series of hydraulic rams could also be a possible solution. [45]

Change Mode 2: Increase the Number of Tool Joints

Since the tool joint has a larger outer diameter than the rest of the drill pipe, it causes the stripper rubber to expand as it passes through. It may be determined that the majority of the wear on the seal is caused by this interaction. So future testing may need to increase the number of tool joints on the test stroke. [45]

The current system only has one tool joint on its stroke which is representative of full scale. If the frequency of tool joints contacting in each direction of the test cycle is desired to increase then the drill pipe assembly will have to be redesigned. Adding more tool joints will require that the tool joints pass through both ends of the pressure vessel. This will require changing the inner diameter of the back seal support shim. [45]

Change Mode 3: Increase Field of View

The current field of view is limited to only the top profile of the stripper rubber being tested. It is likely that any future test system would require a better field of view. [45]

The field of view on the current testing system is the largest possible for the current size of pressure vessel. Therefore, a larger pressure vessel will need to be designed that does not have the inner wall so close to the test specimen. It also may include increasing the number of sight ports so that all sides of the stripper rubber can be viewed. [45]

Change Mode 4: Increase Drill Pipe Speed

The current maximum speed of the drill pipe on the test system is 1.5 feet per second. It may be desired to test at greater speeds to simulate more extreme drilling rig operating conditions. [45]

The motor and ball screw system on the current system is the limiting factor for the maximum speed. Increasing the speed would require the current linear motion system to be replaced. Possible solutions are to use a cable system or to use hydraulic rams. Since the stroke is not being increased in this change mode, hydraulic rams are a good option. [45]

Change Mode 5: Use Drilling Mud Instead of Water in Tests

In drilling applications a liquid referred to as ‘drilling mud’ is pushed through the center of the drill string to lubricate the drill bit and to lift debris to the top of the hole around the drill string. The stripper rubber prevents the flow of drilling mud and debris to continue around the drill string at the surface and deflects it to the mud pits. Both the lubricating effects of the drilling mud and the abrasive effects of the debris are not being simulated in the current system by using water. [45]

With the use of drilling mud in the test vessel, visual inspection of the stripper rubber would no longer be possible. Therefore the vision system and the sight glasses would no longer be needed. It may be possible to use ultrasonic scanning or some other type of imaging to inspect the stripper rubber during testing, but this would require further research into the matter. The current pressure circuit contains components that will not be able to handle drilling mud with abrasive debris in it. However, a large transfer-barrier accumulator could be installed between the pressure vessel and the pressure circuit. [45]

Change Mode 6: Increase Stripper Rubber Size for Static Pressure Validation

It may be desired to be able to validate the similitude analysis of different stripper rubber designs by being able to test both full-scale and quarter-scale stripper rubbers in the same testing machine. Due to the forces and stroke length involved with full scale testing, this change mode would only offer the ability to statically test full scale stripper rubbers. [45]

The current pressure vessel design is not capable of statically testing full size stripper rubbers. The pressure vessel would have to be redesigned to have a larger inner diameter. Since dynamic testing is not going to be done on the full size stripper rubbers, the current linear motion systems will still be adequate. [45]

Change Mode 7: Increase Scaling Factor of Stripper Rubber

It may be found that the quarter scale stripper rubbers do not accurately simulate all design variations and therefore a machine capable of testing larger or even full scale stripper rubbers may be desired. [45]

This would require a larger pressure vessel to be designed. The motor and ball screw system would be inadequate since larger forces over a greater distance would be required. The support structure under the pressure vessel and new linear motion system would need to be redesigned to handle the larger forces that will be experienced during operation. [45]

Change Mode 8: Change of Environment

The current system is designed to be operated and installed indoors. If the ability to have more testing done simultaneously is desired, it may be required for the next system to be placed outdoors. [45]

The current design will not perform well outdoors. The manufacturer of the motor and ball screw system lists operating conditions between 0°-40° C and 5%-95% relative humidity. These conditions would be exceeded on a hot day or if it rains. Using hydraulic rams to produce the linear motion would be much more robust to the environmental conditions. There are many examples of hydraulic equipment that is used in all types of outdoor conditions in construction, mining, and farming applications. [45]

Change Mode 9: Quicker Test Setup

The current system has ten threaded studs on each end of the pressure vessel to hold on the modified flanges and stripper rubbers. The baffle containment systems clamp onto both ends of the pressure vessel using six bolts each. An overhead crane must be used to remove and install the modified flanges and baffle containment systems. [45]

When installing the stripper rubbers for a new test, the greatest amount of time is spent unbolting, moving, and bolting the modified flanges and baffle containment systems. To make the process of setting up for a test faster, the pressure vessel and baffle containment systems could be redesigned. Instead of using bolt on flanges, the pressure vessel could have hinged flanges that are able to swing open and have a cam lock to hold them shut. This would not only reduce the amount of time spent tightening down the nuts but would also remove the need for the overhead crane. [45]

Change Mode 10: Decrease the Scaling Factor

If it is found that the quarter scale stripper rubber testing works exceptionally well, it may be desired to further scale down the stripper rubber to reduce testing costs. [45]

The current design could be easily modified to make this change. The drill pipe and tool joint would need to be scaled down and the stripper rubber support shims would need to be redesigned to interface with the new size of seal. [45]

6.2.2 Change Modes and Effects Analysis

The CMEA results for the scaled seal testing system are shown in Table 6.4. The average CPN for the scaled seal testing system is significantly worse than that for the welding test station. However, the average Design Flexibility *F* rating is approximately the same.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	**Design Flexibility (F)**	**Occurrence (O)**	**Readiness (R)**	**CPN**	**Description**
CM #1	35	148	76%	3	4	2	24	Longer Stroke
CM #2	2	148	99%	1	2	2	4	More Tool Joints
CM #3	18	148	88%	2	7	4	56	Increase Field of View
CM #4	25	148	83%	2	2	3	12	Increase Speed
CM #5	13	148	91%	1	10	3	30	Use Drilling Mud
CM #6	22	148	85%	2	5	4	40	Full Size Static Calibration
CM #7	65	148	56%	4	4	4	64	Increase Scaling Factor
CM #8	31	148	79%	2	6	3	36	Run Tests Outside
CM #9	9	148	94%	1	9	3	27	Quicker Test Setup
CM #10	7	148	95%	1	1	2	2	Decrease Scaling Factor
				1.9			33	Average

Table 6.4: Scaled seal testing system CMEA results [45]

Tilstra provides an excellent discussion of how the system features affect the Design Flexibility *F* rating in the CMEA table for the scaled seal testing system [45].

> There is no right or wrong answer for what the CPN of a change mode should be, but it is useful to compare the ranked order of the change modes to expectations. [Change modes 3, 6, and 7] all require significant changes to the pressure vessel. The pressure vessel contains the most difficult parts to design and manufacture due to the safety concerns of high pressures. Therefore, the change modes requiring changes to the pressure vessel get a high Design Flexibility rating... This agrees with what was found during the redesign process since a large amount of the pressure vessel design was already set at project takeover. The small size selected for the pressure vessel made it difficult to design for the current product. A larger vessel would have been useful for the addition of heaters and implementation of the vision system.
>
> Change Mode 10 received [one of] the lowest [*F* ratings] which was also expected due to the lack of propagation required for this change mode. Unlike Change

Mode 7 which increases the scaling factor and pushes the operating limits, Change Mode 10 could be easily implemented and could in fact be done as an upgrade to the current system.

There are several other cases of the system features having an effect on the CMEA ratings that are not worth mentioning here. All of the details of the CMEA for the scaled seal testing system are listed in Appendix C.

6.3 GAS PRESSURE BLOW FORMING

There are four change modes that are used in the Change Modes and Effects Analysis of the scaled seal testing system. In Table 6.5, these change modes and their respective evolution responses are summarized in an Evolution Response Table. In addition, the calculation of the "Readiness Rating" in the CMEA table is described briefly.

Change Mode		Evolution Response	Readiness
1	Increase the strain measurement range	A longer range micrometer must be integrated into the bottom subassembly. The entire bottom sub assembly must be lengthened to house the new micrometer.	The current vendor can provide a new micrometer. New materials for the bottom sub-assembly can be purchased from the current vendor and manufactured in-house.
2	Increase specimen diameter	Larger die-holders and dies must be machined. Wider columns are necessary. A larger furnace is necessary to enclose the larger components.	The current vendor can supply a new furnace. New dies and die holders can be machined in-house.
3	Add a vision system inside the pressure camber.	Holes must be drilled in the bottom column for fiber optic cables. The cables must not interfere with strain measurement rod.	A vendor must be located for the vision system equipment. Changes to the columns can be made in-house.
4	Compensate for thermal expansion automatically	A feedback control loop must be integrated with the load cell and hydraulic ram so that constant pressure is applied to specimen as columns heat up and expand.	No vendor is necessary. All changes can be made in-house.

Table 6.5: Gas-pressure blow-forming evolution response table

6.3.1 Change Modes

Change Mode 1: Increase the Strain Measurement Range

The first change mode that is listed in Table 6.5 is to Increase the Strain Measurement Range. The current design is capable of measuring deformation in the specimen up to a length of 1.000 inch. This is a significant limitation on the capabilities of the system because larger specimens may form a bulge that is greater than 1.000 inch in height.

Implementation of this change mode involves replacing the current strain gauge with one that has a longer stroke. This change propagates through many of the components in the strain gauge module, which is specifically designed to support a 1.000 inch strain gauge. To implement this change mode, the dimensions of many of the components in this module are increased to fit a longer strain measurement device.

Change Mode 2: Increase the Specimen Diameter

The second change mode that is listed Table 6.5 is to Increase the Specimen Diameter. The current design has a set specimen size and geometry which is determined by the shape and size of the die rings on the load columns. It may be of interest to test a larger specimen size for research purposes.

Implementation of this change mode requires the current die rings to be replaced with larger ones. The die rings are affixed to the load columns with removable mechanical fasteners, and can be replaced easily. The size of the furnace is increased, and its mounting hardware is redesigned to interface with the new furnace.

Change Mode 3: Add a Vision System Inside the Pressure Chamber

The third change mode that is listed in Table 6.5 is to Add a Vision System Inside the Pressure Chamber. In addition to monitoring the behavior of the material during testing with a strain gauge, it may be of interest to monitor it with a visual inspection system. A vision system enables an operator to view the test piece from inside the pressure chamber and make valuable observations of the test that cannot be captured with a simple strain measurement.

Implementation of this change mode requires the insertion of fiber optic cables into the pressure chamber. Special care must be taken to ensure that the selected vision system can withstand the high temperatures associated with the test process. The load columns are modified to allow the fiber optic cables to access the pressure chamber.

Change Mode 4: Compensate for Thermal Expansion Automatically

The fourth change mode that is listed in Table 6.5 is to Compensate for Thermal Expansion Automatically. Thermal expansion in the load columns must be compensated for in order to keep constant pressure on the specimen during testing. This change mode was implemented immediately after the initial construction of the system. Although it has already been implemented, it was at one time a change mode and valuable insights are obtained by studying its implementation.

Originally, the servo-hydraulic unit on which the gas-pressure blow-forming (GPBF) system is built was intended to act as a mounting frame. During commissioning, it became apparent that the thermal expansion in the load columns would be too great to ignore, and must be controlled carefully during the testing process. The advantages of using a powered, adjustable frame were harnessed by implementing a computer control system to compensate for the thermal expansion in the load columns.

6.3.2 Change Modes and Effects Analysis

The CMEA results for the gas-pressure blow-forming system are given in Table 6.6.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Design Flexibility (F)	Occurrence (O)	Readiness (R)	CPN	Description
CM #1	9	36	75%	3	5	2	30	Increase strain range
CM #2	9	36	75%	3	4	3	36	Increase specimen size
CM #3	3	36	92%	1	5	3	15	Add vision system
CM #4	2	36	94%	1	10	2	20	Compensate for CTE
				2.0			25	Average

Table 6.6: Gas-pressure blow-forming CMEA results

There are several features of the GPBF system that affect the *F* ratings in the CMEA table. The two change modes with the worst ratings are Change Modes 1 and 2. For both of these change modes, a lack of excess space causes the changes to propagate to the other components in their respective modules. For example, Change Mode 1 (Increase strain measurement range) requires a longer strain gauge. The strain gauge is nested inside the strain gauge module, and its elongation requires many of the components in its module to be elongated as well. Change Mode 2 (Increase specimen size) requires a larger furnace for successful implementation. A larger (more massive) furnace requires stronger mounting hardware, and all of the mounting components must be replaced in addition to the furnace.

The favorable *F* rating for Change Mode 3 is primarily the result of the proposed concept for the evolution response. The suggested evolution response is to feed fiber-optic cables through the lower load column into the pressure chamber. Due to their small size and compliant nature, fiber optic-cables are easy to insert into the small space in the underside of the pressure chamber. Only the load columns are modified with holes drilled into them so that the cables gain access to the pressure chamber.

The decision to mount the system on an adjustable framework significantly improved the *F* rating for Change Mode 4. If the system were mounted on a rigid frame, implementing this change mode would have been a serious issue and would have most likely resulted in the replacement of the entire frame. Because the system is mounted on a controllable and adjustable servo-hydraulic unit, this change mode required very little effort to implement and almost all of the system components were reusable.

For all of the details of the CMEA for the gas-pressure blow-forming system, refer to Appendix D.

6.4 THERMODYNAMIC IN-CLASS DEMONSTRATION DEVICE

There are five change modes that are used in the Change Modes and Effects Analysis of the P-V-T measurement device. In Table 6.7, these change modes and their respective evolution responses are summarized in an Evolution Response Table. In addition, the calculation of the "Readiness Rating" in the CMEA table is described briefly.

Change Mode		Evolution Response	Readiness
1	Increase the stroke length	The master cylinder, full-threads, rack and scale will need to be lengthened.	All materials can be purchased from current vendor and parts can be fabricated in-house.
2	Increase the stroke diameter	Larger diameter components will be employed to increase the stroke area.	All materials can be purchased from current vendor and parts can be fabricated in-house.
3	Add a locking mechanism to the piston	A ratcheting mechanism will be added to top gear. The Mechanism does not need to be reversible, but must be easily released.	It is uncertain whether the current vendor can provide the necessary parts. Modifications to the existing components can be performed in-house.
4	Add tunable, constant temperature	A heating element will need to be added to the copper base plate. Leads will extend from the interior of the chamber through the base components. The cylinder may need to be widened to create room for heating element.	A vendor will need to be located for the heating element. Modifications to existing parts can be performed in-house.
5	Provide means for excess air to escape from the chamber	A valve will need to be added to the top of the piston cylinder. The valve must be able to be opened and closed from the top of the device, outside of the chamber.	A vendor will need to be located for the valve. Modifications to the existing parts can be performed in-house.

Table 6.7: P-V-T measurement device evolution response table

6.4.1 Change Modes

Change Mode 1: Increase the Stroke Length

The first change mode that is listed in Table 6.7 is to Increase the Stroke Length. Currently, the P-V-T demonstration device is capable of producing a stroke length of approximately 10 inches. In some cases, it may be necessary to allow a longer stroke to achieve complete transformation from liquid to gas in the pressure chamber.

To implement this change mode, all of the lengthwise components are replaced with longer ones. These include the master cylinder, full-threads, rack, and the scale.

Change Mode 2: Increase the Stroke Diameter

The second change mode that is listed in Table 6.7 is to Increase the Stroke Diameter. As an alternative to Change Mode 1, an increased stroke diameter enables the device to achieve lower interior pressure with the same stroke length.

Implementation of this change mode requires many of the components to be replaced with ones that have a larger diameter. These components include the piston cylinder, master cylinder, o-rings, base, cylinder base, and cylinder head.

Change Mode 3: Add a Locking Mechanism to the Piston

The third change mode that is listed in Table 6.7 is to Add a Locking Mechanism to the Piston. In the current design, there is no means to lock the piston in a given position. The user is required to hold the piston in place while an assistant records the position of the piston, the temperature of the fluid, and the pressure of the interior chamber.

On the cylinder head, there is a pinion gear that moves the rack on the piston assembly. To implement this change mode, this gear is locked in place with a ratcheting mechanism, thus relieving the operator from the burden of holding it steady. The ratcheting mechanism is mounted on the existing gear holder, implying that the current gear holder requires redesign and is not considered reusable in the change modes and effects analysis.

Change Mode 4: Enable Tunable Temperature Settings

The fourth change mode that is listed in Table 6.7 is to Enable Tunable Temperature Settings. Currently, the device only operates at room temperature. This imposes significant limitations on the capabilities of the device. For example, only a single isotherm can be plotted for a given fluid. In addition, lack of temperature control limits the types of fluids that can be studied. For example, it would be very difficult to completely transition pure H_2O from liquid to gas with this device at room temperature. The only fluids that can be used are those that boil at a relatively small drop in pressure such as ethyl alcohol. Thus, the ability to set the temperature of the interior chamber at an elevated value would significantly increase the functionality of the device.

To implement this change mode, an electric heating element is added to the copper plate that is nested inside the cylinder base. The copper plate is modified to hold this heating element. Electric leads must be able to reach the heating element, and holes are drilled in the cylinder base to meet this requirement.

Change Mode 5: Provide Means for Excess Air to Escape from the Chamber

The fifth change mode that is listed in Table 6.7 is to Provide Means for Excess Air to Escape from the Chamber. When the test fluid is injected into the cylinder chamber, there is excess air that remains in the system. It is a difficult and tedious task to let this unwanted air out of the pressure chamber. The user must tilt the device completely sideways and use the release valve on the gauge assembly. It would increase the user friendliness of the device significantly if there were a way to release the air from the top of the cylinder while the device remains upright.

To implement this change mode, a release valve is placed on top of the piston cylinder. To enable a user to open and close the valve, a handle is inserted through the cylinder top that extends down into the master cylinder where it interfaces with the release valve.

6.4.2 Change Modes and Effects Analysis

The CMEA results for the P-V-T measurement device are shown in Table 6.8.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	**Design Flexibility (F)**	**Occurrence (O)**	**Readiness (R)**	**CPN**	**Description**
CM #1	5	30	83%	2	2	2	8	Increase stroke length
CM #2	9	30	70%	3	2	2	12	Increase stroke diameter
CM #3	1	30	97%	1	9	3	27	Locking mechanism
CM #4	9	30	70%	3	8	2	48	Tunable constant T
CM #5	3	30	90%	1	7	3	21	Excess air release
				2.0			23	Average

Table 6.8: P-V-T measurement device CMEA results

There are several features of the P-V-T measurement device that affect the Design Flexibility *F* ratings for its change modes. The change mode with the poorest *F* rating is Change Mode 2 (Increase stroke area). Increasing the diameter of the stroke requires increasing the diameters of most of the components in the system. All of the circular components are nested inside one another, and increasing the diameter of the innermost component (the piston) is a change that propagates to the outside of the system. There is little that could be done to avoid this problem, because the piston must mate perfectly with the master cylinder in order to form an adequate seal for operation. However, if some of the external circular components were oversized, such as the cylinder base and the cylinder head, there would be additional room to expand the stroke area, and fewer components would need to be redesigned or replaced.

Change Mode 4 is another change mode that has a particularly poor *F* rating. This high metric is the result of the system being incapable of importing or storing excess energy. The lack of an energy storage feature requires all of the base components to be modified, replaced, or redesigned for the implementation of an electric heating element. If a heating element were integrated in the system during initial construction, the user would be able to control the interior temperature of the device without any redesign effort.

The change mode with the best *F* rating is Change Mode 3, which is to add a locking mechanism to the piston assembly. The main reason for this favorable result is that the only component that must be changed (gear holder) is located on the exterior of the device. Its external placement makes it accessible so that changes can be made to it. Parts on the external portion of any system are less likely to interfere with other components in the system, because there is free space to expand the outer dimensions without interfering with internal components.

For the details of the CMEA for the P-V-T measurement device, refer to Appendix E.

6.5 BEAM PATTERN MEASUREMENT SYSTEM

There are four change modes that are used in the Change Modes and Effects Analysis of the beam pattern measurement (BPM) system. In Table 6.9, these change modes and their respective evolution responses are summarized in an Evolution Response Table. In addition, the calculation of the “Readiness Rating” in the CMEA table is described briefly.

Change Mode		Evolution Response	Readiness
1	Add controlled motion to the second TD mount	New motors and lead screws for all axes of motion for the second TD mount are required. New carriages are needed that can be driven with lead screws.	All of the relevant components are standard motion control hardware and can be supplied by the current vendor.
2	Add a door to one end of the tank for easy access	The Support frame end is replaced with a door that can be opened or locked shut. The tank end is replaced with a door that can be opened or sealed shut.	The current frame and tank vendors can implement the change with significant effort.
3	Lengthen the test tank	The X-axis motion components, tank, and support frame are all lengthened.	The current vendor can lengthen the tank with little effort. The frame vendor can lengthen tank with significant effort. The motion components can be easily replaced from current vendor.
4	Deepen the test tank	The top surface of the support frame is raised up. The tank panels are replaced with taller ones.	The current vendor can raise the walls of the tank with minimal effort. The current frame vendor needs to send longer frame legs.

Table 6.9: Beam pattern measurement system evolution response table

6.5.1 Change Modes

Change Mode 1: Add Controlled Motion to the Second Transducer Mount

The first change mode that is listed in Table 6.9 is to Add Controlled Motion to the Second Transducer Mount. Currently, only one of the two transducer mounts on the Beam Pattern Measurement (BPM) system is controlled by motors. The other transducer is set manually and remains stationary during testing. To broaden the capabilities of the system by making it more automated and easier to use, it may be of interest to implement motorized motion control for the second transducer mount. For simplicity, the transducer mount that is currently controlled with motors is referred to as Mount A, and the non-controlled mount is referred to as Mount B.

To implement this change mode, drive capability is added to the system for each of the four axes of motion (x, y, z, and θ) of Mount A. The carriages that allow motion in the x and y directions for Mount B are currently platforms on linear bearings, and do not have the appropriate components to be driven with a lead screw. Thus, they are replaced or modified so that they can be moved with motor driven lead screws. The current rotary table on Mount B is completely manual, and cannot be moved with a motor. Thus, it is replaced with one that is identical to the rotary table on Mount A so that the transducer can be rotated about the *z* axis. Lastly, a vertical motion column like that on Mount A is attached to Mount B, to allow controlled motion in the *z* direction.

Change Mode 2: Add a Door to One End of the Tank for Easy Access

The second change mode that is listed in Table 6.9 is to Add a Door to One End of the Tank for Easy Access. There are several reasons that one may want to gain physical access to the interior of the tank. One motivation is that it is much easier to mount the transducers on their appropriate rotary table from inside the tank. Another reason an operator may want to gain access to the tank is to insert or remove objects or substances for beam pattern testing. For example, it is often of interest to place a layer of sand at the bottom of the tank to test the reflection of sound beams off of it.

In its current configuration, it is difficult for an operator to gain access to the inside of the tank. He or she must climb over the upper edge and into the tank being careful not to damage the tank side panels or positioning system components. Change Mode 2 suggests adding a door to one end of the tank so that the operator can gain easy access to the interior of the tank.

To implement this change mode, the tank is redesigned to feature a door on one of its ends. The door must lock in place and form a watertight seal so prevent leakage of the tank contents. The solution must have a smooth, featureless inner surface that is consistent with the rest of the tank in order to avoid reflecting the sound waves at odd angles. Implementing this change propagates from the tank to the support frame, because of the nesting of these two modules. Thus, the support frame is also redesigned to feature a door or a gate that opens and closes to allow proper access into the tank interior.

Change Mode 3: Lengthen the Tank

The third change mode that is listed in Table 6.9 is to Lengthen the Tank. The current dimensions of the water tank are set and cannot be adjusted. Research interests may demand a longer tank to gain adequate distance between the two transducers.

To implement this change mode, every lengthwise (x direction) component is replaced with longer ones. These include the tank frame bars, the tank side panels, the lengthwise support frame components, and the x-direction positioning system components.

Change Mode 4: Deepen the Tank

The fourth change mode that is listed in Table 6.9 is to Deepen the Tank. Similar to the lengthwise dimension of the tank, as discussed for Change Mode 3, is the height constraint of the water tank. The height is currently set and cannot be adjusted. Research interests may require more range of motion in the z direction, and the height of the tank must be increased to meet this demand.

To implement this change mode, the vertical side and end panels of the tank are replaced with taller ones. This change propagates to the support frame module because the tank is nested inside the support frame, and failure to raise the upper surface of the support frame results in interference of these two modules. The legs of the support frame are removable, and replacing them with longer ones is all that is needed to raise the upper surface of the support frame along with all of the positioning system components.

6.5.2 Change Modes and Effects Analysis

The CMEA results for the beam pattern measurement system are given in Table 6.10. On average, the Design Flexibility *F* ratings are quite favorable. The change mode with the lowest percentage of readily reusable parts is Change Mode 3, with only 79% of the parts being reusable for the change mode. This percentage resulted in an *F* rating of 2, which is still very good.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Design Flexibility (F)	Occurrence (O)	Readiness (R)	CPN	Description
CM #1	8	52	85%	2	4	3	24	Add control to 2nd mount
CM #2	7	52	87%	2	6	4	48	Door to tank end
CM #3	11	52	79%	2	2	4	16	Lengthen tank
CM #4	4	52	92%	1	2	4	8	Deepen tank
				1.8			24	Average

Table 6.10: Beam pattern measurement system CMEA

There are several features of the layout of the beam pattern measurement system that directly affect the Design Flexibility *F* ratings in the CMEA table. For Change Mode 1, the modularity of the two separate transducer positioners eliminates the change propagation from one to the next when the motorized control components are added to the second rotary table. Also, motorized controls are easy to integrate into Mount B due to the adjustable nature of the components on which it is mounted.

Change Mode 3 has the worst *F* rating of the four change modes. A critical feature of the overall layout of the system creates this result. The water tank module is nested inside the support frame. It cannot expand in any direction without interfering with the support frame which completely envelops it. Lengthening the water tank requires all of the lengthwise support frame members to be lengthened in addition to the lengthwise members of the tank.

Change Mode 4 has the most favorable *F* rating of the four change modes. It is natural to assume that the nesting of the tank inside the support frame would cause the *F* rating to be high for the same reasons that it is for Change Mode 3. However, the removable legs of the support frame make it very easy to raise the height of the frame without having to change any of the other components in the support frame module.

For the details of the CMEA for the beam pattern measurement system, refer to Appendix F.

6.6 CHAPTER SUMMARY

In this chapter, each of the five case studies considered in this research is analyzed for evolvability using change modes and effects analysis. For clarity, each change mode for each case study is explained in detail along with a concept that represents a proposed evolution response to that change mode. Once the change modes for the five case studies are explained, the systems are analyzed for evolvability using change modes and effects analysis.

Recall from Chapter 3 that the goal of this research is to investigate the effectiveness of using the guidelines for FFE on the design of evolvable small-lot systems. Although the full CMEA is performed for each system, only the results for the Design Flexibility *F* rating are discussed. This is because the guidelines for FFE directly affect this metric, but they have only secondary effects on the *R* rating and no effect on the *O* rating. For most of the change modes, the system features are correlated to the *F* ratings for each change mode.

In Chapter 7, the use or non-use of the guidelines for FFE are correlated with system features that that improve or worsen the CMEA results in this chapter. By studying the use or non-use of the guidelines for FFE, conclusions can be drawn about whether the guidelines did, did not, or would have had an effect on the evolvability of each system.

Chapter 7: Guideline Effectiveness and Expansion

In this chapter, steps are taken to complete the two primary objectives of this research. Recall from previous chapters that the first objective of this research is to determine the effectiveness of using the guidelines for flexibility for future evolution (FFE) in the design of small-lot systems. The second objective of this research is to expand the current list of guidelines in the “Adjustability Approach” category into a more detailed list of guidelines that are more useful to designers.

In the previous chapter, the five case-studies considered in this research are analyzed for evolvability using Change Modes and Effects Analysis (CMEA). In this chapter, the CMEA results are correlated with the use or nonuse of flexibility guidelines to address the two research objectives.

Recall from Chapter 3 that the first five steps taken to meet the two objectives of this research are identical, and the final three steps for each objective vary significantly. The research approach is shown again in Figure 7.1, with the steps that are completed in this chapter shaded in gray. The first four steps shown in Figure 7.1 are completed in Chapter 6. In the first section of this chapter, steps related to the first research objective are discussed. In the second section, steps are discussed for the second objective.

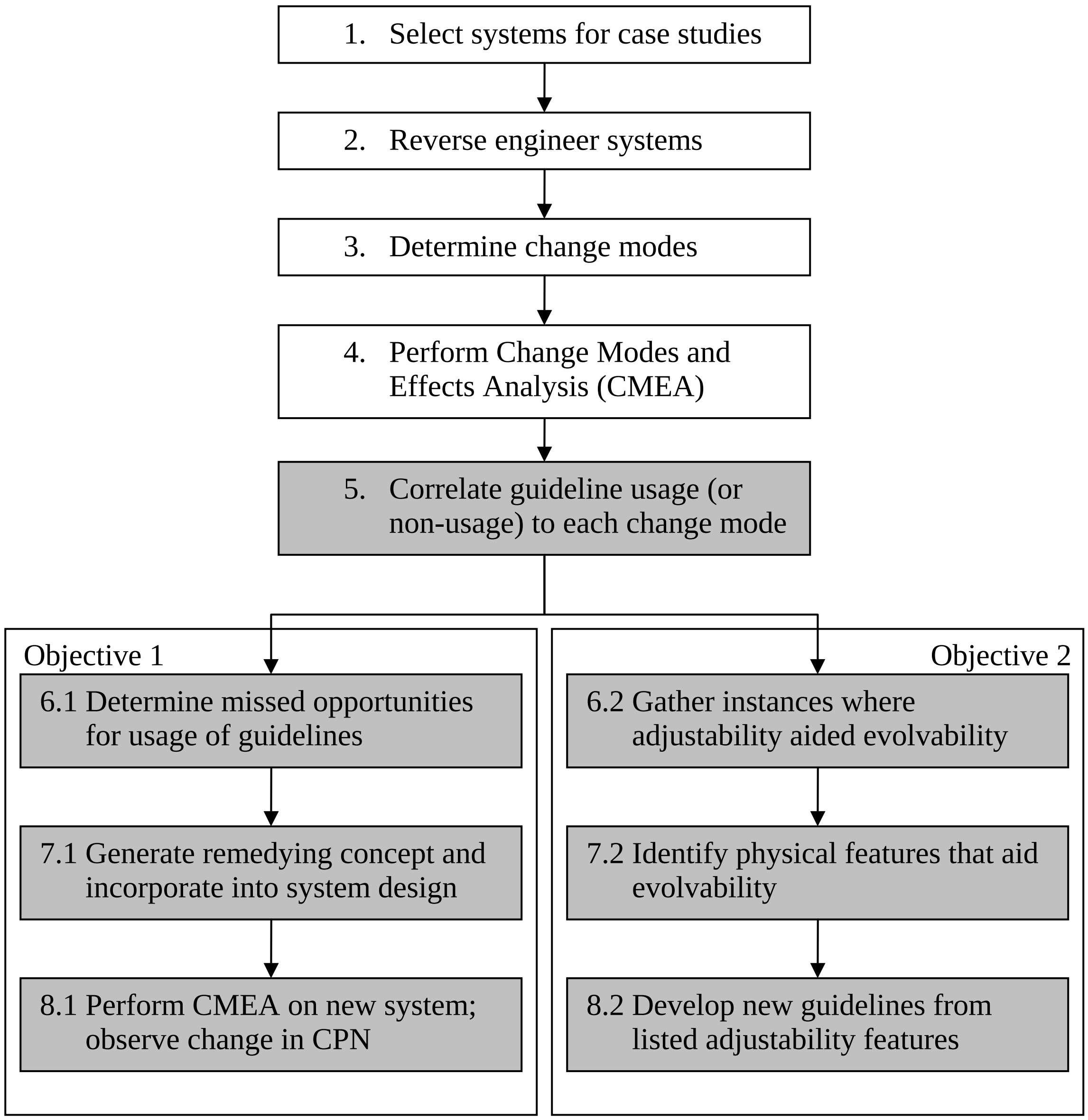

Figure 7.1: Research approach

7.1 EFFECTIVENESS OF THE GUIDELINES FOR FFE

In this section, the final steps are taken to meet the first objective of this research, which is to verify the effectiveness of using the guidelines for FFE in the design of small lot systems. For each system, four steps are taken in addition to the evolvability analysis that was performed in Chapter 6.

First, a Use of Guidelines report is generated for each of the systems studied in this research (Step 5). An example of a blank Use of Guidelines report is given in Table 3.1 in Chapter 3.

Second, the Use of Guidelines report is used to identify all missed opportunities for guideline usage (Step 6.1). Any situation where a guideline is listed as not implemented (deliberately or inadvertently) but would have been helpful in increasing the evolvability of a given change mode is considered a missed opportunity.

Third, a concept is generated for each missed guideline usage opportunity (Step 7.1). These concepts are then assembled and implemented into a hypothetical proposed redesign for each system.

Finally, the complete Change Modes and Effects Analysis process is performed again in Step 8.1 with the hypothetically more evolvable concepts implemented. This process includes regeneration of the evolution response table, module change report, and bill of materials for the new concept, along with the CMEA, based on the reusability of the components in the new bill of materials.

In the following subsections, the results of these three steps are presented for each mechanical system.

7.1.1 Scaled Seal Testing System

Upon inspection of the Use of Guidelines report for the scaled seal testing system, several opportunities for implementing the guidelines in the design of the system are identified. In Table 7.1, each missed opportunity for guideline usage is listed along with a proposed design feature to implement the guidelines. The first column is titled “CM” which stands for “Change Modes.” In this column, the numbers that correspond to the system specific change modes are listed. The second column is titled “GL” which is an abbreviation for “Guidelines.” In this column, the number of the guideline that could have been used to improve the system’s evolvability to that change mode is listed. In the third column, titled “Explanation,” the explanations from the Use of Guidelines report are listed for convenience. In the fourth column, titled “Suggested Design Feature,” the suggested design features that implement the guidelines are given. Tables 7.3, 7.5, 7.7, and 7.9 follow an identical format.

CM	GL	Explanation	Suggested Design Feature
1	4	If hydraulics were used, multiple small rams could be used together. Use multiple track sections to increase length.	Use multiple, small hydraulic rams and modular frame section lengths.
1	11	Using the ball screws constrained the available area on the transmission of the device. A cable pulley system would have been better.	Use a cable pulley system to drive the linear motion components.
2	9	If more space was created around the drill pipe as it passes through the backside shim, redesign would not be required.	Use a larger diameter orifice in the backside shim.
2	18	If the tool joint is to be removed, the two ends of the opposing drill pipe sections cannot be attached.	Use a single drill pipe with grooves to attach simulated pipe joints.
2	19	If the tool joints somehow clamped on that would be neat.	Use a single drill pipe with grooves to attach simulated pipe joints.
2	20	The drill pipe could have been a single rod with little groves onto which the tool joints could attach.	Use a single drill pipe with grooves to attach simulated pipe joints.
3	1	The sight glass ports are limited by the pressure vessel design.	Use a larger pressure vessel.
3	9	The original pressure vessel tube was 'optimized' to be just large enough for the stripper rubber.	Use a larger pressure vessel.
3	13	The original pressure vessel tube was 'optimized' to be just large enough for the stripper rubber.	Use a larger pressure vessel.
4	1	The conversion transmission functions are tightly tied in the Linear Motion Assembly module.	Use multiple, small hydraulic rams and modular frame section lengths.
4	4	If hydraulics were used, multiple small rams could be used together.	Use multiple, small hydraulic rams and modular frame section lengths.
4	11	Using the ball screws constrained the available area on the transmission of the device.	Use multiple, small hydraulic rams and modular frame section lengths.
6	9	The size of the stripper rubber does not have room to expand.	Use a larger pressure vessel.
6	12	The stripper rubber mounts inside of the pressure vessel. Maybe it could have been designed to bolt onto the outside of the pressure vessel.	Use a larger pressure vessel with exterior stripper rubber mounts.
7	4	If hydraulics were used, multiple small rams could be used together. Use multiple track sections to increase length.	Use multiple, small hydraulic rams and modular frame section lengths.

7	11	Using the ball screws constrained the available area on the transmission of the device.	Use multiple, small hydraulic rams and modular frame section lengths.
8	1	The conversion transmission functions are tightly tied in the linear motion assembly module.	Use multiple, small hydraulic rams and modular frame section lengths.
8	4	If hydraulics were used, multiple small rams could be used together.	Use multiple, small hydraulic rams and modular frame section lengths.
9	10	There is not a good place to mount a flange hinge.	Use an oversized flange interface on the pressure vessel ends.
9	14	The main flanges require many bolts, however, the shim attaches by a single acme thread.	Use an oversized flange interface on the pressure vessel ends.

Table 7.1: Scaled seal testing system: missed opportunities for guideline usage [45]

From the list of missed opportunities to use the guidelines in the design of the scaled seal testing system, a new concept is developed with the four new features. In the list given below and in other similar lists given throughout the chapter, the numbers in parentheses represent the guidelines from which each concept was inspired.

- Use multiple small hydraulic rams instead of ball screws and multiple, modular frame section lengths (4).
- Use a backside shim with a larger orifice that can pass tool joints (9).
- Use a single drill pipe with grooves for attaching multiple tool joints (20).
- Use a larger pressure vessel with oversized flange interfaces on ends (9, 10, 12, 13).

With these new features implemented, the CMEA is performed again. The results of the CMEA on the design that implements the guidelines more thoroughly are given in Table 7.2.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	**Design Flexibility (F)**	**Occurrence (O)**	**Readiness (R)**	**CPN**	**Description**
CM #1	14	148	91%	1	4	2	8	Longer Stroke
CM #2	2	148	99%	1	2	2	4	More Tool Joints
CM #3	18	148	88%	2	7	4	56	Increase Field of View
CM #4	5	148	97%	1	2	3	6	Increase Speed
CM #5	13	148	91%	1	10	3	30	Use Drilling Mud
CM #6	22	148	85%	2	5	4	40	Full Size Static Calibration
CM #7	24	148	84%	2	4	3	24	Increase Scaling Factor
CM #8	11	148	93%	1	6	3	18	Run Tests Outside
CM #9	9	148	94%	1	9	3	27	Quicker Test Setup
CM #10	4	148	97%	1	1	2	2	Decrease Scaling Factor
				1.3			24	Average

Table 7.2: Scaled seal test system CMEA with guidelines implemented in the design

The results presented in Table 7.2 suggest that implementing the guidelines in the design of the scaled seal testing system reduces the average design flexibility *F* rating from 1.9 to 1.3, which is a 32% reduction.

Implementation of the guidelines also reduces the *R* rating from a value of 4 to a value of 3 for Change Mode 7. Change Mode 7 is to increase the scaling factor of the test specimen. A necessary design requirement for implementing this change mode is to increase the speed of the drill pipe. The concept of using multiple, small hydraulic rams meets this need and improves the readiness. This concept improves the readiness because the hypothetical vendor of the hydraulic would be able to provide higher speed rams with very little effort because it is a standard component that is part of a family of products. The ball screw system in the current system features custom-made, high-precision components which require significant effort for the vendor to change. Thus, the readiness is improved by using modular, standardized components.

Implementation of the guidelines reduces the average CPN from 33 to 24, which is a 27% reduction. These results show that implementing the guidelines in the initial design of the scaled seal testing system results in a design that is more evolvable to the selected change modes.

7.1.2 Gas-Pressure Blow-Forming System

Upon inspection of the Use of Guidelines report for the gas-pressure blow-forming (GPBF) system, several opportunities for implementing the guidelines in the design of the system are identified. In Table 7.3, each missed opportunity for guideline usage is listed along with its corresponding change mode and a proposed design feature to implement the guidelines.

CM	GL	Explanation	Suggested Design Feature
1	2	The micrometer could have been made a separate module from the strain measurement rod and bottom assembly.	Mount the micrometer on the outside of the bottom assembly.
1	9	The bottom sub assembly could have been designed to be longer, allowing a longer measuring stroke to be used.	Design the strain measurement rod and the bottom subassembly with oversized travel capabilities.
1	12	The strain gauge could have been mounted on the outside.	Mount the micrometer on the outside of the bottom assembly.
2	7	Die and die holder could be combined.	Combine the die and die holder into a single part.
2	9	Furnace could have been bigger, allowing room for larger components inside.	Use an oversized furnace used to create additional interior space.
2	24	Stronger than necessary furnace mounting components could have been used.	Use an oversized furnace used to create additional interior space.
3	4	If loading column was divided into separate smaller modules, only the module closest to the specimen would need to be modified.	Divide the loading into separate, smaller ones that are connected in series.

Table 7.3: Gas-pressure blow-forming system: missed opportunities for guideline usage

From the list of missed opportunities to use the guidelines in the design of the GPBF system, a new concept is developed with the following features:

- Use a strain measurement rod and a bottom assembly with oversized travel capabilities (9).
- Mount the micrometer on the outside of the bottom sub assembly for easy replacement (2, 12).
- Combine the die and die holder into a single part (7).
- Use an oversized furnace to create additional interior space (9, 24).
- Divide the loading column into separate, smaller ones that are connected in series (4).

With these new features implemented, the CMEA is performed again. The results of the CMEA on the redesign are given in Table 7.4.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	**Design Flexibility (F)**	**Occurrence (O)**	**Readiness (R)**	**CPN**	**Description**
CM #1	1	36	97%	1	5	3	15	Increase strain range
CM #2	3	36	92%	1	4	2	8	Increase specimen size
CM #3	2	36	94%	1	5	3	15	Add vision system
CM #4	2	36	94%	1	10	2	20	Compensate for CTE
				1.0			15	Average

Table 7.4: Gas-pressure blow-forming CMEA with guidelines implemented in the design

The results presented in Table 7.4 suggest that implementing the guidelines in the design of the GPBF system reduces the average design flexibility *F* rating from a value of 2.0 to a value of 1.0, which is a 50% reduction.

The *R* ratings change for two of the four change modes with the guidelines implemented. For Change Mode 1, the readiness rating increases from a value of 2 to a value of 3. Recall that the readiness for each change mode is the average readiness to change each component on the bill of materials. Without the guidelines implemented, a large number of high readiness (in-house) changes are made to execute the change mode. With the change modes implemented, only one part is changed (the micrometer) and it is easily done by the current vendor (Readiness = 3). For change Mode 2, the readiness decreases from a value of 3 to a value of 2 with the guidelines implemented. This decrease is primarily the result of using an oversized furnace, which eliminates the need to change it when implementing the guideline. A change is done to this component with a readiness of 6, which significantly increases the average *R* rating for Change Mode 2. Using an oversized furnace, as suggested by the guidelines, eliminates the need to make this change and improves the readiness rating.

Implementation of the guidelines in the design of the gas-pressure blow-forming system reduces the CPN from a value of 25 to a value of 15, which is a 40% reduction. These results show that implementing the guidelines in the initial design of the gas-pressure blow-forming system results in a design that is more evolvable to the selected change modes.

7.1.3 P-V-T In-Class Demonstration Device

Upon inspection of the Use of Guidelines report for the P-V-T in-class demonstration device, several opportunities for implementing the guidelines in the design of the device are identified. In Table 7.5, each missed opportunity for guideline usage is listed along with its corresponding change mode and a proposed design feature to implement the guidelines.

CM	GL	Explanation	Suggested Design Feature
1	7	The master cylinder could theoretically have been made more robust eliminating the need for full threads.	Eliminate the full threads by implementing a more robust master cylinder.
1	16	Full threads create extra contact points between top and base and could be eliminated.	Eliminate the full threads by implementing a more robust master cylinder.
2	8	Top and base could be made identical, with a plug in the base instead of a hole for the rack.	Use an identical part or assembly for the top and base.
2	9	Wider area could have been used for full threads	Use a wider top and base.
2	21	A compliant seal system that automatically expands to larger cylinder may have eliminated the need to redesign the piston.	Use a compliant seal around the master cylinder that can fit to larger diameter cylinders.
3	20	A small frame could have been used to mount a locking ratchet.	Erect a small frame around the top of the cylinder.
4	2	If base were a conducting material, the heating function could have been implemented in a different external module.	Make the base assembly out of a single plate which is made thinner and entirely out of a conducting material with space for a heating element to be attached.
4	6	A copper base plate (thermal component) could have been split into a separate module from the fluid component (base / chamber).	Make the base assembly out of a single plate which is made thinner and entirely out of a conducting material with space for a heating element to be attached.
4	9	Extra room on the copper base plate would have eliminated need for redesign.	Make the base and top wider than necessary.
4	10	A heating element could be added underneath the base, but base plate is too thick.	Make the base assembly out of a single plate which is made thinner and entirely out of a conducting material with space for a heating element to be attached.
4	12	Changing component is on the interior, adding to number of components that need to be changed. It could be on the exterior.	Make the base assembly out of a single plate which is made thinner and entirely out of a conducting material with space for a heating element to be attached.
4	13	The copper base plate is nested inside the aluminum base and could be avoided.	Make the base assembly out of a single plate which is made thinner and entirely out of a conducting material with space for a heating element to be attached.

4	19	The base could have been made detachable so that it could be replaced with a heating element.	Make the base detachable.
4	24	Excess energy storage could be used to create heat in the chamber and control the temperature.	Use a battery and a heating element to generate heat.
5	10	Slots in the head plate could have been used to allow a valve opener to pass through.	Add slots to the cylinder head to allow a valve opener and the TC probe to pass through.
5	16	Open head plates could have been used to allow passing of a valve opener.	Add slots to the cylinder head to allow a valve opener and the TC probe to pass through.

Table 7.5: P-V-T In-class demonstration device: missed opportunities for guideline usage

From the list of missed opportunities to use the guidelines in the design of the P-V-T device, a new concept is developed with the following features:

- The fully threaded supports are eliminated by designing a more robust interface between the master cylinder and the bottom and top pieces (7, 16).
- A compliant, flexible diameter seal system is used instead of o-rings (21).
- A small frame is erected around the cylinder top for mounting additional modules (20).
- The base assembly is constructed from a single plate which is made thinner and entirely out of a conducting material with space for a heating element to be attached (2, 10, 12, 13).
- The base and top are made wider than necessary (9).
- Slots are added to the cylinder head to allow additional modules to pass through to the upper space of the interior (10, 16).

With these new features implemented, the CMEA is performed again. The results of the CMEA on the redesign are given in Table 7.6.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	**Design Flexibility (F)**	**Occurrence (O)**	**Readiness (R)**	**CPN**	**Description**
CM #1	4	26	85%	2	2	2	8	Increase stroke length
CM #2	2	26	92%	1	2	2	4	Increase stroke area
CM #3	0	26	100%	1	9	1	9	Locking mechanism
CM #4	1	26	96%	1	8	2	16	Tunable constant T
CM #5	1	26	96%	1	7	3	21	Excess air release
				1.2			12	Average

Table 7.6: P-V-T device CMEA with guidelines implemented in the design

The results presented in Table 7.6 suggest that implementing the guidelines in the design of the GPBF system reduces the average design flexibility *F* rating from a value of 2.0 to a value of 1.2, which is a 40% reduction.

Implementation of the guidelines also reduced the *R* rating from a value of 3 to a value of 1 for Change Mode 3. With the guidelines implemented, the small frame around the top of the cylinder enables easy mounting of a locking mechanism. In this case, 100% of the current components in the device are reused to implement the change mode. Thus, the readiness rating defaults to a value of 1.

Implementation of the guidelines in the design of the P-V-T device reduces the CPN from a value of 23 to a value of 12, which is a 48% reduction. These results show that implementing the guidelines in the initial design of the device results in a design that is more evolvable to the selected change modes.

7.1.4 Beam Pattern Measurement System

Upon inspection of the Use of Guidelines report for the beam pattern measurement (BPM) system, several opportunities for implementing the guidelines in the design of the system are identified. In Table 7.7, each missed opportunity for guideline usage is listed along with its corresponding change mode and a proposed design feature to implement the guidelines.

CM	GL	Explanation	Suggested Design Feature
1	8	Identical carriages for the driven and non driven axes could have been used.	Make all carriages for corresponding axes so that they are identical and can be driven with lead screws.
2	7	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
2	12	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
2	13	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
2	19	Components on the tank and frame ends could have been made detachable.	Make all components on the tank and frame detachable.
2	20	A single frame could have been used to mount the tank and the positioning system	Integrate the support frame and tank into a single module.
3	1	A modular frame could have been used to support the test tank and positioning system	Make all components on the tank and frame detachable.
3	7	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
3	12	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
3	13	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
3	20	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
3	23	Slotted or telescoping tank frame members and sliding panel ends would have enabled adjustability.	Use telescoping frame member in length and height directions.
4	12	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
4	13	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
4	20	Tank and the frame could have been implemented into a single module.	Integrate the support frame and tank into a single module.
4	23	Adjustable length table legs and sliding height tank panels could have been used.	Enable the height of the sliding tank base to be adjustable.

Table 7.7: Beam pattern measurement system: missed opportunities for guideline usage

From the list of missed opportunities to use the guidelines in the design of the beam pattern measurement system, a new concept is developed with the following features:

- Make all carriages identical for corresponding axes and drivable with lead screws (8).
- Combine the support frame and tank into a single module (7, 12, 13, 20).
- Make all components on the tank and frame detachable (1, 19).
- Enable the height of the test tank floor surface to be adjustable (23).
- Enable the length of the sliding end panel to be adjustable (23).
- Use telescoping frame members in the length and height directions (23).

With the new features implemented, the CMEA is performed again. The results of the CMEA on the redesign are given in Table 7.8.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Design Flexibility (F)	Occurrence (O)	Readiness (R)	CPN	Description
CM #1	2	52	96%	1	4	3	12	Add 2nd controlled mount
CM #2	6	52	88%	2	6	4	48	Gate to tank end
CM #3	2	52	96%	1	2	4	8	Lengthen tank
CM #4	0	52	100%	1	2	1	2	Deepen tank
				1.3			18	Average

Table 7.8: BPM CMEA with guidelines implemented in the design

The results presented in Table 7.8 suggest that implementing the guidelines in the design of the GPBF system reduces the average design flexibility *F* rating from a value of 1.8 to a value of 1.3, which is a 28% reduction.

Implementation of the guidelines also reduces the *R* rating from a value of 4 to a value of 1 for Change Mode 4. With the guidelines implemented, the adjustability of the tank bottom surface enables the change mode to be implemented without having to change any of the system components. In this case, 100% of the current components in the device are reused to implement the change mode. Thus, the readiness rating defaults to a value of 1.

Implementation of the guidelines in the design of the beam pattern measurement system reduces the CPN from a value of 24 to a value of 18, which is a 25% reduction. These results show that implementing the guidelines in the initial design of the device results in a design that is more evolvable to the selected change modes.

7.1.5 Welding Test Station

Even though the welding test station was designed using the guidelines for flexibility for future evolution, a handful of opportunities were found for implementing the guidelines. In Table 7.9, each missed opportunity for guideline usage is listed along with its corresponding change mode and a proposed design feature to implement the guidelines.

CM	GL	Explanation	Suggested Design Feature
2	9	Additional room on the breadboard would have allowed for easier extension of other components.	Use a longer than necessary breadboard and frame.
2	10	Additional surface area on the breadboard would have allowed for easier extension of other components.	Use a longer than necessary breadboard and frame.
2	23	Sliding pillow blocks that reduce the span, combined with a longer rack, could increase the stroke length.	Use sliding pillow blocks for a shorter span and a longer rack.
3	2	Integration of the pulley and the pinion complicate the redesign. Pinion could be removable.	Use a removable pinion gear.
3	11	Additional drive area could allow for other gears to be added, increasing the available speed range.	Use a longer than necessary pinion gear.
3	14	A standardized connector on each end of the shaft would have eliminated the need to redesign the shaft for a change in pinion gear.	Use a symmetrical shaft that has the same diameter at each end with a removable pinion gear.
3	19	A detachable pinion gear would simplify redesign.	Use a detachable pinion gear.
3	23	An adjustable drive ratio with the belt pulleys (like those found in drill presses) could have been implemented to allow adjustable speed ranges.	Use a multi-pulley system with several drive ratio combinations.
6	8	The ends of the bracket are different, but could be the same.	Make the end pieces identical with a compliant liner for holding different torch diameters.
6	21	A compliant torch holder would have been able to adapt to different torch geometries.	Make the end pieces identical with a compliant liner for holding different torch diameters.

Table 7.9: Welding station: missed opportunities for GL usage

From the list of missed opportunities to use the guidelines in the design of the Welding Test Station, a new concept is developed with the following features:

- Use a longer than necessary breadboard and support frame assembly (9, 10).
- Use sliding pillow block on the motion table that can be made closer together and a longer rack to enable adjustable maximum stroke (23).
- Make the pinion gear removable with a set screw and a symmetrical shaft with identical ends for a standardized connection (14).

- Make the torch mount with identical ends and a compliant liner for different diameter torches (8, 21).

With these new features implemented, the CMEA is performed again. The results of the CMEA on the redesign are given in Table 7.10.

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	**Design Flexibility (F)**	**Occurrence (O)**	**Readiness (R)**	**CPN**	**Description**
CM #1	12	34	65%	4	8	2	64	Radial Welds
CM #2	3	34	91%	1	4	2	8	Weld Pass Length
CM #3	2	34	94%	1	5	3	15	Weld Speed Range
CM #4	2	34	94%	1	10	2	20	Raise Weld Surface
CM #5	1	34	97%	1	4	1	4	Glass Shield
CM #6	2	34	94%	1	4	3	12	Other weld types
CM #7	1	34	97%	1	9	2	18	Mount IR camera
CM #8	5	34	85%	2	2	5	20	Torch motion
				1.5			20	Average

Table 7.10: Welding station CMEA with flexible concepts implemented

Recall from chapter 6 that the system in its current form is found to have an average *F* rating of 1.9, and an average change potential number (CPN) of 22. Implementation of the missed opportunities for guidelines usage results in an average *F* rating of 1.5 (21% reduction) and a CPN of 22 (9% reduction).

Implementation of the missed opportunities for guideline usage increases the readiness *R* ratings of Change Modes 3 and 6 from values of 2 to values of 3. In both cases, a large quantity of low *R* rating changes must be performed on the system in its current configuration. With the missed opportunities for guideline usage implemented, only a handful of components are not reusable. However, the few non-reusable components happen to have higher readiness ratings which increase the average readiness for their respective change modes.

These results suggest that it is still possible to improve the evolvability of the welding test station even though the guidelines for FFE were used in its original design. Recall from Chapter 4 that the guidelines for FFE were used ad hoc at various steps in the design of the welding station. However, the steps that are taken in this research to identify missed opportunities for implementing the guidelines were not performed during the design of the welding station. These missed opportunities could have been identified before the system was fully implemented if the steps in the approach to this research were carried out after the detailed design phase of the design process.

7.1.6 Summary of Results

The results of the analysis performed above are summarized in Table 7.11. In each case study, the hypothetical implementation of the guidelines for FFE resulted in a notable reduction in the Design Flexibility *F* rating and in the Change Potential Number (CPN).

System	Current F	Redesigned F	% F Reduction	Current CPN	Redesigned CPN	% CPN Reduction
SST	1.9	1.3	32	33	24	27
GPBF	2.0	1.0	50	25	15	40
PVT	2.0	1.2	40	23	12	48
BPM	1.8	1.3	28	24	18	25
Welding	**1.9**	**1.5**	**21**	**22**	**20**	**9**

Table 7.11: Summary of results

Of the five case studies that are the consideration of this work, the welding station has the least amount of potential for improvement. This is to be expected because the welding station was originally designed using the guidelines for FFE, and the other systems were not.

For each of the other four case studies, implementation of the guidelines for FFE results in percent reductions in the CPN ranging from 25% to 48%. In no case does implementing the guidelines result in higher CPN ratings.

In all five case studies, the process of determining missed opportunities for guideline usage and implementing those guidelines yielded valuable flexible system design insights. The redesigned systems have physical features that make them more evolvable to the identified change modes. These results strongly suggest that using the guidelines for FFE in the design of small-lot systems has a positive effect on the evolvability of the resulting designs.

It is fair to claim that a CPN reduction corresponds to a reduction of the time and cost of implementing a change mode, but the magnitude of these time and cost reductions is unknown. Currently, no general method exists for correlating CPN ratings to time and money savings. Such a method would be very valuable to the firms that manufacture systems that are similar to the ones considered in this research and should be studied in future work.

It is also important to consider the cost of implementing the guidelines for FFE in a design in addition to the potential savings associate with added flexibility. In some cases, implementation of the guidelines increases the overall cost of the original design. This added cost may or may not outweigh the benefits of added evolvability to certain change modes. A method for measuring and comparing monetary costs and benefits of guideline implementation would also be valuable to manufacturing firms and should be studied in future work.

7.2 EXPANSION OF "ADJUSTABILITY APPROACH" GUIDELINES

In this section, the final steps are taken to meet the second objective of this research, which is to expand the guidelines for FFE in the "Adjustability Approach" category. For each system, three steps are taken in addition to the evolvability analysis that was performed in Chapter 6.

In a similar fashion to the method for Objective 1, the Use of Guidelines report is used as a starting point to meet this objective. The first step for meeting Objective 2 is to use the Use of Guidelines report to identify all situations in which using the Adjustability guidelines (23 and 24) helped the evolvability of the system under consideration. A table is generated of these instances, along with an explanation of what is being adjusted and how that entity is being adjusted.

Second, a set of physical features that enable evolvability are deduced from the table that is generated in Step 1.

Finally, the list that is created in the second step is used to develop new guidelines for FFE. This goal is achieved by generalizing what is adjusted and how it is adjusted into a concise set of guidelines that capture the overall, physical features that enable or enhance adjustability.

In the following subsections, the results of the three steps listed above are presented.

7.2.1 Adjustability Aiding Instances

In this section, the use of guidelines report is used to determine any situations that enable evolvability by utilizing the "Adjustability Approach" guidelines. In Table 7.12, each instance in which either of guidelines 23 or 24 aided or could have aided the evolvability of each system is listed. In the first column in Table 7.12, each system is listed in an abbreviated form. The change mode and guideline indexes are listed in the second and third columns, respectively. The statements in the fourth column are taken directly from the explanation columns of the Use of Guidelines reports for each system. In the "Enabling Feature" column, the architectural features that enable adjustability are listed for use in the second of the final steps to meet the second objective of this research.

System	CM	GL	Explanation	Enabling Feature
SST	1	23	The bolt holes were oversized to allow adjustment during setup.	Using sliding surfaces to adjust position.
SST	1	24	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses from increasing the length.	Using stronger than necessary members to withstand additional forces.
SST	4	23	The bolt holes were oversized to allow adjustment during setup.	Using sliding surfaces to adjust position.
SST	4	24	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses.	Using stronger than necessary members to withstand additional forces.
SST	7	23	Shims were used and bolt holes oversized to offer alignment to counteract tolerance stack up.	Using sliding interfaces to adjust position.
SST	7	24	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses. Pressure is adjustable through the pressure circuit.	Using stronger than necessary members to withstand additional forces.
SST	8	23	The bolt holes were oversized to allow adjustment during setup	Using sliding surfaces to adjust position.
SST	8	24	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses.	Using stronger than necessary members to withstand additional forces.
GPBF	1	23	The micrometer mount can slide on the column. The counterweights will need to be changed, and could be tunable to make for easy accommodation.	Using varying amounts of mass to adjust counteractive force.

GPBF	4	23	The mounting frame is fully adjustable	Using sliding surface to adjust position. Using hydraulics (pressure) to adjust force.
PVT	4	23	The temperature could be a tunable design parameter, but is not which creates the need for redesign effort.	Using electrical power flow to vary the temperature of thermal energy transferring components.
PVT	4	24	Excess energy storage could be used to create heat in the chamber and control the temperature.	Allowing the storage of excess energy for use as a thermal power supply.
BPM	1	23	The 2nd mount is entirely tunable and adjustable, so controls are easy to implement.	Using sliding surfaces to adjust position. Using pivoting interfaces to adjust angle.
BPM	3	23	Slotted or telescoping tank frame members and sliding panel ends would have enabled adjustability.	Using sliding surfaces to adjust position.
BPM	4	23	Adjustable length table legs and sliding height tank panels could have been used.	Using sliding surfaces to adjust position
Welding	1	23	Slotted holes allow the drive shaft to be adjusted vertically to interface with a new motion assembly.	Using sliding surfaces to adjust position
Welding	2	24	The motor was sized to be larger than necessary, and is able to move a (potentially) more demanding radial motion module.	Using adjustable torque to vary the speed of rotating components. Varying power input to adjust the velocity of moving components.
Welding	2	23	Sliding pillow blocks that reduce the span, combined with a longer rack could increase the stroke length.	Using sliding surface to adjust position.
Welding	3	23	An adjustable drive ratio with the belt pulleys (like those found in drill presses) could have been implemented to allow adjustable speed ranges.	Using adjustable drive ratios to vary the speed of moving components.
Welding	4	23	Sliding stanchions allow the torch to be easily raised.	Using sliding surfaces to adjust position.

Welding	6	23	Slotted T-Frame members and pivoting torch mount allow for different heights and angles of torches.	Using sliding surfaces to adjust position. Using pivoting interfaces to adjust angle.
Welding	7	23	Slotted frame members allow for adjustable camera placement.	Using sliding surfaces to adjust position.
Welding	7	24	The frame is stronger than it needs to be, allowing it to hold a heavy camera.	Using stronger than necessary members to withstand additional forces.
Welding	8	23	Slotted frame members allow for easy height adjustment.	Using sliding surfaces to adjust position.

Table 7.12: Adjustability aiding features

In Table 7.12, twenty four instances of adjustability aiding features are identified. Each adjustability enabling feature represents a situation in which adjustability aids, or could have aided the evolvability of the system under consideration.

Of the five systems studied in this research, the welding test station yielded the highest number of adjustability enabling features. The type of frame members used to construct the frame on the test station is a significant contributor to this result. The slotted cross section enables attachments to be adjusted to any desired location. In addition, the frame is stronger than necessary for the current system configuration. This additional load bearing capability enables the addition of auxiliary components such as an IR camera without requiring the redesign or replacement of the frame members.

The scaled seal testing system also yielded a high number of adjustability enabling features. During the initial design of the system, wide flange beams were selected for the support members to keep deflection within the allowable range for the ball screws. This additional strength and stiffness can also handle a potentially heavier linear motion assembly such as a series of piston rams.

There are two adjustability aiding features on the gas-pressure blow-forming system that enable adjustability for the identified change modes. First, the counterweights in the strain gauge module that provide force to support the strain measurement rod could have been made adjustable. The ability to vary this counteractive force would have eliminated the need to replace the counterweights should the weight of the strain gauge rod change. Second, the length of the mounting frame is fully adjustable and controllable. This feature enables the user to adjust the position of the loading columns so that the thermal expansion induced stresses can be relieved.

The P-V-T device has two adjustability enabling features. Both of these features are hypothetical and are not part of the device in its current form. First, the temperature could have been made a tunable design parameter. The feature would have been best implemented with the usage of tunable electrical power flow to a heating element in the cylinder base. Second, excess energy storage could have been used to increase the interior temperature of the chamber. A practical solution for this problem would have been to use a battery for energy storage that would feed electrical power to a heating element in the cylinder base.

The beam pattern measurement system has three adjustability enabling features. All three of the features enable adjustability by allowing the user to tune the position or angle of the system components. The first adjustability enabling feature is the position adjustability of the second transducer mount. The position of the mount can be tuned in the x, y, and z direction and it can rotate about the z-axis. The second and third adjustability enabling features enable the overall dimensions of the test tank to be adjusted. Telescoping frame member and adjustable length table legs would allow the dimensions of the test tank to be adjusted without needing to replace any of the current system components. These features rely on the concept of using sliding surfaces at component interfaces to adjust position.

Although the adjustability enabling features in Table 7.12 could be used as a list of design guidelines, the entries are still very case-specific in their current form. Significant refinement is necessary before they can be added to the list of Guidelines for FFE. The process of refinement begins in the next subsection.

7.2.2 Enabling Features

In order to develop the guidelines, it is necessary to assemble the adjustability enabling features from Table 7.12 into a concise list of design guidelines. In the final column in Table 7.12, several of the statements are repeated. This is to be expected because those statements are intended to be generalized statements that are not specific to the individual systems under consideration. In Table 7.13, a condensed list of the enabling features from Table 7.12 is given.

#	GL	Enabling Feature	Occurrences	Category
1	23	Using sliding surfaces to adjust position.	13	1
2	23	Using pivoting interfaces to adjust angle.	2	1
3	23	Varying pressure to adjust the force of power transferring modules	1	3
4	23	Using varying amounts of mass to adjust counteractive force.	1	5
5	23	Using electrical power flow to vary the temperature of thermal energy transferring components.	2	3
6	24	Varying the power input to adjust the velocity of moving components.	1	2
7	24	Varying power input to adjust the pressure of power transferring modules.	1	3
8	24	Using stronger than necessary members to withstand additional forces.	5	5
9	24	Allowing the storage of excess energy for use as a thermal power supply.	1	4
10	24	Using adjustable torque to vary the speed of rotating components.	1	2

Table 7.13: Adjustability enabling features

In the first column in Table 7.13, each adjustability enabling feature is given a number for ease of reference. In the second column, the current guideline for FFE that most closely corresponds to the enabling feature is listed. The enabling features that are determined in section 7.2.1 are listed in the third column. The number of times each adjustability enabling feature occurs in the set of systems is given in the fourth column.

The fifth column in table 7.13 is used to place the enabling features into different categories. If two features are similar enough to be captured by a single guideline, they are placed in the same category. For example, rows 1 and 2 suggest using sliding and pivoting interfaces to adjust position and angle, respectively. Both of these features enable adjustability by allowing the user to tune the orientation of parts or modules in a system and are placed in category 1. Rows 6 and 10 both suggest adjusting the linear or rotational speed of moving components and are placed in category 2. Rows 3, 5, and 7 all suggest varying different energy domain parameters to adjust the amount of energy and power that is transferred by energy and power transferring components. Thus, they are all placed in category 3. Row 9 suggests allowing the storage of excess energy for future use. It is the only one of its kind and is placed in category 4. Lastly, rows 4 and 8 suggest varying or allowing the variation of loads to enable the system to accommodate larger loads than initially intended.

By observing the five categories in Table 7.13, five overall physical principles that enable adjustability can be identified. Category 1 is the principle of adjusting position or angle of parts or modules of the system, i.e. orientation of parts or modules. Category 2 is related to the principle of adjusting the linear or angular velocity of moving components. The items in category 3 are related to variable energy or power transfer by means of force, torque, pressure, or heat. Category 4 suggests allowing the capability for excess energy storage. Energy can be stored in a system in many ways. Springs (potential), flywheels (kinetic), and batteries (chemical) are all examples of ways to store excess energy in a system. Category 5 suggests enabling a system to accommodate larger loads than are necessary for the original system requirements. This is accomplished by either designing stronger than necessary components, or by allowing the importation of additional mass to balance an increased load.

In the next subsection, the five categories that are identified in this subsection are used to develop new guidelines for FFE that can be added to the currently existing list.

7.2.3 Guidelines for Flexibility for Future Evolution

In this section, additional guidelines for FFE are derived. The goal is to transpose the five categories of adjustability enabling features that are identified in Section 7.2.1 into useful design guidelines. There are two important points to consider when performing this task. First, some of the categories may be very similar in nature. In this case, they should be combined into a single category in order to keep the list concise and manageable. Second, some of the categories of adjustability enabling features may be too specific. In this case, they must be restated so that they capture the idea that is meant to be conveyed while remaining general enough to span the full range of design possibilities. Third, the guidelines must be stated in a manner that is consistent with the other guidelines on the list of guidelines for FFE.

In Table 7.14, the five categorized adjustability enabling features that are derived in the previous subsection are listed for reference. In the third column, the number of times that each category occurs in the systems that are studied in this research is given.

#	Adjustability Enabling Category	Occurrences
1	Using sliding or pivoting interfaces between parts to adjust position.	15
2	Varying the velocity or rotational speed of moving components.	2
3	Varying the force, torque, pressure or temperature of energy transferring modules.	4
4	Providing the capability for excess energy storage or importation.	1
5	Providing load bearing components the capability to sustain excess force or torque.	6

Table 7.14: Categorized adjustability enabling features

Combining Similar Adjustability Enabling Categories

Before the adjustability enabling categories in Table 7.14 can be added to the list of guidelines for FFE, they must be studied carefully to check if any of them are similar enough to be combined. Category 1 is the only category that deals with position or angle of stationary components or modules. Furthermore, there are 15 occurrences of Category

1 adjustability enabling features in the systems that are studied in this research. Thus, it is the most common approach to enable adjustability and is deserving of its own category.

Categories 2 and 3 have subtle differences, but are similar enough to be combined into a single category. In general, Category 2 suggests varying the *flow* of energy transfer (velocity, angular velocity, etc.) to enable adjustability. Category 3 suggests adjusting the *effort* of energy transfer (force, torque, pressure, etc.) to enable adjustability. Although this notable difference exists between these two categories, both of them suggest varying energy transmission of components or modules and they can be combined into a single category.

There is only one occurrence of Category 4 adjustability in the five systems that are studied in this research which may suggest that it is not well supported. However, it is deserving of its own category for two reasons. First, allowing excess energy storage or importation is currently a guideline on the list of guidelines for FFE, and its importance is justified in the previous works of Keese et al. [44,31]. Second, none of the other categories suggest allowing excess energy storage or importation. The only ones that are similar are categories 2 and 3, which suggest varying the transfer of energy between components and modules as opposed to the storage of energy.

Lastly, Category 5 is deserving of its own category because of its high number of occurrences and because of its dissimilarity to the other categories in Table 7.14. There are six occurrences of Category 5 adjustability enabling features in the systems studied in this research, which is the second most of the five categories. Furthermore, no other system suggests enabling additional load bearing capability.

In Table 7.15, the categorized adjustability enabling features are shown with similar categories combined. Categories 2 and 3 are combined into a single category due to their similar nature. Category 1 is the same, Category 4 is now Category 3, and Category 5 is now Category 4.

GL	Adjustability Enabling Guideline
1	Using sliding or pivoting interfaces between parts to adjust position.
2	Varying the velocity, rotational speed, force, torque, pressure, or temperature of energy transferring components.
3	Providing the capability for excess energy storage or importation.
4	Providing load bearing components the capability to sustain excess force or torque.

Table 7.15: Adjustability enabling guidelines with similar categories combined

Because the adjustability enabling categories in Table 7.15 are now condensed to the greatest level of possible conciseness, it is fair to say that each row in Table 7.15 represents a future guideline that will be added to the list of guidelines for FFE. Thus, they are referred to as guidelines rather than categories from this point forward. Furthermore, the number of occurrences of each of the categories is no longer relevant to this discussion and is omitted from Table 7.15.

Adjusting the Level of Specificity of Adjustability Enabling Guidelines

Now that similar categories of adjustability enabling features are combined into condensed guidelines (Table 7.15), their level of specificity must be checked. If a design guideline is too specific, the main idea may be lost in the details and the designer that is using it may rule it out as irrelevant even if an opportunity exists for its implementation.

For example, Guideline 1 is in a general form and does not need to be reworded. However, it could be too specific if it were worded differently. Instead of saying, “Using sliding or pivoting interfaces... to adjust position" it could say, "Using T-slotted connections between parts to adjust position." Using T-slots is one possible way to enable position adjustability, and many other possibilities such as telescoping members or linear guide rails are ignored. Keeping the statement general does not eliminate these possibilities.

Guideline 2 is not too specific in its current form. However, the broadness of the statement is attributed to the unnecessarily long list of specific modes of energy transfer that it contains. Rather than attempting to list all of the possible modes of energy transfer in a single guideline, it is better to capture the comma separated list in Guideline 2 in a single phrase. To meet this need, Guideline 2 is reworded to say, "Tuning the energy transmission capabilities of modules or components."

The level of detail of Guideline 3 is acceptable in its current form and the statement does not need revision. This guideline suggests "Providing the capability of excess energy storage or importation." Written this way, this guideline encompasses the importation or storage of all forms of energy (kinetic, thermal, chemical, etc.) and does not ignore any energy storage or importation possibilities.

Guideline 4 in Table 7.15 suggests allowing load bearing components the ability to sustain excess force or torque. Specifying force and torque ignores many other possible types of loads such as higher temperatures, fatigue loading, and vibration. In this case, it is best to formulate a broader statement that conveys the same idea. To address this issue, Guideline 4 of Table 7.15 is restated to say, "Increasing the load-bearing capacity of components and modules."

The reformulated adjustability enabling guidelines from the above discussion are presented in Table 7.16.

GL	Adjustability Enabling Guideline
1	Using sliding or pivoting interfaces between parts to adjust position.
2	Tuning the energy transmission capabilities of modules or components.
3	Providing the capability for excess energy storage or importation.
4	Increasing the load-bearing capacity of modules or components.

Table 7.16: Generalized adjustability enabling guidelines

Checking the Guidelines for Style Consistency

Although the enabling features in Table 7.16 are clear enough to be useful to designers, some of them may be worded in a way that is not in a similar fashion to the current guidelines for FFE. When refining the categorized principles into new guidelines, special care must be taken to compose the new guidelines in a style and at a level of detail that is consistent with the other guidelines on the list. Telenko et al. [36] suggest the following four criteria for the formulation of design guidelines:

- Designer-oriented: the principle must be within the scope of a product designer.
- Actionable: the principle must propose an avenue for improving the design.
- General: the principle must apply to a large range of products.
- Positive Imperative: the principle must focus on creating the best possible solution.

All of the current guidelines for FFE fit the four criteria listed above, and following these criteria for the development of future guidelines ensures consistent results. Taking the above discussion into consideration, the four adjustability enabling guidelines are all found to fit the four criteria listed above. First, all of them are designer-oriented. That is, they are helpful in guiding designers, rather than managers, toward evolvable solutions. Second, each of them is actionable, because they propose specific avenues to meet the goal of aiding evolvability by enabling adjustability. Third, each of the guidelines is general. The measures that are taken to ensure the generality of each guideline are discussed above in this subsection. Lastly, each of the guidelines is a positive imperative. That is, each of them provides suggestions as to what should be done, as opposed to pointing out what should not be done.

One last point remains to be addressed before the four new guidelines for FFE are added to the current list of guidelines. Each category of the guidelines for FFE features its own introductory statement. The current statement for the “Adjustability Approach” guidelines states, “Enable the device to respond to minor changes by...” This statement is in need of minor adjustment if it is to properly convey the intent of the new guidelines for FFE. When the adjustability enabling guidelines are implemented in a new project, the resulting device is not responding to minor changes. Rather, it is allowing the *user* to adjust it to accommodate minor changes. Thus, it is more appropriate to say, “Enable adjustment of the device during its useful life by...” When posed in this manner, the introductory statement for the “Adjustability Approach” guidelines properly conveys the idea that implementation of the guidelines should enable adjustability by the user.

In Figure 7.2, an updated list of guidelines that includes the expanded guidelines for FFE is shown. In addition, the introductory statement for the “Adjustability Approach” guidelines is revised to reflect the changes discussed above.

Modularity Approach

Increase the degree of modularity of a device by…

1 Using separate modules to carry out functions that are not closely related.
2 Confining functions to single modules
3 Confining functions to as few unique components as possible.
4 Dividing modules into multiple smaller, identical modules.
5 Collecting parts which are not anticipated to change in time into separate modules.
6 Collecting parts which perform functions associated with the same energy domain into separate modules.

Parts Reduction Approach

Reduce the number of parts requiring manufacturing changes by…

7 Sharing functions in a module or part if the functions are closely related.
8 Using duplicate parts as much as possible without raising part count.

Spatial Approach

Facilitate the addition of new functionality and rearrangement or scaling of parts by…

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces.
11 Extending the available area on the transmission components of the device.
12 Locating those parts which are anticipated to change near the exterior of the device.
13 Reducing nesting of parts and modules.

Interface Decoupling Approach

Reduce the communications between modules, and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules, by…

14 Standardizing or reducing the number of different connectors used between modules.
15 Reducing the number of fasteners used, or eliminating them entirely.
16 Reducing the number of contact points between modules.
17 Simplifying the geometry of modular interfaces.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need.
19 Creating detachable modules.
20 Using a framework for mounting multiple modules.
21 Using compliant materials.
22 Simplifying the geometry of each component.

Adjustability Approach

Enable adjustment of the device during its useful life by…

23 Using sliding or pivoting interfaces between modules and components.
24 Tuning the energy transmission capabilities of modules or components.
25 Providing the capability for excess energy storage or importation.
26 Increasing the load bearing capability of modules or components.

Figure 7.2: Updated guidelines for flexibility for future evolution

It should be noted that the third guideline in the above list already exists in the current list of guidelines for flexibility for future evolution. Also, Guideline 23 on the current list of guidelines for FFE is not included in the new list of guidelines for FFE because the first two guidelines in the list expand this guideline into two guidelines that have a higher level of detail. Thus, the concept that Guideline 23 is meant to convey is fully captured by the two new guidelines and it is no longer needed.

7.3 EXAMPLES OF ADJUSTABILITY GUIDELINE USAGE

In this section, each new "Adjustability Approach" guideline is explained and supporting examples are given to help the reader understand the idea that each guideline is intended to convey.

Guideline 23: Using sliding or pivoting interface between modules and components

Using sliding and pivoting interfaces between components and modules enables the user to adjust the orientation of certain parts and components during a system's useful life. For example, the welding torch in Figure 7.3 can slide in the vertical and horizontal directions and pivot about the mounting beam. The frame stanchions on either side of the mounting beam can slide in the slotted vertical frame member for height adjustment. The welding torch mounting bracket can slide along the length of the mounting beam for horizontal adjustment. Lastly, the torch mounting bracket can pivot about the mounting beam for angle adjustment. These three position parameters are very important to the welding process because the tip of the welding torch must be at an appropriate distance and angle relative to the work piece that is being welded. Using sliding and pivoting interfaces between parts enable this adjustability with no need to redesign any of the system components.

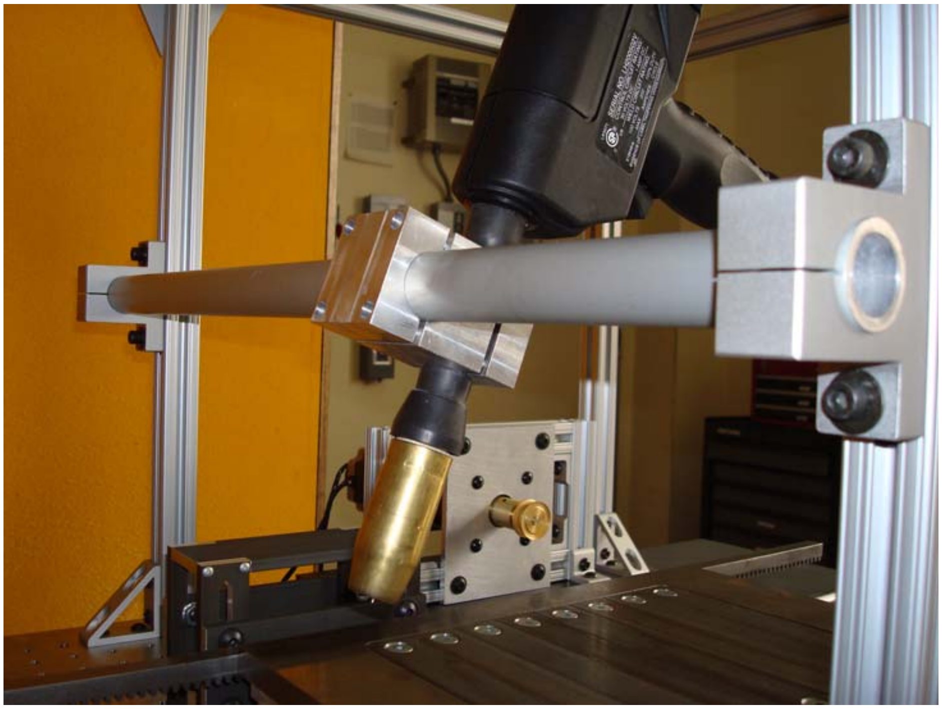

Figure 7.3: Sliding and pivoting welding torch

Guideline 24: Tuning the energy transmission capability of modules and components

Tuning the energy transmission capability of modules and components enables the user to adjust the flow of power between system components to meet current needs. Energy is transmitted in a variety of ways, all of which can be tuned. Kinetic energy transmission can be tuned to control the speed of moving components. For example, the rotational speed of the blades in many household kitchen blenders can be tuned to chop, mix, or blend food products. Thermal energy transmission can be adjusted to tune the rate of heat transfer between parts. For example, the average rate of heat transfer from the interior heating coils of a household kitchen oven can be adjusted to control the temperature of the oven. Tuning the energy transmission capabilities of components and modules enables users to make adjustments to meet their individual needs without requiring a redesigned device or system.

Guideline 25: Providing the capability for excess energy storage or importation

Providing the capability for excess energy storage or importation enables the user to store or import excess energy to meet unforeseen energy consuming needs. The bicycle pump that is shown in Figure 7.4 is one of a class of pumps that utilize a pressurized CO_2 gas cartridge which is used to pressurize a bicycle tire. Most pumps of this type are constrained to the amount of pressurizing energy that is stored in the cartridge. However, the pump in Figure 7.4 has the unique ability to import excess energy by converting to a manual hand pump. The ability to import excess energy enables a user to perform a higher number of bicycle tire inflations without requiring a larger or higher capacity CO_2 cartridge.

Figure 7.4: Excess energy importing CO_2 bicycle pump [67]

Guideline 26: Increasing the load bearing capability of modules or components

Increasing the load bearing capability of modules or components enables the user to subject the device or system to more intense loading conditions without requiring replacement or redesign of the parts that are subjected to the loads. For example, the frame members in the welding test station are selected to withstand forces that are far greater than those required during its initial deployment. Also, the driveshaft in the welding station that moves the linear motion table is designed to withstand torque that is greater than initially required, so that more massive objects such as large work-piece fixtures can be placed on the motion table. Application of Guideline 26 is not limited to force and torque loading conditions. The ability to withstand heightened temperatures, cyclic (fatigue) loading, and excessive vibration are also types of loads that can be accommodated by implementing Guideline 26.

7.4 CHAPTER SUMMARY

In this chapter, the steps that are taken to meet the two objectives of this research are presented. The first objective of this research is to verify the effectiveness of using the guidelines for flexibility for future evolution (FFE) on designing small-lot products and systems. By investigating the Use of Guidelines reports that are generated for each system during the CMEA process, missed opportunities for guideline usage are identified. New system concepts are generated based on these missed opportunities, and the systems are reanalyzed for evolvability. It is found that implementing the missed opportunities for guideline usage significantly reduces the Change Potential Number of each system studied in this research. In light of this finding, it is concluded that using the guidelines for flexibility for future evolution to design small-lot systems has the potential to significantly improve that system’s ability to evolve to changing needs.

The second objective of this research is to improve the guidelines in the "Adjustability Approach" category of the guidelines for FFE so that they have a higher level of detail. The systems studied in this work feature or have opportunities to feature several adjustable features that can improve their evolvability. By studying these features, the two "Adjustability Approach" guidelines are expanded into four new guidelines that are more specific and insightful. This new level of detail makes the new guidelines more useful to designers.

In Chapter 8, a critical analysis of this work is presented along with proposed avenues for future work in this subject of research.

Chapter 8: Conclusions and Future Work

In this chapter, conclusions about the findings of this research are presented. In Section 8.1, the contributions that this research makes to the study of design flexibility for future evolution are discussed. In Section 8.2, the limitations of this work and suggestions for future work are given. Lastly, a brief closure is given in Section 8.3.

8.1 RESEARCH CONTRIBUTIONS

8.1.1 Effectiveness of the Guidelines for Flexibility for Future Evolution

Prior to the completion of this work, the effectiveness of implementing the guidelines for flexibility for future evolution (FFE) was not fully verified. The guidelines for FFE were derived by studying the evolvable features of a selection of patents and consumer products, but they had never been used to design a product or system from the start of the design process. That the guidelines are effective in designing evolvable products and system was only a hypothesis.

In this research, five case studies of small-lot systems are used to verify the effectiveness of using the guidelines for FFE. One of the case studies, an automated gas metal arc welding test station, was designed and fabricated using the guidelines for FFE. All five of the systems that are studied are shown to benefit by using the guidelines for FFE in their design. Of the five systems, the welding test station is shown to have the least potential to benefit from the guidelines for FFE with improvements in the Design Flexibility rating and Change Potential Number of 21% and 9%, respectively. This reduced potential for improvement is attributed to the implementation of the guidelines in the original design of the station, resulting in a level of evolvability that was already very high. Implementation of the guidelines for FFE in the other four case studies is shown to result in improvements of the Design Flexibility ratings ranging from 28% to 50%. Likewise, guideline implementation is also shown to result in improvements of the Change Potential Number ranging from 25% to 48%.

The findings of this research show that using the guidelines for flexibility for future evolution in the design of small-lot systems is effective in improving the evolvability of such systems. The effectiveness of using the guidelines for FFE in the design of mass produced products is yet to be determined.

8.1.2 Expansion of the "Adjustability Approach" Guidelines

While the current list of guidelines for FFE is very thorough, it is by no means exhaustive. In particular, the guidelines in the "Adjustability Approach" category are very general and are not at the same level of detail as the other guidelines on the list. In this respect, there is an opportunity to refine and expand Guidelines 23 & 24 to a higher level of detail so that they are more similar to the others on the list.

The second objective of this research is to expand the "Adjustability Approach" guidelines by gathering and categorizing adjustable and tunable features that increase evolvability and generalize them into a set of design guidelines. This set of guidelines is added to the current set of guidelines for FFE so that the new list includes "Adjustability Approach" guidelines that are more useful to designers during the design process.

The selection of small-lot systems that are studied in this research provides a unique opportunity to expand these guidelines. By identifying the physical features of the systems that aid evolvability by way of adjustability, four guidelines are developed that are useful to designers.

Of the four new guidelines, two of the new guidelines (Guidelines 23 and 24) are an expansion of the former Guideline 23 which suggests tuning design parameters. One of the new guidelines is on the current list of guidelines for FFE (Guideline 25) which suggests providing the capability for excess energy storage. Lastly, a new guideline was developed that relies on the idea of increasing the load bearing capability of modules or components (Guideline 26).

8.2 LIMITATIONS AND FUTURE WORK

8.2.1 Objective 1: Effectiveness of the Guidelines for FFE

The systems that are studied in this work to meet the objectives of this research are all small-lot, complex systems. It is effectively shown in this research that using the guidelines for FFE to design such systems results in notable improvement in their evolvabilities. However, a similar study conducted on mass produced products may yield different results. This is because the issues involved with implementing changes to small-lot systems are very different from those for mass produced products. Changes to small-lot system are often made by in-house designers and machinists and are made to the units themselves after they have been deployed. To implement a change to a mass produced product, the manufacturing process and equipment must be changed. Furthermore, the systems that are studied in this research are analyzed for evolvability using a style of CMEA that is specifically tailored to small-lot systems. A study that is similar to this one on mass produced products would be beneficial to the field of research and would provide valuable insights about the effectiveness of using the guidelines for FFE on the design of mass produced products.

8.2.2 Objective 2: Expanded "Adjustability Approach" Guidelines

The new guidelines that are developed in this research are at a higher level of detail than the previous "Adjustability Approach" guidelines. They are more useful to designers and provide specific suggestions about how to implement adjustability aiding features in a design. However, no steps were taken to ensure that the list of "Adjustability Approach" guidelines is exhaustive. Five systems are studied in this research, which is a relatively small number. The resulting guidelines that are developed depend heavily on the systems that are studied and on the change modes that are used in the analysis. Furthermore, all of the systems in this research are a subset of small-lot systems. They are actually one-off systems. That is, only one realization of each system exists because they are all custom designed for a specific customer. They are also all test rigs that are designed and built for conducting research. A similar study that includes a higher quantity and a broader selection of systems would be beneficial to this research. A different selection of systems and change modes may reveal classes of adjustability enabling features that are not exhibited by the systems in this research and are therefore not captured by the updated list of guidelines for FFE.

The adjustability enabling guidelines that are developed in this research are derived from real systems. Therefore, the case studies from which they stem serve as strong evidence for their validity. However, it would be interesting to assign multiple design teams to the same design problem with one team tasked with applying the adjustability enabling guidelines and the other team isolated from the guidelines. It would be difficult to perform this experiment on the types of in-depth case studies presented in this thesis because of the costs of duplicate efforts, but a set of simpler and more manageable sample problems could be developed for this potential study.

Further work could also be done to investigate the completeness of the "Adjustability Enabling" guidelines. Only five case studies were analyzed in this research, which is a relatively low quantity. The five case studies yielded three new guidelines and one guidelines that is on the previous list of guidelines for FFE. This high ratio of guidelines discovered to systems studied suggests that there may be more guidelines that have yet to be discovered. If only one or zero guidelines were discovered from this research, then it would be fairly certain that the list of "Adjustability Approach" guidelines is complete and are not in need of further development.

8.2.3 Additional Potential Research Contributions

Improving Change Modes and Effects Analysis

A current limitation of Change Modes and Effects Analysis is that the resulting Change Potential Number (CPN) cannot be compared across multiple systems. The change potential number is heavily dependent on the change modes selected for a given system and on the complexity of the system. A major change with a high CPN may be faster and less expensive to implement to a simple system than a minor change with a low CPN to a relatively complex system. The approach that is used in this research eliminates this problem by comparing % change in CPN, rather than the CPN itself across the systems under consideration. Some authors have attempted to "normalize" change modes so that CPN comparisons could be made on a common basis. Another, possible solution to this problem, as suggested by Tilstra [45], is to develop a set of generic change modes that can be used to analyze the evolvability of all systems.

Lastly, the meaning of the CPN could use further development. Ultimately, the cost of implementing a redesign is what matters most. Time is important as well, but time eventually affects cost as firms begin to lose customers due to untimely delivery. If there were a method to correlate CPN to cost, this would be very beneficial to the companies that manufacture these systems.

Method for Implementing Guidelines in the Design Process

A structured method for implementing the guidelines for FFE throughout the design process is needed. Recall from Chapter 4 that the guidelines for FFE were used in an ad hoc way to design the welding test station. Although it is straightforward to identify specific steps of the design process where the guidelines can be used, it was ultimately the designer's intimate knowledge of the guidelines that allowed him to implement them at appropriate points. However, a structured process for implementing the guidelines for FFE is needed so that designers can use them without first needing to gain a deep understanding of them. Part of this process could use the steps that are followed to meet Objective 1 of this research. That is, performing CMEA and generating a Use of Guidelines report is a fine approach for identifying missed opportunities for guideline usage in a detailed design. However, a structure process would still be useful for implementing the guidelines for FFE in the conceptual and embodiment design phases of a design project.

8.3 CLOSURE

Two advancements in the research area of design flexibility are made in this research. First, the effectiveness of using the guidelines for flexibility for future evolution (FFE) on the design of small-lot systems is investigated. Five cases of small-lot systems are measured for evolvability using Change Modes and Effects Analysis and the use or nonuse of the guidelines for FFE is correlated to the results. Second, the guidelines in the "Adjustability Approach" category are expanded to a higher level of detail so that they are more similar to the other guidelines on the list of guidelines for FFE. Adjustable and tunable features of the five case studies in this research are gathered and organized to achieve this task. Both of these objectives are met successfully and it is concluded that using the guidelines for FFE in the design of small-lot systems improves their evolvability. Furthermore, the inclusion (or exclusion) of adjustable features in the case studies is used to develop three new guidelines for FFE in the "Adjustability Approach" category.

One of the case studies in this research, a welding test station, was designed using the guidelines for flexibility for future evolution throughout its original design. The resulting system is truly unique and is found to have the ability to accommodate the foreseeable change modes with very little effort from the user. The welding station is of great value to the institution that uses it because it can be used for a multitude of projects after its immediate needs have been fulfilled. The successful implementation of the guidelines for FFE in this case strengthens the argument that the guidelines for FFE should be used in the design of small-lot systems that are anticipated have varying design requirements throughout their useful life. Designers should take note of these results and consider the impact that the guidelines for FFE may have on design and development of their future projects.

Appendix A: Welding Test Station Bill of Material

Bill of Materials: GMA Welding Test Station

Project: ***GMA Braze-Welding of Beryllium***

Module / Part #		Description	Qty	Mftr.	Mftr. PN	Vendor
A: Frame / Base						
A	1	97"x1"x1" T-Slot Alu	4	8020	1010-97	Shepherd Controls
A	4	5 Hole T Joining Plate	4	8020	4140	Shepherd Controls
A	5	4 Hole Corner Bracket	20	8020	4136	Shepherd Controls
A	6	1/4-20x.5", FBHSCS and economy nuts	50	8020	3321	Shepherd Controls
A	7	1/4-20x.5", BHSCS and economy nuts	200	8020	3393	Shepherd Controls
A	8	2'x3' bread board	1	Newport	TD-23	Newport
A	9	Leveling feet, 1/4-20 thread	4	8020	2192	Shepherd Controls
A	10	Cart	1	CartOutlet	SE348	CartOutlet
A	11	Inside Corner Bracket	20	8020	4119	Shepherd Controls
B: Torch Mount						
B	1	Stanchion, Single Horizontal Base	4	8020	5860	Shepherd Controls
B	2	97"x1" Dia, .125" Thk, Clear Anodized	1	8020	5036/7205	Shepherd Controls
B	3	1/4-20x7/8" SHCS with econ nuts and washers	25	8020	3471	Shepherd Controls
B	4	Gun Bracket, 1.5"x3"x6" Alu Block	1	McMaster	8509K78	McMaster
B	5	SCS, #8-32x1"			USE C13	
C: Linear Motion Table						
C	1	48" Rail, 0.5" Shaft Diameter	2	McMaster	59585K53	McMaster
C	2	Linear Bearing, 0.5" Shaft Diameter	4	McMaster	8974T7	McMaster
C	3	Retaining Rings	10	McMaster	9968K24	McMaster
C	4	Alu bar stock, 2"x2"x12"	1	McMaster	9008K531	McMaster
C	5	Rail Support, 36"x2"x.5" Alu	2	McMaster	8975K743	McMaster
C	6	SCS, 1/4-20x3/4, Lot of 50	1	McMaster	90128A245	McMaster
C	7	BHCS, #4-40x1/2", Lot of 50	1	McMaster	91306A318	McMaster

C	8	SCS, #6-32x1/2", Lot of 50	1	McMaster	91306A324	McMaster
C	9	Steel Sheet, 12"x10", 0.5" thick	1	McMaster	4473T13	McMaster
C	10	Steel Bar, 36"x1", 0.25" thick	2	McMaster	6554K113	McMaster
C	11	FHS, 1/4-20x1/2, Lot of 25	1	McMaster	91263A553	McMaster
C	12	Rack, 16 Pitch, 2' Long	1	McMaster	6295K14	McMaster
C	13	SCS, #8-32x1", Lot of 50	1	McMaster	90128A199	McMaster
C	14	Bumper, Lot of 25	1	McMaster	9541K8	McMaster
C	15	BHCS, #8-32x1/2	36	McMaster	91355A075	McMaster
D: Mechanical Belt Drive						
D	1	Pinion, 16 Pitch, 0.75 pd	2	McMaster	6325K11	McMaster
D	2	Set Screw, #4-40, Length .125", Lot of 100	1	McMaster	91375A103	McMaster
D	3	Flanged Ball Bearing, .5" OD, .25" Shaft Diameter	4	McMaster	4262T16	McMaster
D	4	Rod, .375" Alu, 36" Long	1	McMaster	6750K153	McMaster
D	5	Bar, 6061, 0.25"x2"x36"	1	McMaster	6023K283	McMaster
D	6	Bar, 6061, 0.25"x1"x36"	1	McMaster	6023K173	McMaster
D	7	SCS, #6-32x0.5", Lot of 100	1	McMaster	90128A148	McMaster
D	8	SCS, Flange Button, 1/4-20x.75", Lot of 50	1	McMaster	91355A082	McMaster
D	9	Hex Nut w conical washer, 1/4-20, Pack of 25	2	McMaster	95170A390	McMaster
D	10	Timing Belt Pulley, MXL Series, 1/4" Belt Width, 36 Teeth	2	McMaster	1375K54	McMaster
D	11	Timing Belt, 200MXL, 1/4" Width, 20 in	2	McMaster	7887K91	McMaster
E: Motor Controls						
E	1	Motion controller components package, 2-Axis controller, UMI, PC-UMI interface cable	1	Design and Assembly		
E	2	MotionPlus drivetrane package, NEMA23 stepper	1	Design and Assembly		
E	3	MotionPLUS Basic software, LabView Code, Single Axis Control	1	Design and Assembly		
F: Data Acquisition						
F	1	Thermocouple Welder	1	DCC Corp	10-A10120	DCC Corp
F	2	NI PCI-6229, M Series DAQ	1	NI	779068-01	NI
F	3	SHC68-68-EPM Shielded Carrier with SCC-PWR02	1	NI	192061-02	NI

F	4	SC-2345 Shielded Carrier with SCC-PWR02	1	NI	777458-02	NI
F	5	SCC-TC02 Thermocouple Input Module, with Screw Terminals	8	NI	777459-04	NI
F	6	RTSI Bus Cables for 2 PCI or AT/ISA Devices	1	NI	776249-02	NI
G: Base Metals						
G	1	C22000, 24"x24"x0.25	8	McMaster	9757K57	McMaster
H: Filler Wire						
H	1	ER4047, 4" Spool, 0.030" wire diameter	10			Alamo
H	2	ER4047, 4" Spool, 0.035" wire diameter	5			Alamo
I: Data Aqu.						
I	1	Insulated Thermocouple Wire, Type K, 1000' spool	1	Omega	HH-K-24-1000	Omega
I	2	TC Connector, MF Pair	24	Omega	HMPW-K-MF	Omega
J: Other						
J	1	Contact Tips, FasTip, 0.030" Al	50	Miller	206186	Alamo
J	2	Contact Tips, FasTip, 0.035" Al	25	Miller	206187	Alamo
J	4	Other Contact Tips	20	Miller		Alamo
J	5	Temp Paints	8	Omega		
J	6	Diamond Saw Blade	1	Struers	330CA	Struers
K: Mig Gun						
K	1	Spoolmatic	1	Miller	15A	Alamo

Table A.1: Welding test station bill of materials

Appendix B: Welding Test Station Evolvability Analysis

Module	Change Mode 1: Perform Radial Welds on Round Specimens	Change Mode 2: Increase Weld Pass Length
Frame / Base (FB)	Same	Change
Torch Mount (TM)	Same	Same
Linear Motion Table (LMT)	Remove	Change
Mechanical Belt Drive (MBD)	Same	Same
Motor Mount (MM)	Same	Same
Change Effect	Linear motion table will be completely removed and replaced with a radial weld fixture. The radial module will be driven with the same motor and mechanical belt drive.	The overall device will need to be lengthened. This means a longer breadboard, frame, and linear motion components.

Table B.1.1: Welding station module change report (Part 1 of 4)

Module	Change Mode 3: Increase Weld Speed Range	Change Mode 4: Raise Sliding Weld Surface
Frame / Base (FB)	Same	Same
Torch Mount (TM)	Same	Same
Linear Motion Table (LMT)	Same	Change
Mechanical Belt Drive (MBD)	Change	Change
Motor Mount (MM)	Same	Same
Change Effect	Change will rely on increasing the pinion gear diameter. This change will propagate to other components in the MBD module.	Rail supports may need to be modified to sit on stilts and drive shaft will need to be raised.

Table B.1.2: Welding station module change report (Part 2 of 4)

Module	Change Mode 5: Add a Protective Glass Shield	Change Mode 6: Perform other types of welds
Frame / Base (FB)	Change	Same
Torch Mount (TM)	Same	Change
Linear Motion Table (LMT)	Same	Same
Mechanical Belt Drive (MBD)	Same	Same
Motor Mount (MM)	Same	Same
Change Effect	Very minor change to brackets on frame.	New bracket will need to be designed and machined for different torch geometry. An auto-feed module will need to be mounted adjacent to the GTAW torch. Beam may not be reusable.

Table B.1.3: Welding station module change report (Part 3 of 4)

Module	Change Mode 7: Mount an IR camera	Change Mode 8: Include welding torch motion
Frame / Base (FB)	Same	Same
Torch Mount (TM)	Change	Change
Linear Motion Table (LMT)	Same	Same
Mechanical Belt Drive (MBD)	Same	Same
Motor Mount (MM)	Same	Same
Change Effect	Additional frame support members shall be added to the upper horizontal beams of the frame. A mounted bracket will need to be designed and machined. A shield will need to be fashioned to block the angle of view from the arc.	Horizontal torch mount bar will need to be replaced with a motorized carriage on a track.

Table B.1.4: Welding station module change report (Part 4 of 4)

Item	-	Sub#	Module	Part Name	CM 1	Readiness
1	-	1	FB	Vertical Bar, 18"x1"x1" T-Slot Aluminum		
1	-	2	FB	Lengthwise Frame Bar, 32"x1"x1" T-Slot Aluminum		
1	-	3	FB	Widthwise Frame Bar, 22"x1"x1" T-Slot Aluminum		
1	-	4	FB	5 Hole T Joining Plate		
1	-	5	FB	4 Hole Corner Bracket		
1	-	6	FB	2'x3' Breadboard, 1/4-20 1" Square Matrix		
2	-	1	TM	Stanchion, Single Horizontal Base		
2	-	2	TM	Gun Mount Beam, 1" dia 1/8" Thick Alu. Tubing		
2	-	3	TM	Gun Mount - Gun Clamp		
2	-	4	TM	Gun Mount - Body		
2	-	5	TM	Gun Mount - Beam Clamp		
3	-	1	LMT	36" Linear Bearing Rail, 0.5" Shaft Diameter	N	
3	-	2	LMT	Linear Bearing, 0.5" Shaft Diameter	N	
3	-	3	LMT	Retaining Rings	N	
3	-	4	LMT	Pillowblock, 0.5" Linear Ball Bearing	N	
3	-	5	LMT	Rail Support, 2"x0.5"x36"	N	
3	-	6	LMT	Linear Weld Surface	N	
3	-	7	LMT	Table Segment - End (Rounded Corners)	N	
3	-	8	LMT	Table Segment - Middle	N	
3	-	9	LMT	Rack - 2' x 0.5", 16 Pitch	N	
4	-	1	MBD	Pinion - 16 Pitch, 0.75 Pitch Diameter	N	2
4	-	2	MBD	Pinion Adapter	N	2
4	-	3	MBD	Drive Shaft	N	2
4	-	4	MBD	Flanged Ball Bearing, 0.5" OD, 0.25" Shaft Diameter		
4	-	5	MBD	Shaft Mount, Base		
4	-	6	MBD	Shaft Mount, Vertical Bar		
4	-	7	MBD	Shaft Mount, Bearing Plate		
4	-	8	MBD	Timing Belt Pulley, 1/4" Belt Width, 36 Teeth		
4	-	9	MBD	Timing Belt, 1/4" Width, 20 Inches		
5	-	1	MM	Motor Base, Nylon Block, 8"x6"x0.25"		
5	-	2	MM	Motor Face Plate		
5	-	3	MM	Vertical Mount Bar, 5"x1"x1" T-Slot Aluminum		
5	-	4	MM	Horizontal Mount Bar, 6"x1"x1" T-Slot Aluminum		
5	-	5	MM	Inside Corner Bracket		
				Number of Non-Reusable Parts	12	
				Percentage of Non-Reusable Parts (34 total)	65%	
				Flexibility Rating	4	
				Average Readiness Rating		2

Table B.2.1: Welding station reusability matrix (Part 1 of 3)

Item - Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness	CM 5	Readiness
1 - 1	FB								
1 - 2	FB	N	1						
1 - 3	FB								
1 - 4	FB							N	1
1 - 5	FB								
1 - 6	FB	N	3						
2 - 1	TM								
2 - 2	TM								
2 - 3	TM								
2 - 4	TM								
2 - 5	TM								
3 - 1	LMT	N	2						
3 - 2	LMT								
3 - 3	LMT								
3 - 4	LMT								
3 - 5	LMT	N	2			N	2		
3 - 6	LMT	N	2						
3 - 7	LMT								
3 - 8	LMT								
3 - 9	LMT	N	3						
4 - 1	MBD			N	3				
4 - 2	MBD			N	2				
4 - 3	MBD			N	2				
4 - 4	MBD			N	3				
4 - 5	MBD								
4 - 6	MBD					N	2		
4 - 7	MBD			N	2				
4 - 8	MBD								
4 - 9	MBD								
5 - 1	MM								
5 - 2	MM								
5 - 3	MM								
5 - 4	MM								
5 - 5	MM								
		6		5		2		1	
		82%		85%		94%		97%	
		2		2		1		1	
			2.17		2.4		2		1

Table B.2.2: Welding station reusability matrix (Part 2 of 3)

Item - Sub#	Module	CM 6	Readiness	CM 7	Readiness	CM 8	Readiness
1 - 1	FB						
1 - 2	FB						
1 - 3	FB						
1 - 4	FB						
1 - 5	FB						
1 - 6	FB						
2 - 1	TM					N	2
2 - 2	TM	N	3			N	7
2 - 3	TM	N	2	N	2	N	5
2 - 4	TM	N	2			N	5
2 - 5	TM	N	2			N	5
3 - 1	LMT						
3 - 2	LMT						
3 - 3	LMT						
3 - 4	LMT						
3 - 5	LMT						
3 - 6	LMT						
3 - 7	LMT						
3 - 8	LMT						
3 - 9	LMT						
4 - 1	MBD						
4 - 2	MBD						
4 - 3	MBD						
4 - 4	MBD						
4 - 5	MBD						
4 - 6	MBD						
4 - 7	MBD						
4 - 8	MBD						
4 - 9	MBD						
5 - 1	MM						
5 - 2	MM						
5 - 3	MM						
5 - 4	MM						
5 - 5	MM						
		4		1		5	
		88%		97%		85%	
		2		1		2	
			2.25		2		4.8

Table B.2.3: Welding station: Reusability Matrix (Part 3 of 3)

	Used	Helpful	Change Mode 1: Radial welds	Used	Helpful	Change Mode 2: Welds pass length
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	Motion table, drive shaft, and motor are separate modules, allowing reuse of drive shaft and motor.	y	y	Surrounding platform will change, but modular interior components can remain the same.
2 Confining functions to single modules	y	y	Torch is stationary, and table moves to provide the linear motion. If the torch moved to provide linear motion, it would likely need redesign.	y	n	The linear motion components and the base are separate, but lengthening the LMA requires lengthening the platform as well.
3 Confining functions to as few unique components as possible	n	n	Functions are split into separate modules.	y	y	The base is used to support the LMA and the frame.
4 Dividing modules into multiple smaller, identical modules	n	n	Change mode is not a scaling issue	y	y	Segmented motion table allows for different specimen lengths.
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	Motor and drive shaft assembly are not anticipated to change for this change mode.	y	y	Motor and drive shaft assembly are not anticipated to change for this change mode.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	y	y	Electric motor is in a separate module than the mechanical drive shaft and motion table.	y	y	Electric motor is in a separate module than the mechanical drive shaft and motion table.
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	y	y	Holding and moving the specimen are both done by the linear motion table.	n	n	No function sharing involved.
8 Using duplicate parts as much as possible without raising part count	n	n	No duplicates used, nor would they help remedy the situation.	y	y	Duplicate frame members, rails, and pillowblocks reduce redesign effort.
Spatial						

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	Spacious work envelope allows for the addition of a taller, radial motion fixture.	n	y	Additional room on the breadboard would have allowed for easier extension of other components.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	Breadboard provides multiple attachment points on the base of the station.	n	y	Additional surface area on the breadboard would have allowed for easier extension of other components.
11 Extending the available area on the transmission components of the device	n	y	Free space on the pinion could have been used to drive a radial fixture in addition to the linear motion table.	n	n	No transmission components involved.
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Motor was placed near the outside of the station.	y	y	Motor was placed near the outside of the station, away from the linear motion assembly
13 Reducing nesting of parts and modules	y	y	Motor, drive shave assembly, and linear motion table are not nested inside one another	n	n	LMA must be nested inside the frame assembly.
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	n	n	Interfaces had specific requirements to transfer mechanical power.	y	y	Corner brackets used to connect frame members are all the same.
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Fasteners allow the detachability from the base	n	n	Fasteners allow the detachability of frame members that need to be redesigned.
16 Reducing the number of contact points between modules	y	y	The only contact points were those that were necessary to transfer power.	y	n	Did not help in this case.
17 Simplifying the geometry of modular interfaces	n	n	Interfaces had specific requirements to transfer mechanical power.	y	y	Redesign of rail supports will be rapid due to the simplicity of the part.

18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	All energy must pass through the related modules.	n	n	All energy must pass through the related modules.
19 Creating detachable modules	y	y	Linear motion table is detachable.	y	y	LMA is detachable and can be replaced with longer redesign.
20 Using a framework for mounting multiple modules	y	y	All modules rest on the same breadboard base.	y	n	The frame adds to the redesign effort in this case.
21 Using compliant materials	n	n	No compliant materials used, nor would they help remedy the situation.	n	n	No compliant materials used, nor would they help remedy the situation.
22 Simplifying the geometry of each component	n	n	Not relevant in this case	y	y	Frame member simply need to be lengthened.
Adjustability						
23 Controlling the tuning of design parameters	y	y	Slotted holes allow the drive shaft to be adjusted vertically to interface with a new motion assembly.	n	y	Sliding pillowblocks that reduce the span, combined with a longer rack, could increase the stroke length.
24 Providing the capability for excess energy storage or importation	y	y	Motor was sized to be larger than necessary, and is able to move a (potentially) more demanding radial motion module.	n	n	Not relevant in this case.

Table B.3.1: Welding station Use of Guidelines Report (Part 1 of 4)

	Used	Helpful	Change Mode 3: Weld speed range	Used	Helpful	Change Mode 4: Raise weld surface
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	Change is confined to the drive shaft assembly	y	y	Modular linear motion assembly can be raised without propagating
2 Confining functions to single modules	n	y	Integration of the pulley and the pinion complicate the redesign.	y	y	Modular linear motion assembly can be raised without propagating
3 Confining functions to as few unique components as possible	y	y	Single shaft reduces redesign effort.	n	n	Not relevant to this change mode
4 Dividing modules into multiple smaller, identical modules	n	n	Module could not be split, nor would it be of assistance in this case	n	n	Not a scaling issue
5 Collecting parts which are not anticipated to change in time into separate modules	n	n	Not relevant to this change mode.	y	y	Motor not anticipated to change.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant to this change mode.	y	y	Electric motor is in a separate module than the mechanical drive shaft and motion table.
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	y	n	Import and export mechanical power done by drive shaft, not helpful though.	n	n	No function sharing involved
8 Using duplicate parts as much as possible without raising part count	n	n	Not relevant to this change mode.	y	y	Duplicate rail supports reduce redesign effort.
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	n	n	Not relevant to this change mode.	y	y	Spacious work envelope provides additional room to raise the weld surface.

10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	n	n	Not relevant to this change mode.	n	n	No new interfaces for this change mode.
11 Extending the available area on the transmission components of the device	n	y	Additional drive area could allow for other gears to be added, increasing the available speed range.	n	n	No new components that need to be powered.
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Pinion is located on the outside	n	y	Changing module is in the interior of the device
13 Reducing nesting of parts and modules	y	y	Pinion is not nested, and can be enlarged without interference.	n	y	Changing module is in the interior of the device
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	n	y	A standardized connector on each end of the shaft would have eliminated the need to redesign the shaft for a change in pinion gear	y	y	Standardized hole pattern on the base reduces redesign effort of the fasteners.
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Using a fastener on the pinion would actually make it detachable and easier to replace.	n	n	Fasteners allow the detachability of the linear motion assembly
16 Reducing the number of contact points between modules	y	n	Did not help in this case.	y	n	Did not help in this case
17 Simplifying the geometry of modular interfaces	y	y	Gear interface is a commercially available component.	y	y	Simple attachment between the linear motion assembly and the base
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	All energy must pass through the related modules.	n	n	All energy must pass through the related modules.
19 Creating detachable modules	n	n	Relevant module must remain.	y	y	LMA is detachable allowing it to be raised
20 Using a framework for mounting multiple modules	y	n	Frame does not interact with these modules.	y	n	No new modules being added to the frame

21 Using compliant materials	n	n	No compliant materials used, nor would they help remedy the situation.	n	n	No compliant materials used, nor would they help remedy the situation.
22 Simplifying the geometry of each component	n	n	Not relevant to this change mode.	y	y	Simple geometry of rail supports allow for easy redesign.
Adjustability						
23 Controlling the tuning of design parameters	n	y	An adjustable drive ratio with the belt pulleys (like those found in drill presses) could have been implemented to allow adjustable speed ranges.	y	y	Sliding stanchions allow the torch to be easily raised.
24 Providing the capability for excess energy storage or importation	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode

Table B.3.2: Welding station Use of Guidelines Report (Part 2 of 4)

	Used	Helpful	Change Mode 5: Glass shield	Used	Helpful	Change Mode 6: Other weld types
Modularity						
1 Using separate modules to carry out functions that are not closely related	n	n	Not relevant to this change mode.	y	y	Change is limited to the gun mount beam and does not propagate to other modules.
2 Confining functions to single modules	n	n	Not relevant to this change mode.	y	y	Mounting bracket is a single module.
3 Confining functions to as few unique components as possible	n	n	Not relevant to this change mode.	y	y	Minimal parts are used to mount the torch, resulting in fewer non-reusable parts.
4 Dividing modules into multiple smaller, identical modules	n	n	Not relevant to this change mode.	n	n	No segmentation involved.
5 Collecting parts which are not anticipated to change in time into separate modules	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode.
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	n	n	Not relevant to this change mode.	y	y	Holding the torch and mounting to the beam are done by the same module.
8 Using duplicate parts as much as possible without raising part count	y	y	Duplicated frame members provide a standard attachment method.	n	y	Ends of bracket are different, but could be the same.
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	Room on frame exterior allows for easy mounting	y	y	Spacious work envelop allows for addition of necessary modules.

10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	Frame members provide long free interfaces for mounting a glass shield.	y	y	Frame member are long and unobstructed.
11 Extending the available area on the transmission components of the device	n	n	No transmission components involved.	n	n	No transmission components involved.
12 Locating those parts which are anticipated to change near the exterior of the device	n	n	Not relevant to this change mode	n	n	Entire module is on the interior of the device.
13 Reducing nesting of parts and modules	n	n	Not relevant to this change mode	n	n	No nesting involved.
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	Standard frame connector components allow for easy substitution of face plates.	y	y	Frame stanchions are a standardized component.
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Fasteners allow detachability of the face plates.	n	n	Fasteners allow detachability.
16 Reducing the number of contact points between modules	n	n	Not relevant to this change mode	y	y	Single contact from torch to work, and double contact from stanchions to frame.
17 Simplifying the geometry of modular interfaces	y	y	T-slot framing allows for easy attachment of shield.	y	y	Simple connection between stanchions and frame.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not relevant to this change mode	y	y	All energy flows directly through the torch, bypassing the mounting components.
19 Creating detachable modules	n	n	Not relevant to this change mode	y	y	Entire torch mount is detachable
20 Using a framework for mounting multiple modules	y	y	A frame work is already in place to allow easy mounting of a glass shield.	y	y	Module is mounted to a frame and can easily be replaced with something different.

21 Using compliant materials	n	n	No compliant materials used, nor would they be helpful.	n	y	Compliant torch holder would have been able to adapt to different torch geometries.
22 Simplifying the geometry of each component	y	y	Simple frame member geometry allows for easy shield attachment.	n	n	Not relevant to this change mode.
Adjustability						
23 Controlling the tuning of design parameters	n	n	Not relevant to this change mode.	y	y	Slotted T-Frame members and pivoting torch mount allow for different heights and angles of torches.
24 Providing the capability for excess energy storage or importation	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode.

Table B.3.3: Welding station Use of Guidelines report (Part 3 of 4)

	Used	Helpful	Change Mode 7: Mount IR camera	Used	Helpful	Change Mode 8: Include torch motion
Modularity						
1 Using separate modules to carry out functions that are not closely related	n	n	No modules are changed	y	y	Torch mount module can simply be replaced.
2 Confining functions to single modules	n	n	No modules are changed	n	n	Holding and steadying the torch have to be part of the same module.
3 Confining functions to as few unique components as possible	n	n	No modules are changed	y	y	Few components are used to mount the torch, resulting in fewer non-reusable parts.
4 Dividing modules into multiple smaller, identical modules	n	n	Not a scaling issue	n	n	Not a scaling issue
5 Collecting parts which are not anticipated to change in time into separate modules	n	n	Not relevant to this change mode.	y	y	Torch mount is its own module which is anticipated to change.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode.
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	y	y	Mounting functions are confined to the single frame	y	y	Holding and steadying the torch are done by the same module.
8 Using duplicate parts as much as possible without raising part count	y	y	Duplicated frame members	n	y	Ends of torch clamp are different, could have been the same.
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	Room around the sliding table to provide clear angle of view from camera	y	y	Spacious work envelope allows addition of carriage system.

10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	Free space on frame exterior for mounting IR camera	y	y	Frame members provide room for additional modules.
11 Extending the available area on the transmission components of the device	n	n	No transmission components involved.	n	n	No transmission components involved.
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Frame members are external.	n	n	Not relevant to this change mode.
13 Reducing nesting of parts and modules	y	y	Sliding table is not nested so nothing blocks the angle of view.	n	n	No nesting involved.
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	Standardized frame mount components.	y	y	Standardized frame stanchions
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant to this change mode.	n	n	Fasteners enable detachability of torch mount module.
16 Reducing the number of contact points between modules	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode.
17 Simplifying the geometry of modular interfaces	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not relevant to this change mode.	y	y	Torch energy bypasses mounting functions.
19 Creating detachable modules	n	n	Nothing needs to be detached for this change mode.	y	y	Torch mount is detachable
20 Using a framework for mounting multiple modules	y	y	Framework is available for mounting the IR camera.	y	y	Frame is used for mounting the torch mount assembly.

21 Using compliant materials	n	n	Not relevant to this change mode.	n	n	Not relevant to this change mode.
22 Simplifying the geometry of each component	n	n	Not relevant to this change mode.	y	y	Beam and mount have simple geometries.
Adjustability						
23 Controlling the tuning of design parameters	y	y	Slotted frame members allow for adjustable camera placement.	y	y	Slotted frame members allow for easy height adjustment.
24 Providing the capability for excess energy storage or importation	y	y	Frame is stronger than it needs to be, allowing it to hold a heavy camera.	n	n	Not relevant to this change mode.

Table B.3.4: Welding station Use of Guidelines report (Part 4 of 4)

Change Mode		Evolution Response	Readiness
1	Perform radial welds on circular specimens	The weld surface and bearing rails will be completely removed and replaced with a radial weld fixture. The radial module will be driven with the same motor and mechanical belt drive.	The radial motion module will need to be completely designed. The current vendor can supply necessary materials and the design can be manufactured in-house.
2	Increase weld pass length	The linear guide rails will need to be lengthened.	Longer guide rails can be ordered from the current vendor.
3	Increase possible weld speed range	The pinion gear diameter will be increased. Gear will be replaced with a larger one.	Larger pinion gear can be purchased from the current vendor.
4	Raise sliding weld surface	The rail supports may need to be modified to sit on stilts and the drive shaft will need to be raised.	Some new materials will need to be ordered from the current vendor. All of the parts can be fabricated in-house.
5	Add a protective glass shield	The joining plates on the outside of the frame will need to be replaced with inside corner brackets, so the shield can sit flat on the outside of the frame.	Vendor will need to be located for the shield materials. It can be cut, drilled, and attached in-house.
6	Perform other types of welds (GTAW, Laser, etc.)	Compliant material in the bracket can accommodate a larger variety of torch sizes.	A vendor will need to be located for the auto-feed components. A compatible OEM assembly may not be obtainable.
7	Integrate IR camera	Additional frame support members shall be added to the upper horizontal beams of the frame. A mounted bracket will need to be designed and machined. A shield will need to be fashioned to block the angle of view from the arc.	Raw materials need to be purchased for the additional beams and the bracket. The same vendor can be used as was used for the rest of the frame.
8	Include torch motion	Horizontal torch mount bar will need to be replaced with a motorized carriage on a track.	A vendor for the motorized carriage will need to be located. If no OEM assembly is available, a solution will need to be designed from scratch.

Table B.4: Welding station redesign: Evolution Response Table

Module	Change Mode 1: Perform Radial Welds on Round Specimens	Change Mode 2: Increase Weld Pass Length
Frame / Base (FB)	Same	Same
Torch Mount (TM)	Same	Same
Linear Motion Table (LMT)	Remove	Change
Mechanical Belt Drive (MBD)	Same	Same
Motor Mount (MM)	Same	Same
Change Effect	Linear motion table will be completely removed and replaced with a radial weld fixture. The radial module will be driven with the same motor and mechanical belt drive.	The linear guide rails will need to be lengthened.

Table B.5.1: Welding station redesign: Module Change Report (Part 1 of 4)

Module	Change Mode 3: Increase Weld Speed Range	Change Mode 4: Raise Sliding Weld Surface
Frame / Base (FB)	Same	Same
Torch Mount (TM)	Same	Same
Linear Motion Table (LMT)	Same	Change
Mechanical Belt Drive (MBD)	Change	Change
Motor Mount (MM)	Same	Same
Change Effect	The pinion gear diameter will be increased. Gear will be replaced with a larger one.	Rail supports may need to be modified to sit on stilts and drive shaft will need to be raised.

Table B.5.2: Welding station redesign: Module Change Report (Part 2 of 4)

Module	Change Mode 5: Add a Protective Glass Shield	Change Mode 6: Perform other types of welds
Frame / Base (FB)	Change	Same
Torch Mount (TM)	Same	Change
Linear Motion Table (LMT)	Same	Same
Mechanical Belt Drive (MBD)	Same	Same
Motor Mount (MM)	Same	Same
Change Effect	Very minor change to brackets on frame.	Compliant material in the bracket can accommodate a larger variety of torch sizes.

Table B.5.3: Welding station redesign: Module Change Report (Part 3 of 4)

Module	Change Mode 7: Mount an IR camera	Change Mode 8: Include welding torch motion
Frame / Base (FB)	Same	Same
Torch Mount (TM)	Change	Change
Linear Motion Table (LMT)	Same	Same
Mechanical Belt Drive (MBD)	Same	Same
Motor Mount (MM)	Same	Same
Change Effect	Additional frame support members shall be added to the upper horizontal beams of the frame. A mounted bracket will need to be designed and machined. A shield will need to be fashioned to block the angle of view from the arc.	Horizontal torch mount bar will need to be replaced with a motorized carriage on a track.

Table B.5.4: Welding station redesign: Module Change Report (Part 4 of 4)

Item	-	Sub#	Module	Part Name	CM 1	Readiness
1	-	1	FB	Vertical Bar, 18"x1"x1" T-Slot Aluminum		
1	-	2	FB	Lengthwise Frame Bar, 32"x1"x1" T-Slot Aluminum		
1	-	3	FB	Widthwise Frame Bar, 22"x1"x1" T-Slot Aluminum		
1	-	4	FB	5 Hole T Joining Plate		
1	-	5	FB	4 Hole Corner Bracket		
1	-	6	FB	2'x3' Breadboard, 1/4-20 1" Square Matrix		
2	-	1	TM	Stanchion, Single Horizontal Base		
2	-	2	TM	Gun Mount Beam, 1" dia 1/8" Thick Alu. Tubing		
2	-	3	TM	Gun Mount - Gun Clamp		
2	-	4	TM	Gun Mount - Body		
2	-	5	TM	Torch mount - compliant liner		
3	-	1	LMT	36" Linear Bearing Rail, 0.5" Shaft Diameter	N	
3	-	2	LMT	Linear Bearing, 0.5" Shaft Diameter	N	
3	-	3	LMT	Retaining Rings	N	
3	-	4	LMT	Pillowblock, 0.5" Linear Ball Bearing	N	
3	-	5	LMT	Rail Support, 2"x0.5"x36"	N	
3	-	6	LMT	Linear Weld Surface	N	
3	-	7	LMT	Table Segment - End (Rounded Corners)	N	
3	-	8	LMT	Table Segment - Middle	N	
3	-	9	LMT	Rack - 2' x 0.5", 16 Pitch	N	
4	-	1	MBD	Pinion - 16 Pitch, 0.75 Pitch Diameter	N	2
4	-	2	MBD	Pinion Adapter	N	2
4	-	3	MBD	Drive Shaft	N	2
4	-	4	MBD	Flanged Ball Bearing, 0.5" OD, 0.25" Shaft Diameter		
4	-	5	MBD	Shaft Mount, Base		
4	-	6	MBD	Shaft Mount, Vertical Bar		
4	-	7	MBD	Shaft Mount, Bearing Plate		
4	-	8	MBD	Timing Belt Pulley, 1/4" Belt Width, 36 Teeth		
4	-	9	MBD	Timing Belt, 1/4" Width, 20 Inches		
5	-	1	MM	Motor Base, Nylon Block, 8"x6"x0.25"		
5	-	2	MM	Motor Face Plate		
5	-	3	MM	Vertical Mount Bar, 5"x1"x1" T-Slot Aluminum		
5	-	4	MM	Horizontal Mount Bar, 6"x1"x1" T-Slot Aluminum		
5	-	5	MM	Inside Corner Bracket		
				Number of Non-Reusable Parts	12	
				Percentage of Non-Reusable Parts (34 total)	65%	
				Flexibility Rating	4	
				Average Readiness Rating		2

Table B.6.1: Welding station redesign: Reusability Matrix (Part 1 of 3)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness	CM 5	Readiness
1	-	1	FB								
1	-	2	FB								
1	-	3	FB								
1	-	4	FB							N	1
1	-	5	FB								
1	-	6	FB								
2	-	1	TM								
2	-	2	TM								
2	-	3	TM								
2	-	4	TM								
2	-	5	TM								
3	-	1	LMT	N	2						
3	-	2	LMT								
3	-	3	LMT								
3	-	4	LMT								
3	-	5	LMT	N	2			N	2		
3	-	6	LMT								
3	-	7	LMT								
3	-	8	LMT								
3	-	9	LMT	N	3						
4	-	1	MBD			N	3				
4	-	2	MBD			N	2				
4	-	3	MBD								
4	-	4	MBD								
4	-	5	MBD								
4	-	6	MBD					N	2		
4	-	7	MBD								
4	-	8	MBD								
4	-	9	MBD								
5	-	1	MM								
5	-	2	MM								
5	-	3	MM								
5	-	4	MM								
5	-	5	MM								
				3		2		2		1	
				91%		94%		94%		97%	
				1		1		1		1	
					2.33		2.5		2		1

Table B.6.2: Welding station redesign: Reusability Matrix (Part 2 of 3)

Item	-	Sub#	Module	CM 6	Readiness	CM 7	Readiness	CM 8	Readiness
1	-	1	FB						
1	-	2	FB						
1	-	3	FB						
1	-	4	FB						
1	-	5	FB						
1	-	6	FB						
2	-	1	TM					N	2
2	-	2	TM	N	3			N	7
2	-	3	TM			N	2	N	5
2	-	4	TM					N	5
2	-	5	TM	N	2			N	5
3	-	1	LMT						
3	-	2	LMT						
3	-	3	LMT						
3	-	4	LMT						
3	-	5	LMT						
3	-	6	LMT						
3	-	7	LMT						
3	-	8	LMT						
3	-	9	LMT						
4	-	1	MBD						
4	-	2	MBD						
4	-	3	MBD						
4	-	4	MBD						
4	-	5	MBD						
4	-	6	MBD						
4	-	7	MBD						
4	-	8	MBD						
4	-	9	MBD						
5	-	1	MM						
5	-	2	MM						
5	-	3	MM						
5	-	4	MM						
5	-	5	MM						
				2		1		5	
				94%		97%		85%	
				1		1		2	
					2.5		2		4.8

Table B.6.3: Welding station redesign: Reusability Matrix (Part 3 of 3)

Appendix C: Scaled Seal Testing System Evolvability Analysis

Module	Change Mode 1: Longer Stroke	Change Mode 2: Increase Number of Tool Joints
Extension Support Weldment (ESW)	Change	Same
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Same	Change
Linear Motion Assembly (LMA)	Remove	Same
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Motor Assembly (MA)	Remove	Same
Motor Control Group (MCG)	Remove	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Change	Change
Vision System (VS)	Same	Same
Baffle Containment System (BC)	Same	Same
Change Effect	Ball Screws are at their maximum length. Replace prime movers with cable system. Lengthen drill pipe as appropriate	Tool joints will have to pass through both ends of Pressure Vessel so changes to backside will be required. Also may want view of backside also and test simultaneously since can't be certain which will fail first. Change drill pipe assembly to included more tool joints

Table C.1.1: Scaled seal testing system: Module Change Report (Part 1 of 5)

Module	Change Mode 3: Increase Field of View	Change Mode 4: Increase Drill Pipe Speed
Extension Support Weldment (ESW)	Same	Change
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Change	Same
Linear Motion Assembly (LMA)	Same	Remove
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Motor Assembly (MA)	Same	Remove
Motor Control Group (MCG)	Same	Remove
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Same	Same
Vision System (VS)	Change	Same
Baffle Containment System (BC)	Same	Same
Change Effect	Best viewing option is currently in use on vessel. So to get better view a larger vessel would have to be designed that has studded outlet.	Ballscrews are running at maximum speed. Would need to replace prime mover with cable system or possibly hydraulic ram system.

Table C.1.2: Scaled seal testing system: Module Change Report (Part 2 of 5)

Module	Change Mode 5: Use Drilling Mud instead of Water	Change Mode 6: Increase Stripper Rubber Size for Static Calibration
Extension Support Weldment (ESW)	Same	Same
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Change	Change
Linear Motion Assembly (LMA)	Same	Same
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Change	Same
Motor Assembly (MA)	Same	Same
Motor Control Group (MCG)	Same	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Same	Change
Vision System (VS)	Same	Change
Baffle Containment System (BC)	Remove	Same
Change Effect	Vision system could no longer be used and therefore sight glass flanges are not needed. Transfer barrier accumulator would need to be mounted onto PV Support Weldment. Current hose from pressure circuit would attach to transfer barrier accumulator.	This change mode only involves being able to test full size stripper rubbers in static or low pressure tests so that results can be compared to quarter scale stripper rubber behavior. This would allow a reality check of the quarter scale parameters.

Table C.1.3: Scaled seal testing system: Module Change Report (Part 3 of 5)

Module	Change Mode 7: Increase Scaling Factor of Stripper Rubber	Change Mode 8: Change of Environment (Run tests outside)
Extension Support Weldment (ESW)	Change	Change
PV Support Weldment (PVS)	Change	Same
Pressure Vessel (PV)	Change	Same
Linear Motion Assembly (LMA)	Remove	Remove
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Motor Assembly (MA)	Remove	Remove
Motor Control Group (MCG)	Remove	Remove
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Change
Drill Pipe Assembly (DPA)	Change	Same
Vision System (VS)	Change	Same
Baffle Containment System (BC)	Same	Same
Change Effect	This change is the ability to test half or full size stripper rubbers in the same way the current system can test quarter scale. As a result the PV needs to get larger as does the stroke length. The resulting forces will also increase and therefore the support weldments may require change.	For safety or shop space reasons, it may be desired to run the tests outside away from people. The ballscrews are not recommended for outdoor service and 480VAC may not be available. A hydraulic ram system would be better able to handle the elements. This would require changes to the support weldments and replacement of the Linear Motion Assembly and control group.

Table C.1.4: Scaled seal testing system: Module Change Report (Part 4 of 5)

Module	Change Mode 9: Quicker Test Setup	Change Mode 10: Decrease Scaling Factor
Extension Support Weldment (ESW)	Same	Same
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Change	Change
Linear Motion Assembly (LMA)	Same	Same
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Motor Assembly (MA)	Same	Same
Motor Control Group (MCG)	Same	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Same	Change
Vision System (VS)	Change	Same
Baffle Containment System (BC)	Same	Same
Change Effect	The current pressure vessel design uses large flanges that bolt onto the vessel. A significant portion of test setup time is spent turning on all the nuts. It also requires an overhead crane to move the flanges in and out of place. A hinged flange system with a cam lock may be able to be designed that would make access to the stripper rubber much quicker and easier.	If the scaling is found to be accurate at smaller scales the current system design could be used with very small modification. A decrease in scaling factor would also effectively lengthen the stroke since pipe length scales with the stripper rubber diameter.

Table C.1.5: Scaled seal testing system: Module Change Report (Part 5 of 5)

Item	-	Sub#	Module	Partname	CM 1	Readiness
1	-	1	ESW	Stripper Test Bed, Extension Support Beam.ipt	N	3
1	-	2	ESW	Stripper Test Bed, Extension Leg Gusset.ipt	N	3
1	-	3	ESW	Stripper Test Bed, Rail Mount Bar.ipt	N	1
1	-	4	ESW	Stripper Test Bed, Foot.ipt		
1	-	5	ESW	Stripper Test Bed, Anchor.ipt		
1	-	6	ESW	Stripper Test Bed, Bolt Plate.ipt	N	3
1	-	7	ESW	Stripper Test Bed, Extension Beam Gusset.ipt	N	1
1	-	8	ESW	Stripper Test Bed, Pillow Block Mount Plate.ipt	N	
1	-	9	ESW	Levelling Foot.ipt		
1	-	10	ESW	3_4-2.5-UNC.ipt ESW to PVS Module attachment		
2	-	1	PVS	Stripper Test Bed, PV Support Gusset Top Cap.ipt		
2	-	2	PVS	Stripper Test Bed, Anchor.ipt		
2	-	3	PVS	Stripper Test Bed, Bolt Plate.ipt		
2	-	4	PVS	Stripper Test Bed, Foot.ipt		
2	-	5	PVS	Stripper Test Bed, PV Support Beam.ipt		
2	-	6	PVS	Stripper Test Bed, PV Support Gusset.ipt		
2	-	7	PVS	Stripper Test Bed, PV Support Gusset Side Cap.ipt		
3	-	1.1	PV	Stripper Test Vessel Integral Flange, Rough Machine.ipt		
3	-	1.2	PV	Stripper Test Vessel, Tube.ipt		
3	-	1.3	PV	Test Port 1-2 NPT.ipt		
3	-	1.4	PV	Stripper Test Vessel Sight Glass Weld Flange.ipt		
3	-	2.1	PV	Saddle Plate.ipt		
3	-	2.2	PV	Saddle Side Plate.ipt		
3	-	2.3	PV	Saddle Mid Gusset.ipt		
3	-	2.4	PV	Saddle Mount Plt.ipt		
3	-	2.5	PV	Saddle Tie Plate.ipt		
3	-	3	PV	STUD, 1.375-6 UNC X 8.00.ipt		
3	-	4	PV	1 3_8-UNC.ipt Modified flange nuts		
3	-	5	PV	STUD, 1.125-7 UNC X 8.00.ipt		
3	-	6	PV	1 1_8-UNC.ipt Sight glass flange nuts		
3	-	7	PV	O-RING_AS568A-443.ipt		
3	-	8	PV	Stripper Test Vessel Sight Glass Flange.ipt		
3	-	9	PV	Stripper Test Vessel Blind Flange, Modified.ipt		
3	-	10	PV	Stripper Test Vessel Shim.ipt		
3	-	11	PV	O-RING_AS568A-242.ipt		
3	-	12	PV	Stripper Test Vessel Shim, Short.ipt		
3	-	13	PV	Omega-thermowell.ipt		
3	-	14	PV	Pressure Vessel Spacer.ipt		
3	-	15	PV	1_2-UNC.ipt PV attachment nuts		
3	-	16	PV	1_2-2.5-UNC.ipt PV attachment bolts		

3	-	17	PV	3_8-1-UNC.ipt		
3	-	18	PV	Stripper Test Vessel, Sight Glass.ipt		
3	-	19	PV	O-RING_AS568A-339.ipt		
3	-	20	PV	NPT x NPT Male Union, .750.ipt		
4	-	1.1	LMA	Stripper Test Bed, Rail.ipt	N	
4	-	1.2	LMA	Rail Cover Strip	N	
4	-	1.3	LMA	Rail End Cap	N	
4	-	1.4	LMA	Stripper Test Bed, Runner Block.ipt	N	
4	-	1.5	LMA	1_2-1.5-UNC.ipt Guide rail screws		
4	-	1.6	LMA	M12-30.ipt Runner block attachment screws		
4	-	2.1	LMA	Stripper Test Bed, Carriage Base.ipt	N	
4	-	2.2	LMA	Stripper Test Bed, Carriage Center Block.ipt	N	
4	-	2.3	LMA	Stripper Test Bed, Carriage Side Plate.ipt	N	
4	-	2.4	LMA	1-A-2.ipt 1" Washer		
4	-	2.5	LMA	1-5-UNF.ipt Bolt between carriage block and load cell		
4	-	2.6	LMA	3_4-1.5-UNC.ipt Carriage block screws		
4	-	2.7	LMA	1_2-1.5-UNC.ipt Carriage base screws		
4	-	2.8	LMA	0.5-B-1.ipt Half inch Washer		
4	-	2.9	LMA	0.75-A-1.469.ipt 3/4" Washer		
4	-	3.1	LMA	Stripper Test Bed, Ball Nut.ipt	N	
4	-	3.2	LMA	Stripper Test Bed, Ball Screw.ipt	N	
4	-	3.3	LMA	3D_BK2_500_146.ipt	N	
4	-	3.4	LMA	Stripper Test Bed, Pillow Block.ipt	N	
4	-	3.5	LMA	3_4-UNC.ipt Hex Nut for LMA to ESW attachment		
4	-	3.6	LMA	M20-80.ipt Pillow block attachment screws		
4	-	3.7	LMA	3_4-4-UNC.ipt LMA to ESW attachment		
4	-	4	LMA	Stripper Test Bed, Load Cell.ipt		
5	-	1	TCS	Temperature Controller		
5	-	2	TCS	Set Point Transmission Wire		
5	-	3	TCS	Current Temp Retransmit Wire		
5	-	4	TCS	SS Relay		
5	-	5	TCS	SS Relay Control Wire		
5	-	6	TCS	Terminal Block		
5	-	7	TCS	SS Relay Box		
5	-	8	TCS	Box Mounting Braces		
5	-	9	TCS	Mounting Clamps		
5	-	10	TCS	Plug Heater.ipt		
6	-	1	PCA	Accumulator		
6	-	2	PCA	AutoClave Fitting		
6	-	3	PCA	Check Valve		
6	-	4	PCA	1/2" Cross Fitting		
6	-	5	PCA	Male 1/2" to Female 1/4" NPT Adapter		
6	-	6	PCA	High Pressure Relief Valve		
6	-	7	PCA	1/2" Tee Fitting		
6	-	8	PCA	3/4" Cross		

6	-	9	PCA	1/2" Ball Valve		
6	-	10	PCA	Male 3/4" to Female 1/2" NPT Adapter		
6	-	11	PCA	Male 1-1/4" to Female 3/4" NPT Adapter		
6	-	12	PCA	Male 3/4" to Male 3/4" NPT Adapter		
6	-	13	PCA	3/4" Elbow Fitting		
6	-	14	PCA	Pressure Circuit Mounting Plate		
6	-	15	PCA	Large Mounting Brackets		
6	-	16	PCA	Small Mounting Brackets		
6	-	17	PCA	3/4" High Pressure Hose - 3ft		
6	-	18	PCA	1/2" High Pressure Tubing		
6	-	19	PCA	1/2" Tube Fittings		
6	-	20	PCA	Mounting Bolts for Plate		
6	-	21	PCA	Mounting Nuts		
6	-	22	PCA	Mounting Washers		
6	-	23	PCA	1/2" Bleed Valve		
6	-	24	PCA	Male 3/4" to 1/2" NPT Adapter		
6	-	25	PCA	High Pressure Pump		
6	-	26	PCA	High Pressure Autoclave Hose		
6	-	27	PCA	Instant Water Heater		
6	-	28	PCA	Supply Hose		
6	-	29	PCA	Drain Hose		
7	-	1.1	MA	Stripper Test Bed, Motor Mount, Bottom.ipt	N	
7	-	1.2	MA	Stripper Test Bed, Motor Mount, Front.ipt	N	
7	-	1.3	MA	Stripper Test Bed, Motor Mount, Side.ipt	N	
7	-	2	MA	0.625-A-1.75.ipt Washer		
7	-	3	MA	5_8-2.5-UNC.ipt Motor mount screws		
7	-	4	MA	Stripper Test Bed, Motor Mount, Shim Plt.ipt	N	
7	-	5	MA	5_8-UNC.ipt Motor Mount Nuts		
7	-	6	MA	ac_servo_motorRev3.ipt	N	
7	-	7	MA	motor_blower.ipt	N	
8	-	1	MCG	IndraDrive compact converter, single axis	N	
8	-	2	MCG	Power cable, ready made	N	
8	-	3	MCG	Software	N	
8	-	4	MCG	IndraDrive control unit BASIC, single axis	N	
8	-	5	MCG	IndraDrive Firmware	N	
8	-	6	MCG	IndraDrive Accessories	N	
8	-	7	MCG	Cable, ready made	N	
8	-	8	MCG	IndraDrive Accessories	N	
8	-	9	MCG	IndraDrive Accessories	N	
8	-	10	MCG	Brake resistor	N	
8	-	11	MCG	Feedback and control cable, ready made	N	
9	-	1	DAQ	Pressure Transducer		
9	-	2	DAQ	Thermocouple (ungrounded)		
9	-	3	DAQ	J-type mini connectors		
9	-	4	DAQ	Load Cell Connectors		

9	-	5	DAQ	100ft Spool of Load Cell Cable		
9	-	6	DAQ	LabView Full Dev System		
9	-	7	DAQ	NI PCI-6221, M series DAQ		
9	-	8	DAQ	SCC-68 I/O Connector Block		
9	-	9	DAQ	SCC68-68 Cable		
9	-	10	DAQ	SCC-SG24 2-Channel Full Bridge 10V Excitation		
9	-	11	DAQ	NI PCI-6514 Digital I/O		
9	-	12	DAQ	CB-100 I/O Kit		
9	-	13	DAQ	NI PCI-1426 Camera Card w/ IMAQ		
9	-	14	DAQ	RTSI Bus Cable		
10	-	1	Comp	Mid-Tower CPU		
10	-	2	Comp	Monitor		
10	-	3	Comp	Keyboard		
10	-	4	Comp	Mouse		
11	-	1	Cab	Cabinet		
11	-	2	Cab	24V Power Supplies		
11	-	3	Cab	24V Fans		
11	-	4	Cab	Power Strip		
11	-	5	Cab	Miscellaneous Wire and Connectors		
12	-	1	DPA	1-UNC.ipt DP Coupler Nut		
12	-	2	DPA	DP-longend.ipt	N	1
12	-	3	DPA	DP-Coupling-round.ipt		
12	-	4	DPA	3_8-UNC.ipt Coupling pin nut		
12	-	5	DPA	3_8-3-UNC.ipt coupling pin		
12	-	6	DPA	DP-ToolJoint-01.ipt		
12	-	7	DPA	DP-shortend.ipt		
13	-	1	VS	Monochrome Camera 120 fps		
13	-	2	VS	Zoom Lens		
13	-	3	VS	Power Supply		
13	-	4	VS	CameraLink Cable 5m		
14	-	1.1	BC	Rubber Wiper Casing.ipt		
14	-	1.2	BC	Casing Tab Plate.ipt		
14	-	1.3	BC	Casing Bolting Ring.ipt		
14	-	1.4	BC	Casing Stop Ring.ipt		
14	-	2	BC	Rubber Wiper Spacer.ipt		
14	-	3	BC	Rubber Wiper End Plate.ipt		
14	-	4	BC	Rubber Wiper.ipt		
14	-	5	BC	Clamp Plate.ipt		
14	-	6	BC	Rubber Wiper Brace Bar.ipt		
14	-	7	BC	Water Gutter		
14	-	8	BC	Water Catch Bin		
14	-	9	BC	1_2-1-UNC.ipt Containment Casing centering screws		
14	-	10	BC	1_2-3.5-UNC.ipt Containment System Attachment Bolts		
14	-	11	BC	1_2-3-UNC.ipt Containment System Attachment bolts		
14	-	12	BC	1_2-UNC.ipt Containment System attachment nuts		

15	-	1	SSR	Scaled Stripper Rubber.ipt		
15	-	2	SSR	Scaled Mold, Stripper Insert.ipt		
				Number of Non-Reusable Parts	35	
				Percentage of Non-Reusable Parts (148 total)	76%	
				Flexibility Rating	3	
				Average Readiness Rating		2

Table C.2.1: Scaled seal testing system: Reusability Matrix (Part 1 of 3)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness	CM 5	Readiness	CM 6	Readiness	CM 7	Readiness
1	-	1	ESW					N	3					N	3
1	-	2	ESW					N	3					N	3
1	-	3	ESW											N	3
1	-	4	ESW												
1	-	5	ESW												
1	-	6	ESW											N	3
1	-	7	ESW												
1	-	8	ESW					N						N	3
1	-	9	ESW												
1	-	10	ESW												
2	-	1	PVS											N	3
2	-	2	PVS												
2	-	3	PVS											N	3
2	-	4	PVS												
2	-	5	PVS											N	3
2	-	6	PVS											N	3
2	-	7	PVS											N	3
3	-	1.1	PV			N	6					N	6	N	6
3	-	1.2	PV			N	6			N	3	N	6	N	6
3	-	1.3	PV												
3	-	1.4	PV			N	6			N		N	6	N	6
3	-	2.1	PV			N	6					N	6	N	6
3	-	2.2	PV			N	6					N	6	N	6
3	-	2.3	PV			N	6					N	6	N	6
3	-	2.4	PV			N	6					N	6	N	6
3	-	2.5	PV			N	6					N	6	N	6
3	-	3	PV												
3	-	4	PV												
3	-	5	PV												
3	-	6	PV												
3	-	7	PV			N	2					N	2	N	2
3	-	8	PV							N					
3	-	9	PV									N	6	N	6
3	-	10	PV									N	6	N	6
3	-	11	PV									N	2	N	2
3	-	12	PV	N	1							N	6	N	6
3	-	13	PV												
3	-	14	PV												
3	-	15	PV												
3	-	16	PV												

3	-	17	PV												
3	-	18	PV							N					
3	-	19	PV							N					
3	-	20	PV												
4	-	1.1	LMA											N	
4	-	1.2	LMA											N	
4	-	1.3	LMA											N	
4	-	1.4	LMA											N	
4	-	1.5	LMA												
4	-	1.6	LMA												
4	-	2.1	LMA											N	
4	-	2.2	LMA					N	2					N	
4	-	2.3	LMA											N	
4	-	2.4	LMA												
4	-	2.5	LMA												
4	-	2.6	LMA												
4	-	2.7	LMA												
4	-	2.8	LMA												
4	-	2.9	LMA												
4	-	3.1	LMA					N						N	
4	-	3.2	LMA					N						N	
4	-	3.3	LMA					N						N	
4	-	3.4	LMA					N						N	
4	-	3.5	LMA												
4	-	3.6	LMA												
4	-	3.7	LMA												
4	-	4	LMA											N	1
5	-	1	TCS												
5	-	2	TCS												
5	-	3	TCS												
5	-	4	TCS												
5	-	5	TCS												
5	-	6	TCS												
5	-	7	TCS												
5	-	8	TCS												
5	-	9	TCS												
5	-	10	TCS												
6	-	1	PCA												
6	-	2	PCA												
6	-	3	PCA												
6	-	4	PCA												
6	-	5	PCA												
6	-	6	PCA												
6	-	7	PCA												
6	-	8	PCA												

6 - 9	PCA												
6 - 10	PCA												
6 - 11	PCA												
6 - 12	PCA												
6 - 13	PCA												
6 - 14	PCA							N	2				
6 - 15	PCA												
6 - 16	PCA												
6 - 17	PCA												
6 - 18	PCA												
6 - 19	PCA												
6 - 20	PCA												
6 - 21	PCA												
6 - 22	PCA												
6 - 23	PCA							N	3				
6 - 24	PCA												
6 - 25	PCA												
6 - 26	PCA												
6 - 27	PCA							N					
6 - 28	PCA												
6 - 29	PCA												
7 - 1.1	MA					N						N	
7 - 1.2	MA					N						N	
7 - 1.3	MA					N						N	
7 - 2	MA												
7 - 3	MA												
7 - 4	MA					N						N	
7 - 5	MA												
7 - 6	MA					N						N	
7 - 7	MA					N						N	
8 - 1	MCG					N						N	
8 - 2	MCG					N						N	
8 - 3	MCG					N						N	
8 - 4	MCG					N						N	
8 - 5	MCG					N						N	
8 - 6	MCG					N						N	
8 - 7	MCG					N						N	
8 - 8	MCG					N						N	
8 - 9	MCG					N						N	
8 - 10	MCG					N						N	
8 - 11	MCG					N						N	
9 - 1	DAQ												
9 - 2	DAQ												
9 - 3	DAQ												
9 - 4	DAQ												

9	-	5	DAQ												
9	-	6	DAQ												
9	-	7	DAQ												
9	-	8	DAQ												
9	-	9	DAQ												
9	-	10	DAQ												
9	-	11	DAQ												
9	-	12	DAQ												
9	-	13	DAQ							N					
9	-	14	DAQ												
10	-	1	Comp												
10	-	2	Comp												
10	-	3	Comp												
10	-	4	Comp												
11	-	1	Cab												
11	-	2	Cab												
11	-	3	Cab												
11	-	4	Cab												
11	-	5	Cab												
12	-	1	DPA												
12	-	2	DPA	N	2									N	
12	-	3	DPA											N	
12	-	4	DPA												
12	-	5	DPA												
12	-	6	DPA											N	
12	-	7	DPA											N	
13	-	1	VS							N					
13	-	2	VS							N					
13	-	3	VS							N					
13	-	4	VS							N					
14	-	1.1	BC			N	3					N	3	N	3
14	-	1.2	BC			N	3					N	3	N	3
14	-	1.3	BC			N	3					N	3	N	3
14	-	1.4	BC			N	3					N	3	N	3
14	-	2	BC			N	3					N	3	N	3
14	-	3	BC			N	3					N	3	N	3
14	-	4	BC			N	1					N	1	N	1
14	-	5	BC			N	3					N	3	N	3
14	-	6	BC			N	1					N	1	N	1
14	-	7	BC												
14	-	8	BC												
14	-	9	BC												
14	-	10	BC												
14	-	11	BC												
14	-	12	BC												

15	-	1	SSR												
15	-	2	SSR												
				2		18		25		13		22		65	
				99%		88%		83%		91%		85%		56%	
				1		2		2		1		2		4	
					1.5		4.06		2.67		2.67		4.23		3.76

Table C.2.2: Scaled seal testing system: Reusability Matrix (Part 2 of 3)

Item	-	Sub#	Module	CM 8	Readiness	CM 9	Readiness	CM10	Readiness
1	-	1	ESW	N	3				
1	-	2	ESW	N	3				
1	-	3	ESW						
1	-	4	ESW						
1	-	5	ESW						
1	-	6	ESW	N	3				
1	-	7	ESW						
1	-	8	ESW						
1	-	9	ESW						
1	-	10	ESW						
2	-	1	PVS						
2	-	2	PVS						
2	-	3	PVS						
2	-	4	PVS						
2	-	5	PVS						
2	-	6	PVS						
2	-	7	PVS						
3	-	1.1	PV			N	5		
3	-	1.2	PV						
3	-	1.3	PV						
3	-	1.4	PV						
3	-	2.1	PV						
3	-	2.2	PV						
3	-	2.3	PV						
3	-	2.4	PV						
3	-	2.5	PV						
3	-	3	PV						
3	-	4	PV						
3	-	5	PV						
3	-	6	PV						
3	-	7	PV						
3	-	8	PV						
3	-	9	PV			N	3		
3	-	10	PV			N	3	N	2
3	-	11	PV						
3	-	12	PV			N	3	N	2
3	-	13	PV						
3	-	14	PV						
3	-	15	PV						
3	-	16	PV						

3	-	17	PV						
3	-	18	PV						
3	-	19	PV						
3	-	20	PV						
4	-	1.1	LMA	N					
4	-	1.2	LMA	N					
4	-	1.3	LMA	N					
4	-	1.4	LMA	N					
4	-	1.5	LMA						
4	-	1.6	LMA						
4	-	2.1	LMA						
4	-	2.2	LMA	N	2				
4	-	2.3	LMA						
4	-	2.4	LMA						
4	-	2.5	LMA						
4	-	2.6	LMA						
4	-	2.7	LMA						
4	-	2.8	LMA						
4	-	2.9	LMA						
4	-	3.1	LMA	N					
4	-	3.2	LMA	N					
4	-	3.3	LMA	N					
4	-	3.4	LMA	N					
4	-	3.5	LMA						
4	-	3.6	LMA						
4	-	3.7	LMA						
4	-	4	LMA						
5	-	1	TCS						
5	-	2	TCS						
5	-	3	TCS						
5	-	4	TCS						
5	-	5	TCS						
5	-	6	TCS						
5	-	7	TCS						
5	-	8	TCS						
5	-	9	TCS						
5	-	10	TCS						
6	-	1	PCA						
6	-	2	PCA						
6	-	3	PCA						
6	-	4	PCA						
6	-	5	PCA						
6	-	6	PCA						
6	-	7	PCA						
6	-	8	PCA						

6	-	9	PCA							
6	-	10	PCA							
6	-	11	PCA							
6	-	12	PCA							
6	-	13	PCA							
6	-	14	PCA							
6	-	15	PCA							
6	-	16	PCA							
6	-	17	PCA							
6	-	18	PCA							
6	-	19	PCA							
6	-	20	PCA							
6	-	21	PCA							
6	-	22	PCA							
6	-	23	PCA							
6	-	24	PCA							
6	-	25	PCA							
6	-	26	PCA							
6	-	27	PCA							
6	-	28	PCA							
6	-	29	PCA							
7	-	1.1	MA	N						
7	-	1.2	MA	N						
7	-	1.3	MA	N						
7	-	2	MA							
7	-	3	MA							
7	-	4	MA	N						
7	-	5	MA							
7	-	6	MA	N						
7	-	7	MA	N						
8	-	1	MCG	N						
8	-	2	MCG	N						
8	-	3	MCG	N						
8	-	4	MCG	N						
8	-	5	MCG	N						
8	-	6	MCG	N						
8	-	7	MCG	N						
8	-	8	MCG	N						
8	-	9	MCG	N						
8	-	10	MCG	N						
8	-	11	MCG	N						
9	-	1	DAQ							
9	-	2	DAQ							
9	-	3	DAQ							
9	-	4	DAQ							

9	-	5	DAQ						
9	-	6	DAQ						
9	-	7	DAQ						
9	-	8	DAQ						
9	-	9	DAQ						
9	-	10	DAQ						
9	-	11	DAQ						
9	-	12	DAQ						
9	-	13	DAQ						
9	-	14	DAQ						
10	-	1	Comp						
10	-	2	Comp	N	4				
10	-	3	Comp						
10	-	4	Comp						
11	-	1	Cab	N	4				
11	-	2	Cab						
11	-	3	Cab						
11	-	4	Cab						
11	-	5	Cab						
12	-	1	DPA						
12	-	2	DPA					N	2
12	-	3	DPA					N	2
12	-	4	DPA					N	2
12	-	5	DPA						
12	-	6	DPA					N	2
12	-	7	DPA					N	2
13	-	1	VS						
13	-	2	VS						
13	-	3	VS						
13	-	4	VS						
14	-	1.1	BC			N	3		
14	-	1.2	BC			N	3		
14	-	1.3	BC			N	3		
14	-	1.4	BC			N	3		
14	-	2	BC						
14	-	3	BC						
14	-	4	BC						
14	-	5	BC			N	3		
14	-	6	BC						
14	-	7	BC						
14	-	8	BC						
14	-	9	BC						
14	-	10	BC						
14	-	11	BC						
14	-	12	BC						

15	-	1	SSR						
15	-	2	SSR						
				31		9		7	
				79%		94%		95%	
				2		1		1	
					3.17		3.22		2

Table C.2.3: Scaled seal testing system: Reusability Matrix (Part 3 of 3)

	Used	Helpful	Change Mode 1: Longer Stroke	Used	Helpful	Change Mode 2: Increase Number of Tool Joints
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	Support structure, pv, etc were all very distinct modules			
2 Confining functions to single modules	n	n	Due to the loads involved, the function of reacting the force must be done by all modules	y	y	The drill pipe could have been machined out of a single rod, but instead the tool joint was made separate so it will be easier to increase the number of tool joints
3 Confining functions to as few unique components as possible	y	y	The LMA's are symmetric, the motors are the same, the two sides of the carriage are the same	n	n	The two support shims have similar functions and the parts are slightly different, the short and long end of the DP are similar but slightly different
4 Dividing modules into multiple smaller, identical modules	n	y	If hydraulics were used, multiple small rams could be used together. Use multiple track sections to increase length			
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	The pressure circuit is something that would rarely need to change and it is its own module	y	y	The tool joint shape is based on a standard so it is not likely to change
6 Collecting parts which perform functions associated with the same energy domain into separate modules	y	y	This is largely how the system was divided, although the flows between modules are significant			
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	y	y	The center block in the carriage attaches to both the ball nut and drill pipe, reducing multiple parts and more fasteners			
8 Using duplicate parts as much as possible without raising part count	y	y	The two sides of the carriage are the same. The structure weldment uses many duplicate parts	n		

Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	There is open space around almost all of the modules	n	y	If more space was created around the DP as it passes through the backside shim, redesign would not be required
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	Using the wide flange beam creates a vast surface for interfaces, whereas the previous consultants design was very limited to the ball screw	y	y	The DP itself is a large interface that can be spliced to add tool joints as needed
11 Extending the available area on the transmission components of the device	n	y	Using the ball screws constrained the available area on the transmission of the device	y	y	There is area on the DP where new tool joints can be inserted
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Due to the skeletal structure, pretty much everything is on the exterior	y	y	The DP has to be removed for every test setup, the shims are also available during test setup
13 Reducing nesting of parts and modules				n	n	The DP passes through the shims and therefore, changes to the DP propagate to the shims
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	The module interfaces are connected using standard bolts	y	y	The connection between the tool joint and DP's is a simple threaded connection. The shims are attached by a single acme thread as opposed to a bolt pattern
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Due to the high loads expected, it is better to have multiple fasteners. In the case of the linear guide rail, it required many fasteners	y	y	The connection between the tool joint and DP's is a simple threaded connection.
16 Reducing the number of contact points between modules	y	y	The carriage was designed so that the main block doesn't contact the base block.	y	y	Contact between parts of the drill pipe assembly is as minimal as possible

17 Simplifying the geometry of modular interfaces	y	y	Bolt patterns on the LMA are all simple and symmetric, the DP is attached to the carriage thru a single large bolt			
18 Routing flows of energy, information and materials so that they are able to bypass each module at need				n	y	If the tool joint is to be removed, the two ends of the opposing DP sections cannot be attached.
19 Creating detachable modules	y	y	All of the modules are detachable by unbolting joining surfaces	n	y	If the tool joints somehow clamped on that would be neat.
20 Using a framework for mounting multiple modules	y	y	The wide flange beam support structure acts as a skeletal framework that all modules attach to.	n	y	The drill pipe could have been a single rod with little groves onto which the tool joints could attach
21 Using compliant materials						
22 Simplifying the geometry of each component	y	y	Since machining is the main form of manufacturing for these components, many of them are square. When possible, parts were designed as single extrusions so that water jetting could be used.	n	n	Geometry is determined by similarity to full size drill pipe
Adjustability						
23 Controlling the tuning of design parameters	y	y	Bolt holes were oversized to allow adjustment during setup			
24 Providing the capability for excess energy storage or importation	y	y	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses from increasing the length.			

Table C.3.1: Scaled seal testing system: Use of Guidelines Report (Part 1 of 5)

	Used	Helpful	Change Mode 3: Increase Field of View	Used	Helpful	Change Mode 4: Increase Drill Pipe Speed
Modularity						
1 Using separate modules to carry out functions that are not closely related	n	y	The sight glass ports are limited by the pressure vessel design	n	y	The conversion transmission functions are tightly tied in the lma module
2 Confining functions to single modules	n	n	For the pressure vessel, all parts have other functions but also need to withstand the pressure	n	n	Due to the loads involved, the function of reacting the force must be done by all modules
3 Confining functions to as few unique components as possible	y	y	The modified flanges are the same and the sight glasses and flanges are the same	y	y	The LMA's are symmetric, the motors are the same, the two sides of the carriage are the same
4 Dividing modules into multiple smaller, identical modules				n	y	If hydraulics were used, multiple small rams could be used together
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	The pressure circuit is something that would rarely need to change and it is its own module	y	y	The lma has always been expected to change and it is a separate module
6 Collecting parts which perform functions associated with the same energy domain into separate modules			The heaters and the sight glasses must also hold pressure	y	y	The creation of force is all performed by the lma module
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related						
8 Using duplicate parts as much as possible without raising part count	y	y	There are only two types of ports on the vessel.	y	y	Where possible, duplicate parts were used
Spatial						

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	n	y	The original pressure vessel tube was 'optimized' to be just large enough for the stripper rubber	y	y	There is open space around almost all of the modules
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	The pressure vessel could be redesigned with more ports	y	y	Using the wide flange beam creates a vast surface for interfaces, whereas the previous consultants design was very limited to the ball screw
11 Extending the available area on the transmission components of the device	n		no transmission	n	y	Using the ball screws constrained the available area on the transmission of the device
12 Locating those parts which are anticipated to change near the exterior of the device				y	y	The lma is on top of the device
13 Reducing nesting of parts and modules	n	y	The original pressure vessel tube was 'optimized' to be just large enough for the stripper rubber	y	y	The linear motion system is not nested
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	The sight glass flanges are a standard component	y	y	The module interfaces are connected using standard bolts
15 Reducing the number of fasteners used, or eliminating them entirely						
16 Reducing the number of contact points between modules				y	y	The bolt plate is the only contact point between the linear motion module and pv module
17 Simplifying the geometry of modular interfaces				y	y	The bolt plate is a very simple interface

18 Routing flows of energy, information and materials so that they are able to bypass each module at need				n		
19 Creating detachable modules				y	y	All of the modules are detachable by unbolting joining surfaces
20 Using a framework for mounting multiple modules				y	y	The wide flange beam support structure acts as a skeletal framework that all modules attach to.
21 Using compliant materials	y	y	The hose between the pv ad pressure circuit is flexible, so it can be easily adjust if the PV changes			
22 Simplifying the geometry of each component				y	y	Since machining is the main form of manufacturing for these components, many of them are square. When possible, parts were designed as single extrusions so that water jetting could be used.
Adjustability						
23 Controlling the tuning of design parameters				y	y	Bolt holes were oversized to allow adjustment during setup
24 Providing the capability for excess energy storage or importation				y	y	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses

Table C.3.2: Scaled seal testing system: Use of Guidelines Report (Part 2 of 5)

	Used	Helpful	Change Mode 5: Use Drilling Mud instead of Water	Used	Helpful	Change Mode 6: Increase Stripper Rubber Size for Static Calibration
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	The sight glasses are not built into the pv so removing them just requires taking the holes and welded flanges out of the design.			
2 Confining functions to single modules	n	n	The sight glasses must allow visual inspection and hold pressure	n	n	The PV holds pressure but also provides heat and allows the drill pipe to pass thru and supports the loading of the stripper rubber
3 Confining functions to as few unique components as possible	y	y	Symmetric sight glasses and ports were used	y	y	The pressure vessel uses similar parts where possible
4 Dividing modules into multiple smaller, identical modules						
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	The pressure circuit as currently designed could still be used with the addition of a transfer-barrier accumulator	y	y	The pressure circuit is separate from the PV and connects only by a flexible hose
6 Collecting parts which perform functions associated with the same energy domain into separate modules				y	y	All of the pressure components are in separate modules from the rest of the system
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related						
8 Using duplicate parts as much as possible without raising part count	y	y	Sight glasses and ports are duplicates	y	y	The PV is symmetric so the flanges on each end are the same and many of the ports are the same
Spatial						

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	There is room for the pressure vessel to expand. There is space available to add a transfer barrier accumulator	n	y	The size of the stripper rubber does not have room to expand
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	A mounting location could easily be found for the transfer barrier accumulator, like the other side of the support structure	y	y	The top of the pvs has available space for a new pressure vessel to attach
11 Extending the available area on the transmission components of the device						
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Removing the sight glass ports requires no redesign of the PV	n	y	The stripper rubber mounts inside of the pressure vessel. Maybe it could have been designed to bolt onto the outside of the pressure vessel
13 Reducing nesting of parts and modules				n	n	Nesting of the stripper rubber is required to some extent
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	Connections between pressure systems is standard NPT	y	y	Connections between pressure systems is standard NPT
15 Reducing the number of fasteners used, or eliminating them entirely				n	n	Due to the high loads, fasteners are required and repetition is used
16 Reducing the number of contact points between modules	y	y	The contact between the pressure circuit and the pressure vessel is one flexible hose	y	y	The contact between the pressure circuit and the pressure vessel is one flexible hose; and the PV attaches to the structure along a single plane
17 Simplifying the geometry of modular interfaces				y	y	the bolt pattern is simple and on a single plane

18 Routing flows of energy, information and materials so that they are able to bypass each module at need	y	y	The hose goes directly to the pressure vessel			
19 Creating detachable modules	y	y	The sight glasses are detachable so blanks could be put in their place	y	y	The pressure vessel is not welded to the structure
20 Using a framework for mounting multiple modules	y	y	The framework structure provides opportunity to attach a transfer barrier accumulator	y	y	The wide flange beam provides a simple framework
21 Using compliant materials	y	y	The hose between the pv ad pressure circuit is flexible, so it can be easily moved to go to the transfer-barrier accumulator	y	y	The hose between the pv ad pressure circuit is flexible, so it can easily adjust if the PV changes
22 Simplifying the geometry of each component						
Adjustability						
23 Controlling the tuning of design parameters						
24 Providing the capability for excess energy storage or importation						

Table C.3.3: Scaled seal testing system: Use of Guideline Report (Part 3 of 5)

	Used	Helpful	Change Mode 7: Increase Scaling Factor of Stripper Rubber	Used	Helpful	Change Mode 8: Change of Environment (Run tests outside)
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	The linear motion system is a separate module	n	y	The conversion transmission functions are tightly tied in the lma module
2 Confining functions to single modules	n	n	The PV holds pressure but also provides heat and allows the drill pipe to pass thru and supports the loading of the stripper rubber	n	n	Due to the loads involved, the function of reacting the force must be done by all modules
3 Confining functions to as few unique components as possible				y	y	The LMA's are symmetric, the motors are the same, the two sides of the carriage are the same
4 Dividing modules into multiple smaller, identical modules	n	y	If hydraulics were used, multiple small rams could be used together. Use multiple track sections to increase length	n	y	If hydraulics were used, multiple small rams could be used together
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	The pressure circuit is separate from the PV and connects only by a flexible hose	y	y	The lma has always been expected to change and it is a separate module
6 Collecting parts which perform functions associated with the same energy domain into separate modules	y	y	All of the pressure components are in separate modules from the rest of the system; the linear motion modules are separate modules	y	y	The creation of force is all performed by the lma module
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related						

8 Using duplicate parts as much as possible without raising part count	y	y	The PV is symmetric so the flanges on each end are the same and many of the ports are the same; The linear motion systems are mirrored	y	y	Where possible, duplicate parts were used, such as carriage sides
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	The size of the stripper rubber does not have room to expand but the linear motion systems and pressure vessel do.	y	y	There is open space around almost all of the modules
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	The top of the pvs has available space for a new pressure vessel to attach	y	y	Using the wide flange beam creates a vast surface for interfaces, whereas the previous consultants design was very limited to the ball screw
11 Extending the available area on the transmission components of the device	n	y	Using the ball screws constrained the available area on the transmission of the device			
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	The linear motion systems are on the exterior	y	y	The lma is on top of the device
13 Reducing nesting of parts and modules	y	y	Many of the parts are unconstrained by interface with other parts	y	y	The linear motion system is not nested
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	Connections between modules were kept simple and at a minimum	y	y	The esw bolts onto the pvs with few bolts
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Due to the high loads, fasteners are required and repetition is used			

16 Reducing the number of contact points between modules	y	y	The contact between the pressure circuit and the pressure vessel is one flexible hose; and the PV attaches to the structure along a single plane; LMS connect on single plane	y	y	The bolt plate is the only contact point between the linear motion module and pv module
17 Simplifying the geometry of modular interfaces	y	y	the bolt patterns are simple and on single planes	y	y	The bolt plate is a very simple interface
18 Routing flows of energy, information and materials so that they are able to bypass each module at need						
19 Creating detachable modules	y	y	The pressure vessel is not welded to the structure; linear motion systems are on detachable structures	y	y	All of the modules are detachable by unbolting joining surfaces
20 Using a framework for mounting multiple modules	y	y	The wide flange beam provides a simple framework	y	y	The wide flange beam support structure acts as a skeletal framework that all modules attach to.
21 Using compliant materials	y	y	The hose between the pv ad pressure circuit is flexible, so it can easily adjust if the PV changes			
22 Simplifying the geometry of each component	y	y	Parts were designed to be manufactured from raw material easily	y	y	Since machining is the main form of manufacturing for these components, many of them are square. When possible, parts were designed as single extrusions so that water jetting could be used.
Adjustability						
23 Controlling the tuning of design parameters	y	y	shims are used and bolt holes oversized to offer alignment to tolerance stack up.	y	y	Bolt holes were oversized to allow adjustment during setup

24 Providing the capability for excess energy storage or importation	y	y	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses. Pressure is adjustable through the pressure circuit.	y	y	The wide flange beam selected was designed to keep deflection within the allowable range for the ball screws. If a different prime mover is used that doesn't have as tight of tolerance, the wide flange beam will likely be able to handle the increased stresses

Table C.3.4: Scaled seal testing system: Module Change Report (Part 4 of 5)

	Used	Helpful	Change Mode 9: Quicker Test Setup	Used	Helpful	Change Mode 10: Decrease Scaling Factor
Modularity						
1 Using separate modules to carry out functions that are not closely related						
2 Confining functions to single modules				y	y	The function of positioning the stripper rubber is performed by a single part
3 Confining functions to as few unique components as possible	y	y	The two ends of the PV are similar			
4 Dividing modules into multiple smaller, identical modules						
5 Collecting parts which are not anticipated to change in time into separate modules						
6 Collecting parts which perform functions associated with the same energy domain into separate modules						
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related						
8 Using duplicate parts as much as possible without raising part count	y	y	The two ends of the PV are similar			
Spatial						

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	There is room around the PV for a new flange system to be designed	y	y	There is some room for the positioning shim to change shape
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	n	y	There is not a good place to mount a flange hinge			
11 Extending the available area on the transmission components of the device						
12 Locating those parts which are anticipated to change near the exterior of the device						
13 Reducing nesting of parts and modules	n	n	The stripper rubber position requires nesting of parts			
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	n	y	The main flanges require many bolts, however, the shim attaches by a single acme thread	y	y	The positioning shim attaches using an acme thread so no extra fasteners are required
15 Reducing the number of fasteners used, or eliminating them entirely						
16 Reducing the number of contact points between modules	y	y	Contact is on simple planes	y	y	The positioning shim only attaches to the end flange; the drill pipe coupler only contacts the load cell
17 Simplifying the geometry of modular interfaces	n	n	Seals require specific geometry	n	n	The acme thread is more complex than a bolt pattern

18 Routing flows of energy, information and materials so that they are able to bypass each module at need						
19 Creating detachable modules	y	y	flanges are detachable	y	y	The positioning shim is a detachable module
20 Using a framework for mounting multiple modules						
21 Using compliant materials						
22 Simplifying the geometry of each component						
Adjustability						
23 Controlling the tuning of design parameters						
24 Providing the capability for excess energy storage or importation						

Table C.3.5: Scaled seal testing system: Use of Guidelines Report (Part 5 of 5)

Change Mode		Evolution Response	Readiness
1	Increase pipe stroke length	Add additional hydraulic sections as necessary and add support frame modules to existing frame	New vendors must be sought to locate the hydraulic rams. Support frame must be lengthened as necessary
2	Increase number of tool joints	Pipe joints are simply added to the single piece, grooved drill pipe	The new parts can be manufactured in-house.
3	Increase field of view	No longer necessary because the proposed redesign has a large field of view	No change necessary
4	Increase pipe speed through seal	Individual hydraulic sections are replaced as necessary with ones that have higher speed capability	New vendors must be sought to supply hydraulic components and control systems.
5	Use drilling mud instead of water	Vision system could no longer be used and therefore sight-glass flanges are not needed. Transfer barrier accumulator would need to be mounted onto PV Support Weldment. Current hose from pressure circuit would attach to transfer barrier accumulator.	Pressure circuit mounting plate would need to be modified. This could be done by the in-house machinist.

Table C.4.1: Scaled seal testing system redesign: Evolution Response Table (Part 1 of 2)

6	Increase stripper rubber size for static calibration	An enlarged pressure vessel could accommodate larger stripper rubbers. Only the shims would need to be replaced	Current vendor can provide the necessary shims.
7	Increase scaling factor	The oversized pressure vessel can accommodate larger seals. Hydraulic ram sections are added / replaced as necessary to provide necessary speed / stroke length.	Current hydraulic ram vendor can provide the necessary rams as needed. Current frame manufacturer can provide additional frame sections.
8	Change test environment	The motors and ball screws used on the current system are not suitable for outdoor use. Therefore a new linear motion system module must be designed that uses hydraulic cylinders. The control and data acquisition system must either be redesigned using more rugged components or changed so that it can be operated remotely.	New vendors must be sought to supply hydraulic components and control systems. Although the frame must be redesigned, the current vendor can accommodate the changes.
9	Quicker test setup	Additional attachment area on the pressure vessel flanges is used to implement a hinged flange with a cam lock system.	Pressure vessel flanges will need to be redesigned with hinges and cam lock. Current vendor can perform this task with little effort.
10	Decrease scaling factor	If the scaling is found to be accurate at smaller scales the current system design could be used with very small modification. A decrease in scaling factor would also effectively lengthen the stroke since pipe length scales with the stripper rubber diameter.	Drill pipes and stripper rubber support shims would need to be redesigned for smaller seals. All changes can be performed using in-house capabilities.

Table C.4.2: Scaled seal testing system redesign: Evolution Response Table (Part 2 of 2)

Module	Change Mode 1: Longer Stroke	Change Mode 2: Increase Number of Tool Joints
Extension Support Weldment (ESW)	Change	Same
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Same	Same
Linear Motion Assembly (LMA)	Change	Same
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Change	Same
Vision System (VS)	Same	Same
Baffle Containment System (BC)	Same	Same
Change Effect	Add additional hydraulic sections as necessary and add support frame modules to existing frame	Pipe joints are simply added to the single piece, grooved drill pipe

Table C.5.1: Scaled seal testing system redesign: Module Change Report (Part 1 of 5)

Module	Change Mode 3: Increase Field of View	Change Mode 4: Increase Drill Pipe Speed
Extension Support Weldment (ESW)	Same	Same
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Same	Same
Linear Motion Assembly (LMA)	Same	Change
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Same	Same
Vision System (VS)	Same	Same
Baffle Containment System (BC)	Same	Same
Change Effect	No longer necessary because the proposed redesign has a large field of view	Individual hydraulic sections are replaced as necessary with ones that have higher speed capability

Table C.5.2: Scaled seal testing system redesign: Module Change Report (Part 2 of 5)

Module	Change Mode 5: Use Drilling Mud instead of Water	Change Mode 6: Increase Stripper Rubber Size for Static Calibration
Extension Support Weldment (ESW)	Same	Same
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Change	Change
Linear Motion Assembly (LMA)	Same	Same
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Change	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Same	Change
Vision System (VS)	Same	Change
Baffle Containment System (BC)	Remove	Same
Change Effect	Vision system could no longer be used and therefore sight-glass flanges are not needed. Transfer barrier accumulator would need to be mounted onto PV Support Weldment. Current hose from pressure circuit would attach to transfer barrier accumulator.	An enlarged pressure vessel could accommodate larger stripper rubbers. Only the shims would need to be replaced

Table C.5.3: Scaled seal testing system: Module Change Report (Part 3 of 5)

Module	Change Mode 7: Increase Scaling Factor of Stripper Rubber	Change Mode 8: Change of Environment (Run tests outside)
Extension Support Weldment (ESW)	Change	Change
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Same	Same
Linear Motion Assembly (LMA)	Change	Remove
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Change
Drill Pipe Assembly (DPA)	Change	Same
Vision System (VS)	Change	Same
Baffle Containment System (BC)	Same	Same
Change Effect	The oversized pressure vessel can accommodate larger seals. Hydraulic ram sections are added / replaced as necessary to provide necessary speed / stroke length.	The motors and ball screws used on the current system are not suitable for outdoor use. Therefore a new linear motion system module must be designed that uses hydraulic cylinders. The control and data acquisition system must either be redesigned using more rugged components or changed so that it can be operated remotely.

Table C.5.4: Scaled seal testing system: Module Change Report (Part 4 of 5)

Module	Change Mode 9: Quicker Test Setup	Change Mode 10: Decrease Scaling Factor
Extension Support Weldment (ESW)	Same	Same
PV Support Weldment (PVS)	Same	Same
Pressure Vessel (PV)	Change	Change
Linear Motion Assembly (LMA)	Same	Same
Temperature Control System (TCS)	Same	Same
Pressure Circuit Assembly (PCA)	Same	Same
Data Acquisition and Control Group (DAQ)	Same	Same
Computer (Comp)	Same	Same
Cabinet (Cab)	Same	Same
Drill Pipe Assembly (DPA)	Same	Change
Vision System (VS)	Same	Same
Baffle Containment System (BC)	Same	Same
Change Effect	Additional attachment area on the pressure vessel flanges is used to implement a hinged flange with a cam lock system.	If the scaling is found to be accurate at smaller scales the current system design could be used with very small modification. A decrease in scaling factor would also effectively lengthen the stroke since pipe length scales with the stripper rubber diameter.

Table C.5.5: Scaled seal testing system: Module Change Report (Part 5 of 5)

Item	-	Sub#	Module	Part name	CM 1	Readiness
1	-	1	ESW	Stripper Test Bed, Extension Support Beam.ipt		
1	-	2	ESW	Stripper Test Bed, Extension Leg Gusset.ipt	N	3
1	-	3	ESW	Stripper Test Bed, Rail Mount Bar.ipt	N	1
1	-	4	ESW	Stripper Test Bed, Foot.ipt		
1	-	5	ESW	Stripper Test Bed, Anchor.ipt		
1	-	6	ESW	Stripper Test Bed, Bolt Plate.ipt	N	3
1	-	7	ESW	Stripper Test Bed, Extension Beam Gusset.ipt	N	1
1	-	8	ESW	Stripper Test Bed, Pillow Block Mount Plate.ipt	N	
1	-	9	ESW	Leveling Foot.ipt		
1	-	10	ESW	3_4-2.5-UNC.ipt ESW to PVS Module attachment		
2	-	1	PVS	Stripper Test Bed, PV Support Gusset Top Cap.ipt		
2	-	2	PVS	Stripper Test Bed, Anchor.ipt		
2	-	3	PVS	Stripper Test Bed, Bolt Plate.ipt		
2	-	4	PVS	Stripper Test Bed, Foot.ipt		
2	-	5	PVS	Stripper Test Bed, PV Support Beam.ipt		
2	-	6	PVS	Stripper Test Bed, PV Support Gusset.ipt		
2	-	7	PVS	Stripper Test Bed, PV Support Gusset Side Cap.ipt		
3	-	1.1	PV	Stripper Test Vessel Integral Flange, Rough Machine.ipt		
3	-	1.2	PV	Stripper Test Vessel, Tube.ipt		
3	-	1.3	PV	Test Port 1-2 NPT.ipt		
3	-	1.4	PV	Stripper Test Vessel Sight Glass Weld Flange.ipt		
3	-	2.1	PV	Saddle Plate.ipt		
3	-	2.2	PV	Saddle Side Plate.ipt		
3	-	2.3	PV	Saddle Mid Gusset.ipt		
3	-	2.4	PV	Saddle Mount Plt.ipt		
3	-	2.5	PV	Saddle Tie Plate.ipt		
3	-	3	PV	STUD, 1.375-6 UNC X 8.00.ipt		
3	-	4	PV	1 3_8-UNC.ipt Modified flange nuts		
3	-	5	PV	STUD, 1.125-7 UNC X 8.00.ipt		
3	-	6	PV	1 1_8-UNC.ipt Sight glass flange nuts		
3	-	7	PV	O-RING_AS568A-443.ipt		
3	-	8	PV	Stripper Test Vessel Sight Glass Flange.ipt		
3	-	9	PV	Stripper Test Vessel Blind Flange, Modified.ipt		
3	-	10	PV	Stripper Test Vessel Shim.ipt		
3	-	11	PV	O-RING_AS568A-242.ipt		
3	-	12	PV	Stripper Test Vessel Shim, Short.ipt		
3	-	13	PV	Omega-thermowell.ipt		
3	-	14	PV	Pressure Vessel Spacer.ipt		
3	-	15	PV	1_2-UNC.ipt PV attachment nuts		
3	-	16	PV	1_2-2.5-UNC.ipt PV attachment bolts		

3	-	17	PV	3_8-1-UNC.ipt		
3	-	18	PV	Stripper Test Vessel, Sight Glass.ipt		
3	-	19	PV	O-RING_AS568A-339.ipt		
3	-	20	PV	NPT x NPT Male Union, .750.ipt		
4	-	1.1	LMA	Stripper Test Bed, Rail.ipt	N	
4	-	1.2	LMA	Rail Cover Strip	N	
4	-	1.3	LMA	Rail End Cap	N	
4	-	1.4	LMA	Stripper Test Bed, Runner Block.ipt	N	
4	-	1.5	LMA	1_2-1.5-UNC.ipt Guide rail screws		
4	-	1.6	LMA	M12-30.ipt Runner block attachment screws		
4	-	2.1	LMA	Stripper Test Bed, Carriage Base.ipt	N	
4	-	2.2	LMA	Stripper Test Bed, Carriage Center Block.ipt	N	
4	-	2.3	LMA	Stripper Test Bed, Carriage Side Plate.ipt	N	
4	-	2.4	LMA	1-A-2.ipt 1" Washer		
4	-	2.5	LMA	1-5-UNF.ipt Bolt between carriage block and load cell		
4	-	2.6	LMA	3_4-1.5-UNC.ipt Carriage block screws		
4	-	2.7	LMA	1_2-1.5-UNC.ipt Carriage base screws		
4	-	2.8	LMA	0.5-B-1.ipt Half inch Washer		
4	-	2.9	LMA	0.75-A-1.469.ipt 3/4" Washer		
4	-	3	LMA	Stripper test bed, hydraulic ram	N	
4	-	4	LMA	Stripper Test Bed, Load Cell.ipt		
5	-	1	TCS	Temperature Controller		
5	-	2	TCS	Set Point Transmission Wire		
5	-	3	TCS	Current Temp Retransmit Wire		
5	-	4	TCS	SS Relay		
5	-	5	TCS	SS Relay Control Wire		
5	-	6	TCS	Terminal Block		
5	-	7	TCS	SS Relay Box		
5	-	8	TCS	Box Mounting Braces		
5	-	9	TCS	Mounting Clamps		
5	-	10	TCS	Plug Heater.ipt		
6	-	1	PCA	Accumulator		
6	-	2	PCA	AutoClave Fitting		
6	-	3	PCA	Check Valve		
6	-	4	PCA	1/2" Cross Fitting		
6	-	5	PCA	Male 1/2" to Female 1/4" NPT Adapter		
6	-	6	PCA	High Pressure Relief Valve		
6	-	7	PCA	1/2" Tee Fitting		
6	-	8	PCA	3/4" Cross		
6	-	9	PCA	1/2" Ball Valve		
6	-	10	PCA	Male 3/4" to Female 1/2" NPT Adapter		
6	-	11	PCA	Male 1-1/4" to Female 3/4" NPT Adapter		
6	-	12	PCA	Male 3/4" to Male 3/4" NPT Adapter		
6	-	13	PCA	3/4" Elbow Fitting		
6	-	14	PCA	Pressure Circuit Mounting Plate		

6	-	15	PCA	Large Mounting Brackets		
6	-	16	PCA	Small Mounting Brackets		
6	-	17	PCA	3/4" High Pressure Hose - 3ft		
6	-	18	PCA	1/2" High Pressure Tubing		
6	-	19	PCA	1/2" Tube Fittings		
6	-	20	PCA	Mounting Bolts for Plate		
6	-	21	PCA	Mounting Nuts		
6	-	22	PCA	Mounting Washers		
6	-	23	PCA	1/2" Bleed Valve		
6	-	24	PCA	Male 3/4" to 1/2" NPT Adapter		
6	-	25	PCA	High Pressure Pump		
6	-	26	PCA	High Pressure Autoclave Hose		
6	-	27	PCA	Instant Water Heater		
6	-	28	PCA	Supply Hose		
6	-	29	PCA	Drain Hose		
7	-	1	DAQ	Pressure Transducer		
7	-	2	DAQ	Thermocouple (ungrounded)		
7	-	3	DAQ	J-type mini connectors		
7	-	4	DAQ	Load Cell Connectors		
7	-	5	DAQ	100ft Spool of Load Cell Cable		
7	-	6	DAQ	LabView Full Dev System		
7	-	7	DAQ	NI PCI-6221, M series DAQ		
7	-	8	DAQ	SCC-68 I/O Connector Block		
7	-	9	DAQ	SCC68-68 Cable		
7	-	10	DAQ	SCC-SG24 2-Channel Full Bridge 10V Excitation		
7	-	11	DAQ	NI PCI-6514 Digital I/O		
7	-	12	DAQ	CB-100 I/O Kit		
7	-	13	DAQ	NI PCI-1426 Camera Card w/ IMAQ		
7	-	14	DAQ	RTSI Bus Cable		
8	-	1	Comp	Mid-Tower CPU		
8	-	2	Comp	Monitor		
8	-	3	Comp	Keyboard		
8	-	4	Comp	Mouse		
9	-	1	Cab	Cabinet		
9	-	2	Cab	24V Power Supplies		
9	-	3	Cab	24V Fans		
9	-	4	Cab	Power Strip		
9	-	5	Cab	Miscellaneous Wire and Connectors		
10	-	1	DPA	1-UNC.ipt DP Coupler Nut		
10	-	2	DPA	DP - Single piece grooved with tool joint attachments	N	2
10		3	DPA	3_8-UNC.ipt Coupling pin nut		
10		4	DPA	3_8-3-UNC.ipt coupling pin		
10	-	5	DPA	DP-ToolJoint-01.ipt		
11	-	1	VS	Monochrome Camera 120 fps		
11	-	2	VS	Zoom Lens		

11	-	3	VS	Power Supply		
11	-	4	VS	CameraLink Cable 5m		
12	-	1.1	BC	Rubber Wiper Casing.ipt		
12	-	1.2	BC	Casing Tab Plate.ipt		
12	-	1.3	BC	Casing Bolting Ring.ipt		
12	-	1.4	BC	Casing Stop Ring.ipt		
12	-	2	BC	Rubber Wiper Spacer.ipt		
12	-	3	BC	Rubber Wiper End Plate.ipt		
12	-	4	BC	Rubber Wiper.ipt		
12	-	5	BC	Clamp Plate.ipt		
12	-	6	BC	Rubber Wiper Brace Bar.ipt		
12	-	7	BC	Water Gutter		
12	-	8	BC	Water Catch Bin		
12	-	9	BC	1_2-1-UNC.ipt Containment Casing centering screws		
12	-	10	BC	1_2-3.5-UNC.ipt Containment System Attachment Bolts		
12	-	11	BC	1_2-3-UNC.ipt Containment System Attachment bolts		
12	-	12	BC	1_2-UNC.ipt Containment System attachment nuts		
13	-	1	SSR	Scaled Stripper Rubber.ipt		
13	-	2	SSR	Scaled Mold, Stripper Insert.ipt		
				Number of Non-Reusable Parts	14	
				Percentage of Non-Reusable Parts (120 total)	88%	
				Flexibility Rating	2	
				Average Readiness Rating		2

Table C.6.1: Scaled seal testing system redesign: Reusability Matrix (Part 1 of 3)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness	CM 5	Readiness	CM 6	Readiness	CM 7	Readiness
1	-	1	ESW					N	3						
1	-	2	ESW					N	3					N	3
1	-	3	ESW											N	3
1	-	4	ESW												
1	-	5	ESW												
1	-	6	ESW											N	3
1	-	7	ESW												
1	-	8	ESW					N						N	3
1	-	9	ESW												
1	-	10	ESW												
2	-	1	PVS												
2	-	2	PVS												
2	-	3	PVS												
2	-	4	PVS												
2	-	5	PVS												
2	-	6	PVS												
2	-	7	PVS												
3	-	1.1	PV			N	6					N	6		
3	-	1.2	PV			N	6			N	3	N	6		
3	-	1.3	PV												
3	-	1.4	PV			N	6			N		N	6		
3	-	2.1	PV			N	6					N	6		
3	-	2.2	PV			N	6					N	6		
3	-	2.3	PV			N	6					N	6		
3	-	2.4	PV			N	6					N	6		
3	-	2.5	PV			N	6					N	6		
3	-	3	PV												
3	-	4	PV												
3	-	5	PV												
3	-	6	PV												
3	-	7	PV			N	2					N	2		
3	-	8	PV							N					
3	-	9	PV									N	6		
3	-	10	PV									N	6		
3	-	11	PV									N	2		
3	-	12	PV	N	1							N	6		
3	-	13	PV												
3	-	14	PV												
3	-	15	PV												
3	-	16	PV												

3 - 17	PV												
3 - 18	PV							N					
3 - 19	PV							N					
3 - 20	PV												
4 - 1.1	LMA											N	
4 - 1.2	LMA											N	
4 - 1.3	LMA											N	
4 - 1.4	LMA											N	
4 - 1.5	LMA												
4 - 1.6	LMA												
4 - 2.1	LMA											N	
4 - 2.2	LMA					N	2					N	
4 - 2.3	LMA											N	
4 - 2.4	LMA												
4 - 2.5	LMA												
4 - 2.6	LMA												
4 - 2.7	LMA												
4 - 2.8	LMA												
4 - 2.9	LMA												
4 - 3	LMA					N						N	
4 - 4	LMA											N	1
5 - 1	TCS												
5 - 2	TCS												
5 - 3	TCS												
5 - 4	TCS												
5 - 5	TCS												
5 - 6	TCS												
5 - 7	TCS												
5 - 8	TCS												
5 - 9	TCS												
5 - 10	TCS												
6 - 1	PCA												
6 - 2	PCA												
6 - 3	PCA												
6 - 4	PCA												
6 - 5	PCA												
6 - 6	PCA												
6 - 7	PCA												
6 - 8	PCA												
6 - 9	PCA												
6 - 10	PCA												
6 - 11	PCA												
6 - 12	PCA												
6 - 13	PCA												
6 - 14	PCA							N	2				

6	-	15	PCA												
6	-	16	PCA												
6	-	17	PCA												
6	-	18	PCA												
6	-	19	PCA												
6	-	20	PCA												
6	-	21	PCA												
6	-	22	PCA												
6	-	23	PCA							N	3				
6	-	24	PCA												
6	-	25	PCA												
6	-	26	PCA												
6	-	27	PCA							N					
6	-	28	PCA												
6	-	29	PCA												
7	-	1	DAQ												
7	-	2	DAQ												
7	-	3	DAQ												
7	-	4	DAQ												
7	-	5	DAQ												
7	-	6	DAQ												
7	-	7	DAQ												
7	-	8	DAQ												
7	-	9	DAQ												
7	-	10	DAQ												
7	-	11	DAQ												
7	-	12	DAQ												
7	-	13	DAQ							N					
7	-	14	DAQ												
8	-	1	Comp												
8	-	2	Comp												
8	-	3	Comp												
8	-	4	Comp												
9	-	1	Cab												
9	-	2	Cab												
9	-	3	Cab												
9	-	4	Cab												
9	-	5	Cab												
10	-	1	DPA												
10	-	2	DPA	N	2									N	
10		3	DPA												
10		4	DPA												
10	-	5	DPA											N	
11	-	1	VS							N					
11	-	2	VS							N					

11	-	3	VS							N					
11	-	4	VS							N					
12	-	1.1	BC			N	3					N	3	N	3
12	-	1.2	BC			N	3					N	3	N	3
12	-	1.3	BC			N	3					N	3	N	3
12	-	1.4	BC			N	3					N	3	N	3
12	-	2	BC			N	3					N	3	N	3
12	-	3	BC			N	3					N	3	N	3
12	-	4	BC			N	1					N	1	N	1
12	-	5	BC			N	3					N	3	N	3
12	-	6	BC			N	1					N	1	N	1
12	-	7	BC												
12	-	8	BC												
12	-	9	BC												
12	-	10	BC												
12	-	11	BC												
12	-	12	BC												
13	-	1	SSR												
13	-	2	SSR												
				2		18		5		13		22		24	
				98%		85%		96%		89%		82%		80%	
				1		2		1		1		2		2	
					1.5		4.06		2.67		2.67		4.23		2.57

Table C.6.2: Scaled seal testing system redesign: Reusability Matrix (Part 2 of 3)

Item	-	Sub#	Module	CM 8	Readiness	CM 9	Readiness	CM10	Readiness
1	-	1	ESW	N	3				
1	-	2	ESW	N	3				
1	-	3	ESW						
1	-	4	ESW						
1	-	5	ESW						
1	-	6	ESW	N	3				
1	-	7	ESW						
1	-	8	ESW						
1	-	9	ESW						
1	-	10	ESW						
2	-	1	PVS						
2	-	2	PVS						
2	-	3	PVS						
2	-	4	PVS						
2	-	5	PVS						
2	-	6	PVS						
2	-	7	PVS						
3	-	1.1	PV			N	5		
3	-	1.2	PV						
3	-	1.3	PV						
3	-	1.4	PV						
3	-	2.1	PV						
3	-	2.2	PV						
3	-	2.3	PV						
3	-	2.4	PV						
3	-	2.5	PV						
3	-	3	PV						
3	-	4	PV						
3	-	5	PV						
3	-	6	PV						
3	-	7	PV						
3	-	8	PV						
3	-	9	PV			N	3		
3	-	10	PV			N	3	N	2
3	-	11	PV						
3	-	12	PV			N	3	N	2
3	-	13	PV						
3	-	14	PV						
3	-	15	PV						
3	-	16	PV						

3	-	17	PV						
3	-	18	PV						
3	-	19	PV						
3	-	20	PV						
4	-	1.1	LMA	N					
4	-	1.2	LMA	N					
4	-	1.3	LMA	N					
4	-	1.4	LMA	N					
4	-	1.5	LMA						
4	-	1.6	LMA						
4	-	2.1	LMA						
4	-	2.2	LMA	N	2				
4	-	2.3	LMA						
4	-	2.4	LMA						
4	-	2.5	LMA						
4	-	2.6	LMA						
4	-	2.7	LMA						
4	-	2.8	LMA						
4	-	2.9	LMA						
4	-	3	LMA	N					
4	-	4	LMA						
5	-	1	TCS						
5	-	2	TCS						
5	-	3	TCS						
5	-	4	TCS						
5	-	5	TCS						
5	-	6	TCS						
5	-	7	TCS						
5	-	8	TCS						
5	-	9	TCS						
5	-	10	TCS						
6	-	1	PCA						
6	-	2	PCA						
6	-	3	PCA						
6	-	4	PCA						
6	-	5	PCA						
6	-	6	PCA						
6	-	7	PCA						
6	-	8	PCA						
6	-	9	PCA						
6	-	10	PCA						
6	-	11	PCA						
6	-	12	PCA						
6	-	13	PCA						
6	-	14	PCA						

6	-	15	PCA						
6	-	16	PCA						
6	-	17	PCA						
6	-	18	PCA						
6	-	19	PCA						
6	-	20	PCA						
6	-	21	PCA						
6	-	22	PCA						
6	-	23	PCA						
6	-	24	PCA						
6	-	25	PCA						
6	-	26	PCA						
6	-	27	PCA						
6	-	28	PCA						
6	-	29	PCA						
7	-	1	DAQ						
7	-	2	DAQ						
7	-	3	DAQ						
7	-	4	DAQ						
7	-	5	DAQ						
7	-	6	DAQ						
7	-	7	DAQ						
7	-	8	DAQ						
7	-	9	DAQ						
7	-	10	DAQ						
7	-	11	DAQ						
7	-	12	DAQ						
7	-	13	DAQ						
7	-	14	DAQ						
8	-	1	Comp						
8	-	2	Comp	N	4				
8	-	3	Comp						
8	-	4	Comp						
9	-	1	Cab	N	4				
9	-	2	Cab						
9	-	3	Cab						
9	-	4	Cab						
9	-	5	Cab						
10	-	1	DPA						
10	-	2	DPA					N	2
10		3	DPA						
10		4	DPA						
10	-	5	DPA					N	2
11	-	1	VS						
11	-	2	VS						

11	-	3	VS						
11	-	4	VS						
12	-	1.1	BC			N	3		
12	-	1.2	BC			N	3		
12	-	1.3	BC			N	3		
12	-	1.4	BC			N	3		
12	-	2	BC						
12	-	3	BC						
12	-	4	BC						
12	-	5	BC			N	3		
12	-	6	BC						
12	-	7	BC						
12	-	8	BC						
12	-	9	BC						
12	-	10	BC						
12	-	11	BC						
12	-	12	BC						
13	-	1	SSR						
13	-	2	SSR						
				11		9		4	
				91%		93%		97%	
				1		1		1	
					3.17		3.22		2

Table C.6.3: Scaled seal testing system: Reusability Matrix (Part 3 of 3)

Appendix D: Gas-Pressure Blow-Forming System Evolvability Analysis

Module	Change Mode 1: Increase strain measurement range	Change Mode 2: Increase specimen diameter
Main Assembly (MA)	Same	Change
Bottom Sub Assembly (BSA)	Change	Same
Load, Furnace, Gas System (LFG)	Same	Change
Change Effect	A longer range micrometer must be integrated into the bottom subassembly. The entire bottom sub assembly must be lengthened to house the new micrometer.	Larger die-holders and dies must be machined. A larger furnace is necessary to enclose the larger components.

Table D.1.1: Gas-pressure blow-forming: Module Change Report (Part 1 of 2)

Module	Change Mode 3: Add a vision system inside the pressure chamber	Change Mode 4: Compensate for thermal expansion automatically
Main Assembly (MA)	Change	Same
Bottom Sub Assembly (BSA)	Same	Same
Load, Furnace, Gas System (LFG)	Same	Change
Change Effect	Holes must be drilled in the bottom column for fiber optic cables. Cameras must not interfere with strain measurement rod.	Feedback control loop must be integrated with the load cell and hydraulic ram so that constant pressure is applied to specimen as columns heat up and expand.

Table D.1.2: Gas-pressure blow-forming: Module Change Report (Part 2 of 2)

Item	-	Sub#	Module	Part Name	CM 1	Readiness
1	-	1	MA	Load cell thread adapter		
1	-	2	MA	Heat exchanger		
1	-	3	MA	Heat exchanger quick disconnect		
1	-	4	MA	Loading column pipe		
1	-	5	MA	Die-Holder		
1	-	6	MA	Top die-ring		
1	-	7	MA	Bottom die-ring		
1	-	8	MA	Alignment pins		
1	-	9	MA	Top loading column pipe 1/4" OD, 0.035" wall		
1	-	10	MA	Male connector 1/4" OD, 1/4" NPT		
1	-	11	MA	Union 90 deg elbow		
1	-	12	MA	Gas transfer pipe, 316 SS, 1/4" OD, 0.035" wall		
1	-	13	MA	Ball valve with Yor-Lok, 3-way, 1/4" tube OD		
2	-	1	BSA	Measuring rod tip		
2	-	2	BSA	Measuring rod	N	1
2	-	3	BSA	Top plate, bottom sub assembly		
2	-	4	BSA	Side plate, bottom sub assembly	N	1
2	-	5	BSA	Lock nut for bottom heat exchanger		
2	-	6	BSA	Bottom plate, bottom sub assembly		
2	-	7	BSA	Sliding rail holder	N	2
2	-	8	BSA	Pulley holder		
2	-	9	BSA	Nylon pulley bearing mounted		
2	-	10	BSA	Brass counter weights, m = 154g	N	2
2	-	11	BSA	Measuring rod holder	N	2
2	-	12	BSA	Sliding rail	N	2
2	-	13	BSA	2.0 inch bolt		
2	-	14	BSA	Micrometer	N	3
2	-	15	BSA	Column	N	2
2	-	16	BSA	Micrometer mount	N	2
2	-	17	BSA	Measuring rod, low end		

Table D.2.1: Gas-pressure blow-forming: Reusability Matrix (Part 1 of 4)

3	-	1	LFG	MTS Servo Hydraulic Unit		
3	-	2	LFG	Load Cell		
3	-	3	LFG	ATS 3210 Furnace		
3		4	LFG	Furnace mounting clamps		
3		5	LFG	Furnace mounting pole		
3	-	6	LFG	Gas bottle		
3	-	7	LFG	Gas regulator		
				Number of Non-Reusable Parts	9	
				Percentage of Non-Reusable Parts (36 total)	75%	
				Flexibility Rating	3	
				Average Readiness Rating		1.89

Table D.2.2: Gas-pressure blow-forming: Reusability Matrix (Part 2 of 4)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness
1	-	1	MA	N	3				
1	-	2	MA	N	2	N	4		
1	-	3	MA			N	3		
1	-	4	MA	N	2	N	2		
1	-	5	MA	N	2				
1	-	6	MA	N	2				
1	-	7	MA	N	2				
1	-	8	MA						
1	-	9	MA						
1	-	10	MA						
1	-	11	MA						
1	-	12	MA						
1	-	13	MA						
2	-	1	BSA						
2	-	2	BSA						
2	-	3	BSA						
2	-	4	BSA						
2	-	5	BSA						
2	-	6	BSA						
2	-	7	BSA						
2	-	8	BSA						
2	-	9	BSA						
2	-	10	BSA						
2	-	11	BSA						
2	-	12	BSA						
2	-	13	BSA						
2	-	14	BSA						
2	-	15	BSA						
2	-	16	BSA						
2	-	17	BSA						

Table D.2.3: Gas-pressure blow-forming: Reusability Matrix (Part 3 of 4)

3	-	1	LFG					N	2
3	-	2	LFG					N	2
3	-	3	LFG	N	6				
3		4	LFG	N	2				
3		5	LFG	N	2				
3	-	6	LFG						
3	-	7	LFG						
				9		3		2	
				75%		92%		94%	
				3		1		1	
					2.56		3		2

Table D.2.4: Gas-pressure blow-forming: Reusability Matrix (Part 4 of 4)

	Used	Helpful	Change Mode 1: Increase strain measurement range	Used	Helpful	Change Mode 2: Increase specimen diameter
Modularity						
1 Using separate modules to carry out functions that are not closely related	n	n	All functions in this module are closely related.	y	y	Heating and holding modules are separate.
2 Confining functions to single modules	n	y	Micrometer could have been made a separate module from the strain measurement rod and bottom assembly	n	n	Not helpful due to the limited number of modules involved.
3 Confining functions to as few unique components as possible	y	y	Counter weights, side panels, and support columns are duplicate parts.	y	y	Several duplicate components reduce the redesign effort.
4 Dividing modules into multiple smaller, identical modules	n	n	Not relevant	n	n	Not relevant
5 Collecting parts which are not anticipated to change in time into separate modules	n	n	Not helpful	y	y	Furnace is not anticipated to change, and is divided into a separate module.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant	n	n	Not relevant
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	n	n	Not relevant	n	y	Die and die holder could be combined.

8 Using duplicate parts as much as possible without raising part count	y	y	Counter weights, side panels, and support columns are duplicate parts.	y	y	Columns, die holders, and heat exchangers are duplicated.
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	n	y	Bottom sub assembly could have been designed to be longer, allowing a longer measuring stroke to be used.	n	y	Furnace could have been bigger, allowing room for larger components inside.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	Support column is long allowing adjustability of height of the strain gauge holder.	n	y	Interface on existing die ring for an additional, different sized die ring could have been helpful
11 Extending the available area on the transmission components of the device	n	n	No transmission components involved.	n	n	No transmission components involved.
12 Locating those parts which are anticipated to change near the exterior of the device	n	y	If strain gauge were mounted on outside, other parts could remain the same	n	n	Changing parts must be inside the furnace.
13 Reducing nesting of parts and modules	n	y	All components are nested inside the enclosure.	n	n	Changing parts must be inside the furnace.
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	n	n	Would not have helped, due to the limited number of modules.	n	n	Not relevant
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant	n	n	Not relevant

16 Reducing the number of contact points between modules	y	y	Micrometer mount and sliding rail holder are not in contact.	n	n	Not helpful due to the limited number of modules involved.
17 Simplifying the geometry of modular interfaces	y	y	Interface geometry is very simple.	y	y	Interface geometry is relatively simple
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not relevant	n	n	Not relevant
19 Creating detachable modules	y	y	Micrometer mount is detachable from column	y	y	Die and die holder are detachable
20 Using a framework for mounting multiple modules	n	n	Columns serve as a framework, could be improved though.	y	y	Frame is used to mount the furnace.
21 Using compliant materials	n	n	Not relevant	n	n	Not relevant
22 Simplifying the geometry of each component	y	y	All components have a relatively simple geometry.	y	y	All components have a relatively simple geometry, making them easy to machine in-house.
Adjustability						
23 Controlling the tuning of design parameters	n	y	Micrometer mount can slide on the column. Counterweights will need to be changed, and could be a tunable to make for easy accommodation.	n	n	Although a design parameter is increasing, there is no immediately apparent way to accommodate this with tunability.
24 Providing the capability for excess energy storage or importation	n	n	Not relevant	n	y	Stronger than necessary furnace mounting components could have been used.

Table D.3.1: Gas-pressure blow-forming: Use of Guidelines Report (Part 1 of 2)

	Used	Helpful	Change Mode 3: Add a vision system inside the pressure chamber	Used	Helpful	Change Mode 4: Compensate for thermal expansion automatically
Modularity						
1 Using separate modules to carry out functions that are not closely related	n	n	All functions are closely related.	y	y	Support function is carried out by separate modules from the testing modules.
2 Confining functions to single modules	y	y	Die holder, die, and column are separate, limiting change propagation.	n	n	Not relevant.
3 Confining functions to as few unique components as possible	n	n	Not relevant	n	n	Not relevant.
4 Dividing modules into multiple smaller, identical modules	n	y	If loading column was divided into separate smaller modules, only the module closest to the specimen would need to be modified.	n	n	Not relevant.
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	Die holder, die, and column are separate, limiting change propagation.	y	y	Outer framework is separate from other modules.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant	y	y	Thermal component is separate from the mechanical components.
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	n	n	Not relevant	y	y	Mounting and force providing function are both done by hydraulic frame.

8 Using duplicate parts as much as possible without raising part count	n	n	Not relevant	n	n	Not relevant.
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	Room around the measuring rod allows for addition of vision system components.	n	n	Not relevant.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	Hydraulic press framework could be used to mount vision system components.	n	n	Not relevant.
11 Extending the available area on the transmission components of the device	n	n	Not transmission components involved.	y	y	Entire framework can transmit force and displacement.
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Loading column is on the outside of the device.	y	y	Changing framework is located on the outside.
13 Reducing nesting of parts and modules	n	n	No nesting involved.	n	n	Not relevant.
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	n	n	Not relevant	y	y	Standardized connection point to servo hydraulic frame
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant	n	n	Not relevant.

16 Reducing the number of contact points between modules	y	y	All modules have single contact points.	y	y	Limited contact points between frame and testing components.
17 Simplifying the geometry of modular interfaces	y	y	Interface geometries are simple.	n	n	Not relevant.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not relevant	n	n	Not relevant.
19 Creating detachable modules	y	y	Die, die holder, and loading column are detachable.	n	n	Not relevant.
20 Using a framework for mounting multiple modules	y	y	Hydraulic press framework could be used to mount vision system components.	y	y	Hydraulic unit acts as a framework for mounting modules.
21 Using compliant materials	n	n	Not relevant	n	n	Not relevant.
22 Simplifying the geometry of each component	y	y	Loading column has a relatively simple geometry	n	n	Not relevant.
Adjustability						
23 Controlling the tuning of design parameters	n	n	Not relevant	y	y	Mounting frame is fully adjustable
24 Providing the capability for excess energy storage or importation	n	n	Not relevant	y	y	Mounting frame is motorized and can be controlled during the process.

Table D.3.2: Gas-pressure blow-forming: Use of Guidelines Report (Part 2 of 2)

Change Mode		Evolution Response	Readiness
1	Increase strain measurement range	Replace micrometer with one that has a longer stroke range.	Current vendor can provide a new micrometer.
2	Increase specimen diameter	Replace die with larger diameter die	Change can be made in-house
3	Add a vision system inside the pressure camber.	Uppermost column piece is modified to hold vision system components.	Change can be made in-house
4	Compensate for thermal expansion automatically	Feedback control loop must be integrated with the load cell and hydraulic ram so that constant pressure is applied to specimen as columns heat up and expand	No vendor necessary. All changes can be made in-house.

Table D.4: Gas-pressure blow-forming redesign: Evolution Response Table

Module	Change Mode 1: Increase strain measurement range	Change Mode 2: Increase specimen diameter
Main Assembly (MA)	Same	Change
Bottom Sub Assembly (BSA)	Change	Same
Load, Furnace, Gas System (LFG)	Same	Same
Change Effect	Replace micrometer with one that has a longer stroke range.	Replace die with larger diameter die

Table D.5.1: Gas-pressure blow-forming redesign: Module Change Report (Part 1 of 2)

Module	Change Mode 3: Add a vision system inside the pressure chamber	Change Mode 4: Compensate for thermal expansion automatically
Main Assembly (MA)	Change	Same
Bottom Sub Assembly (BSA)	Same	Same
Load, Furnace, Gas System (LFG)	Same	Change
Change Effect	Uppermost column piece is modified to hold vision system components.	Feedback control loop must be integrated with the load cell and hydraulic ram so that constant pressure is applied to specimen as columns heat up and expand

Table D.5.2: Gas-pressure blow-forming redesign: Module Change Report (Part 2 of 2)

Item	-	Sub#	Module	Part Name	CM 1	Readiness
1	-	1	MA	Load cell thread adapter		
1	-	2	MA	Heat exchanger		
1	-	3	MA	Heat exchanger quick disconnect		
1	-	4	MA	Loading column pipe		
1	-	5	MA	Top die-ring		
1	-	6	MA	Bottom die-ring		
1	-	7	MA	Alignment pins		
1	-	8	MA	Top loading column pipe 1/4" OD, 0.035" wall		
1	-	9	MA	Male connector 1/4" OD, 1/4" NPT		
1	-	10	MA	Union 90 deg elbow		
1	-	11	MA	Gas transfer pipe, 316 SS, 1/4" OD, 0.035" wall		
1	-	12	MA	Ball valve with Yor-Lok, 3-way, 1/4" tube OD		
2	-	1	BSA	Measuring rod tip		
2	-	2	BSA	Measuring rod		
2	-	3	BSA	Top plate, bottom sub assembly		
2	-	4	BSA	Side plate, bottom sub assembly		
2	-	5	BSA	Lock nut for bottom heat exchanger		
2	-	6	BSA	Bottom plate, bottom sub assembly		
2	-	7	BSA	Sliding rail holder		
2	-	8	BSA	Pulley holder		
2	-	9	BSA	Nylon pulley bearing mounted		
2	-	10	BSA	Brass counter weights, m = 154g		
2	-	11	BSA	Measuring rod holder		
2	-	12	BSA	Sliding rail		
2	-	13	BSA	2.0 inch bolt		
2	-	14	BSA	Micrometer	N	3
2	-	15	BSA	Column		
2	-	16	BSA	Micrometer mount		
2	-	17	BSA	Measuring rod, low end		

Table D.6.1: Gas-pressure blow-forming redesign: Reusability Matrix (Part 1 of 4)

3	-	1	LFG	MTS Servo Hydraulic Unit		
3	-	2	LFG	Load Cell		
3	-	3	LFG	ATS 3210 Furnace		
3		4	LFG	Furnace mounting clamps		
3		5	LFG	Furnace mounting pole		
3	-	6	LFG	Gas bottle		
3	-	7	LFG	Gas regulator		
				Number of Non-Reusable Parts	1	
				Percentage of Non-Reusable Parts (36 total)	97%	
				Flexibility Rating	1	
				Average Readiness Rating		3

Table D.6.2: Gas-pressure blow-forming redesign: Reusability Matrix (Part 2 of 4)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness
1	-	1	MA						
1	-	2	MA			N	3		
1	-	3	MA			N	3		
1	-	4	MA						
1	-	5	MA	N	2				
1	-	6	MA	N	2				
1	-	7	MA	N	2				
1	-	8	MA						
1	-	9	MA						
1	-	10	MA						
1	-	11	MA						
1	-	12	MA						
2	-	1	BSA						
2	-	2	BSA						
2	-	3	BSA						
2	-	4	BSA						
2	-	5	BSA						
2	-	6	BSA						
2	-	7	BSA						
2	-	8	BSA						
2	-	9	BSA						
2	-	10	BSA						
2	-	11	BSA						
2	-	12	BSA						
2	-	13	BSA						
2	-	14	BSA						
2	-	15	BSA						
2	-	16	BSA						
2	-	17	BSA						

Table D.6.3: Gas-pressure blow-forming redesign: Reusability Matrix (Part 3 of 4)

3	-	1	LFG						
3	-	2	LFG					N	2
3	-	3	LFG					N	2
3		4	LFG						
3		5	LFG						
3	-	6	LFG						
3	-	7	LFG						
				3		2		2	
				92%		94%		94%	
				1		1		1	
					2		3		2

Table D.6.4: Gas-pressure blow-forming redesign: Reusability Matrix (Part 4 of 4)

Appendix E: P-V-T Measurement Device Evolvability Analysis

Module	Change Mode 1: Increase stroke length	Change Mode 2: Increase stroke area
Base Assembly (BA)	Change	Change
Gauge Assembly (GA)	Same	Same
Master Cylinder Assembly (MCA)	Change	Change
Cylinder Head Assemmbly (CHA)	Same	Change
Piston Rack Assembly (PRA)	Change	Change
Change Effect	Master cylinder, full-threads, rack and scale will need to be lengthened.	Larger diameter components will be employed to increase the stroke area.

Table E.1.1: P-V-T measurement device: Module Change Report (Part 1 of 3)

Module	Change Mode 3: Add a locking mechanism to piston	Change Mode 4: Add controlled, constant temperature
Base Assembly (BA)	Same	Change
Gauge Assembly (GA)	Same	Same
Master Cylinder Assembly (MCA)	Same	Same
Cylinder Head Assemmbly (CHA)	Change	Same
Piston Rack Assembly (PRA)	Same	Same
Change Effect	Ratcheting mechanism will be added to top gear. Mechanism does not need to be reversible, but must be easily released.	A heating element will need to be added to the copper base plate. Leads will extend from the interior of the chamber through the base components. Cylinder may need to be widened to provide room for heating element.

Table E.1.2: P-V-T measurement device: Module Change Report (Part 2 of 3)

Module	Change Mode 5: Provide means for excess air to escape from chamber
Base Assembly (BA)	Same
Gauge Assembly (GA)	Same
Master Cylinder Assembly (MCA)	Same
Cylinder Head Assembly (CHA)	Change
Piston Rack Assembly (PRA)	Change
Change Effect	A valve will need to be added to the top of the piston cylinder. The valve must be able to be opened and closed from the top of the device, outside of the chamber.

Table E.1.3: P-V-T measurement device: Module Change Report (Part 3 of 3)

Item	-	Sub#	Module	Part Name	CM 1	Readiness
1	-	1	BA	Base Plate - aluminum		
1	-	2	BA	Base Plate - nylon		
1	-	3	BA	Base Plate - copper		
1	-	4	BA	Tightener, full threat	N	2
2	-	1	GA	Gauge adapter		
2	-	2	GA	Pressure gauge		
2	-	3	GA	Release valve		
2	-	4	GA	Release valve hose adapter		
2	-	5	GA	Release valve hose		
3	-	1	MCA	Master cylinder	N	2
3	-	2	MCA	Fluid input port		
3	-	3	MCA	Fluid input port plug		
3	-	4	MCA	Fluid input port plug small		
3	-	5	MCA	Scale	N	1
4	-	1	CHA	Head plate - nylon		
4	-	2	CHA	Head plate - aluminum		
4	-	3	CHA	Gear holder		
4	-	4	CHA	Gear		
4	-	5	CHA	Gear bolt		
4	-	6	CHA	Gear bolt socket		
4	-	7	CHA	Gear bolt secure cap		
4	-	8	CHA	Gear bolt secure cap epoxy		
4	-	9	CHA	Roller		
4	-	10	CHA	Roller shaft		
5	-	1	PRA	Piston body		
5	-	2	PRA	Piston O-rings		
5	-	3	PRA	Rack mount		
5	-	4	PRA	Rack gear	N	2
5	-	5	PRA	Thermocouple probe	N	2
5	-	6	PRA	Thermocouple probe mount		
				Number of Non-Reusable Parts	5	
				Percentage of Non-Reusable Parts (30 total)	83%	
				Flexibility Rating	2	
				Average Readiness Rating		1.8

Table E.2.1: P-V-T measurement device: Reusability Matrix (Part 1 of 2)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness	CM 5	Readiness
1	-	1	BA	N	2			N	2		
1	-	2	BA	N	2			N	2		
1	-	3	BA	N	2			N	4		
1	-	4	BA								
2	-	1	GA								
2	-	2	GA								
2	-	3	GA								
2	-	4	GA								
2	-	5	GA								
3	-	1	MCA	N	1			N	1		
3	-	2	MCA	N	2			N	2		
3	-	3	MCA								
3	-	4	MCA								
3	-	5	MCA								
4	-	1	CHA	N	2			N	2	N	2
4	-	2	CHA	N	2			N	2	N	4
4	-	3	CHA			N	3				
4	-	4	CHA								
4	-	5	CHA								
4	-	6	CHA								
4	-	7	CHA								
4	-	8	CHA								
4	-	9	CHA								
4	-	10	CHA								
5	-	1	PRA	N	2			N	2	N	2
5	-	2	PRA	N	2			N	2		
5	-	3	PRA								
5	-	4	PRA								
5	-	5	PRA								
5	-	6	PRA								
				9		1		9		3	
				70%		97%		70%		90%	
				3		1		3		1	
					1.89		3		2.11		2.67

Table E.2.2: P-V-T measurement device: Reusability Matrix (Part 2 of 2)

	Used	Helpful	Change Mode 1: Increase stroke length.	Used	Helpful	Change Mode 2: Increase stroke area.
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	Base and top need not be changed because they are separate modules.	n	n	Seal must be formed, so the geometry of the components interdependent.
2 Confining functions to single modules	y	y	Compressing and expanding are done by piston which is separate form all other modules.	n	n	Not helpful in this case.
3 Confining functions to as few unique components as possible	n	n	Not relevant.	n	n	Not relevant
4 Dividing modules into multiple smaller, identical modules	n	n	Could have been done, but would be difficult to do without causing leakage.	n	n	Not relevant
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	Base and tope are not anticipated to change for this change mode.	n	n	Most parts are anticipated to change in this case.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	y	y	Mechanical and fluid parts (top and chamber) are separate.	y	y	Mechanical and fluid parts (top and chamber) are separate.
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	n	y	Master cylinder could theoretically have been made more robust eliminating the need to full threads.	n	n	Not helpful in this case.
8 Using duplicate parts as much as possible without raising part count	y	y	Full threads are duplicate parts, reducing redesign effort.	n	y	Top and base could have been designed to be more similar, thus reducing redesign effort.
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	n	y	Extra long chamber or full threads may have reduced redesign effort	n	y	More room needed around master cylinder.

10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	n	n	Not helpful for the given redesign concept.	n	n	No new interfaces for this redesign.
11 Extending the available area on the transmission components of the device	n	n	Not relevant.	n	n	No transmission components involved.
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Cylinder and full threads are external.	n	n	Not relevant
13 Reducing nesting of parts and modules	y	y	Cylinder is not nested. Rack is nested but not in the dimension that is likely to change.	n	n	Piston is nested inside master cylinder, but this is fundamental to the functioning of the product.
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	n	n	Not relevant.	n	n	Not relevant
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant.	n	n	Not relevant
16 Reducing the number of contact points between modules	n	y	Full threads create extra contact points between top and base.	y	n	Contact points is almost at a minimum, but does not help.
17 Simplifying the geometry of modular interfaces	y	y	All geometry is very simple, eliminating need for complicated geometric redesign.	y	y	All geometry is very simple, eliminating need for complicated geometric redesign.
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not helpful.	n	n	Not relevant

19 Creating detachable modules	y	y	Top and base are detachable, allowing for replacement of necessary components.	n	n	Not helpful in this case.
20 Using a framework for mounting multiple modules	n	n	Not apparent to be helpful.	n	n	Not relevant
21 Using compliant materials	n	n	Not relevant.	n	y	Compliant seal system that automatically expands to larger cylinder may have eliminated need to redesign piston.
22 Simplifying the geometry of each component	y	y	Master cylinder and full threads have very simple geometry. Just have to select wider length.	n	n	Master cylinder is very simple, just have to choose a wider one.
Adjustability						
23 Controlling the tuning of design parameters	n	n	None of the relevant parameters could be feasible tuned.	n	n	None of the relevant parameters could be tunable.
24 Providing the capability for excess energy storage or importation	n	n	Not relevant.	n	n	Not relevant

Table E.3.1: P-V-T measurement device: Use of Guidelines Report (Part 1 of 3)

	Used	Helpful	Change Mode 3: Add locking mechanism to piston.	Used	Helpful	Change Mode 4: Add tunable, constant temperature.
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	Top module is separate from rest of device, eliminating change propagation.	y	y	Separate base module reduces redesign effort.
2 Confining functions to single modules	n	n	Not relevant	n	y	Heating function could have been confined to a separate module from the base.
3 Confining functions to as few unique components as possible	n	n	Not relevant	n	n	Not relevant

4 Dividing modules into multiple smaller, identical modules	n	n	Not relevant	n	n	Not relevant
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	Non changing components are in separate modules.	y	y	Non changing components are split into separate modules.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant	n	y	Copper base plate (thermal component) could have been split into a separate module from the fluid component (base / chamber).
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	y	y	Moving and locking function are shared by the top module.	n	n	Not relevant
8 Using duplicate parts as much as possible without raising part count	n	n	No duplicate parts used for this change mode.	n	n	Not relevant
Spatial						
9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	Room on gear holder allows for addition locking parts to be added.	n	y	Room is needed for a heating element in the copper base plate.
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	y	y	Free interface on gear holder.	n	y	Heating element could be added underneath the base, but base plate is too thick.
11 Extending the available area on the transmission components of the device	n	n	Not relevant	n	n	No transmission components involved.
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	Gear holder is the only part that is anticipated to change for this change mode, and is located on the outside.	n	y	Changing component is on the interior, adding to number of components that need to be changed.

13 Reducing nesting of parts and modules	y	y	No nesting involved for this change mode.	n	y	Copper base plate is nested inside the aluminum base.
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	n	n	Not relevant	n	n	Not relevant
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant	n	n	Not relevant
16 Reducing the number of contact points between modules	y	y	Gear holder has a single contact point.	y	n	Contact points are minimized, but this does not help in this case.
17 Simplifying the geometry of modular interfaces	y	y	Interface geometry is very simple, reducing redesign effort.	n	n	Not relevant
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not relevant	n	n	Not relevant
19 Creating detachable modules	n	n	Not relevant	n	y	Base could have been made detachable so that it could be replaced with a heating element.
20 Using a framework for mounting multiple modules	n	y	Small frame could have been used to mount a locking ratchet.	n	n	Not relevant
21 Using compliant materials	n	n	Not relevant	n	n	Not relevant
22 Simplifying the geometry of each component	y	y	Geometry of all components involved is very simple.	y	y	Circular geometry is simple and reduces redesign effort.
Adjustability						
23 Controlling the tuning of design parameters	n	n	No tunable parameter would have been helpful for this change mode.	n	y	Temperature could be a tunable design parameter, but is not which creates the need for redesign effort.

24 Providing the capability for excess energy storage or importation	n	n	Not relevant	n	y	Excess energy storage could be used to create heat in the chamber and control the temperature.

Table E.3.2: P-V-T measurement device: Use of Guidelines Report (Part 2 of 3)

	Used	Helpful	Change Mode 5: Allow excess air to escape from chamber.
Modularity			
1 Using separate modules to carry out functions that are not closely related	y	y	Pressurizing piston is separate from other modules.
2 Confining functions to single modules	y	n	Done, but not helpful in this case.
3 Confining functions to as few unique components as possible	n	n	Not relevant.
4 Dividing modules into multiple smaller, identical modules	n	n	Not relevant.
5 Collecting parts which are not anticipated to change in time into separate modules	n	n	Not relevant.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant.
Parts Reduction			
7 Sharing functions in a module or part if the functions are closely related	n	n	Not relevant.
8 Using duplicate parts as much as possible without raising part count	n	n	Not relevant.
Spatial			

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	Room around piston cylinder for opening and closing valve
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	n	y	Slots in head plate could have been used to allow a valve opener to pass through.
11 Extending the available area on the transmission components of the device	n	n	Not relevant.
12 Locating those parts which are anticipated to change near the exterior of the device	n	n	The part that is anticipated to change must be located on the interior of the device.
13 Reducing nesting of parts and modules	n	n	The part that is anticipated to change must be located on the interior of the device.
Interface Decoupling			
14 Standardizing or reducing the number of different connectors used between modules	n	n	Not relevant.
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant.
16 Reducing the number of contact points between modules	n	y	Open head plates could have been used to allow passing of a valve opener.
17 Simplifying the geometry of modular interfaces	n	n	Not relevant.

18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not relevant.
19 Creating detachable modules	n	n	Not relevant.
20 Using a framework for mounting multiple modules	n	n	Not relevant.
21 Using compliant materials	n	n	Not relevant.
22 Simplifying the geometry of each component	y	n	A more complex geometry would have actually bee helpful.
Adjustability			
23 Controlling the tuning of design parameters	n	n	Not relevant.
24 Providing the capability for excess energy storage or importation	n	n	Not relevant.

Table E.3.3: P-V-T measurement device: Use of Guidelines Report (Part 3 of 3)

Change Mode		Evolution Response	Readiness
1	Increase stroke length	Longer master cylinder and rack are implemented	All materials can be purchased from current vendor and parts can be fabricated in-house.
2	Increase stroke area	Wider master cylinder is used. Compliant seal system precludes need for new piston.	All materials can be purchased from current vendor and parts can be fabricated in-house.
3	Add locking mechanism piston	Locking mechanism is added to small frame which is mounted around the cylinder top	It is uncertain whether the current vendor can provide the necessary parts. Modifications to the existing components can be performed in-house.
4	Add tunable, constant temperature	Heating element is added to bottom interface of the conducting base plate.	A vendor will need to be located for the heating element. Modifications to existing parts can be performed in-house.
5	Provide means for excess air to escape from chamber	Valve is inserted into the piston. Valve opening handle is extended trough one of the slots in the top plate.	A vendor will need to be located for the valve. Modifications to the existing parts can be performed in-house.

Table E.4: P-V-T measurement device redesign: Evolution Response Table

Module	Change Mode 1: Increase stroke length	Change Mode 2: Increase stroke area
Base Assembly (BA)	Same	Same
Gauge Assembly (GA)	Same	Same
Master Cylinder Assembly (MCA)	Change	Change
Cylinder Head Assembly (CHA)	Same	Same
Piston Rack Assembly (PRA)	Change	Same
Change Effect	Longer master cylinder and rack are implemented	Wider master cylinder is used. Compliant seal system precludes need for new piston.

Table E.5.1: P-V-T measurement device redesign: Module Change Report (Part 1 of 3)

Module	Change Mode 3: Add a locking mechanism to piston	Change Mode 4: Add controlled, constant temperature
Base Assembly (BA)	Same	Change
Gauge Assembly (GA)	Same	Same
Master Cylinder Assembly (MCA)	Same	Same
Cylinder Head Assembly (CHA)	Same	Same
Piston Rack Assembly (PRA)	Same	Same
Change Effect	Locking mechanism is added to small frame which is mounted around the cylinder top	Heating element is added to bottom interface of the conducting base plate.

Table E.5.2: P-V-T measurement device redesign: Module Change Report (Part 2 of 3)

Module	Change Mode 5: Provide means for excess air to escape from chamber
Base Assembly (BA)	Same
Gauge Assembly (GA)	Same
Master Cylinder Assembly (MCA)	Same
Cylinder Head Assembly (CHA)	Same
Piston Rack Assembly (PRA)	Change
Change Effect	Valve is inserted into the piston. Valve opening handle is extended trough one of the slots in the top plate.

Table E.5.3: P-V-T measurement device redesign: Module Change Report (Part 3 of 3)

Item	-	Sub#	Module	Part Name	CM 1	Readiness	CM 2	Readiness
1	-	1	BA	Base Plate - aluminum				
2	-	1	GA	Gauge adapter				
2	-	2	GA	Pressure gauge				
2	-	3	GA	Release valve				
2	-	4	GA	Release valve hose adapter				
2	-	5	GA	Release valve hose				
3	-	1	MCA	Master cylinder	N	2	N	1
3	-	2	MCA	Fluid input port			N	2
3	-	3	MCA	Fluid input port plug				
3	-	4	MCA	Fluid input port plug small				
3	-	5	MCA	Scale	N	1		
4	-	2	CHA	Head plate - aluminum with slots				
4	-	3	CHA	Gear holder				
4	-	4	CHA	Gear				
4	-	5	CHA	Gear bolt				
4	-	6	CHA	Gear bolt socket				
4	-	7	CHA	Gear bolt secure cap				
4	-	8	CHA	Gear bolt secure cap epoxy				
4	-	9	CHA	Roller				
4	-	10	CHA	Roller shaft				
5	-	1	PRA	Piston body				
5	-	2	PRA	Piston O-rings				
5	-	3	PRA	Rack mount				
5	-	4	PRA	Rack gear	N	2		
5	-	5	PRA	Thermocouple probe	N	2		
5	-	6	PRA	Thermocouple probe mount				
				Number of Non-Reusable Parts	4		2	
				Percentage of Non-Reusable Parts (26 total)	85%		92%	
				Flexibility Rating	2		1	
				Average Readiness Rating		1.75		1.5

Table E.6.1: P-V-T measurement device redesign: Reusability Matrix (Part 1 of 2)

Item	-	Sub#	Module	CM 3	Readiness	CM 4	Readiness	CM 5	Readiness
1	-	1	BA			N	2		
2	-	1	GA						
2	-	2	GA						
2	-	3	GA						
2	-	4	GA						
2	-	5	GA						
3	-	1	MCA						
3	-	2	MCA						
3	-	3	MCA						
3	-	4	MCA						
3	-	5	MCA						
4	-	2	CHA						
4	-	3	CHA						
4	-	4	CHA						
4	-	5	CHA						
4	-	6	CHA						
4	-	7	CHA						
4	-	8	CHA						
4	-	9	CHA						
4	-	10	CHA						
5	-	1	PRA					N	3
5	-	2	PRA						
5	-	3	PRA						
5	-	4	PRA						
5	-	5	PRA						
5	-	6	PRA						
				0		1		1	
				100%		96%		96%	
				1		1		1	
					1		2		3

Table E.6.2: P-V-T measurement device redesign: Reusability Matrix (Part 2 of 2)

Appendix F: Beam Pattern Measurement System Evolvability Analysis

Module	Change Mode 1: Add controlled motion to second TD mount	Change Mode 2: Add a gate to one end for tank access
Support Frame (SF)	Change	Change
Tank Assembly (TA)	No Change	Change
Positioning System (PS)	Change	No Change
Change Effect	New motors and lead screws for all axes of motion for the second TD mount. New carriages needed that can be driven with lead screws.	Support frame end is replaced with a gait that can be opened or locked shut. Tank end is replaced with a door that can be opened or sealed shut.

Table F.1.1: Beam pattern measurement system: Module Change Report (Part 1 of 2)

Module	Change Mode 3: Lengthen the test tank	Change Mode 4: Deepen the test tank
Support Frame (SF)	Change	Change
Tank Assembly (TA)	Change	Change
Positioning System (PS)	Change	No Change
Change Effect	x-axis motion components, tank, and support frame are all lengthened.	Top surface of support frame is raised up. Tank panels are replaced with taller ones.

Table F.1.2: Beam pattern measurement system: Module Change Report (Part 2 of 2)

Item	-	Sub#	Module	Part Name	CM 1	Readiness
1	-	1	SF	Leg Support Block, Aluminum 1" Thick, 4"x4"		
1	-	2	SF	Leg Dampener Block, Plastic, 1" Thick, 4"x4"		
1	-	3	SF	Leg end interface plate		
1	-	4	SF	Leg, 4"x4" L-cross section, 0.25" thick		
1	-	5	SF	Support frame leg interface plate		
1	-	6	SF	Lengthwise support frame lower horizontal beam		
1	-	7	SF	Widthwise support frame lower horizontal beam		
1	-	8	SF	Support frame leg		
1	-	9	SF	Lengthwise diagonal, 45 degree		
1	-	10	SF	Lengthwise diagonal, 30 degree		
1	-	11	SF	Widthwise diagonal, 45 degree		
1	-	12	SF	Lengthwise upper horizontal channel beam		
1	-	13	SF	Widthwise upper horizontal channel beam		
1	-	14	SF	Lengthwise precision cross slide support surface		
1	-	15	SF	Widthwise precision cross slide support surface		
2	-	1	TA	Lengthwise horizontal tank frame beams		
2	-	2	TA	Widthwise horizontal tank frame beams		
2	-	3	TA	Vertical support bars		
2	-	4	TA	Horizontal / Vertical connecting plates		
2	-	5	TA	Tank base surface		
2	-	6	TA	Lengthwise side panel		
2	-	7	TA	Widthwise side panel		
2	-	8	TA	Lengthwise upper decorative trim		
2	-	9	TA	Widthwise upper decorative trim		
3	-	1	PS	x-axis cross slide rails		
3	-	2	PS	x-axis lead screw		
3	-	3	PS	x-axis motor		
3	-	4	PS	x-axis carriage, without lead screw	N	3
3	-	5	PS	x-axis carriage, with lead screw		
3	-	6	PS	x-axis lead screw bearing support bracket		
3	-	7	PS	x-axis lead screw motor support bracket		
3	-	8	PS	y-axis guide rail support plate		
3	-	9	PS	y'-axis guide rail support plate (non-motorized)	N	4
3	-	10	PS	y-axis cross slide rails		
3	-	11	PS	y'-axis cross slide rails (non-motorized)	N	3
3	-	12	PS	y-axis lead screw		

3	-	13	PS	y-axis lead screw bearing support bracket		
3	-	14	PS	y-axis lead screw motor support bracket		
3	-	15	PS	y-axis motor		
3	-	16	PS	y-axis carriage pillow blocks		
3	-	17	PS	theta-axis rotary table (motor controlled)		
3	-	18	PS	theta-axis rotary table support (motor controlled)		
3	-	19	PS	theta'-axis rotary table (non-motorized)	N	3
3	-	20	PS	theta'-axis rotary table support (non-motorized)	N	4
3	-	21	PS	theta-axis motor		
3		22	PS	z-axis motor		
3	-	23	PS	z-axis support tube		
3	-	24	PS	z-axis support tube flange		
3	-	25	PS	z'-axis positioning rod	N	3
3	-	25	PS	Transducer tube rod, upper		
3	-	26	PS	Transducer rod connector		
3	-	27	PS	Transducer tube rod, lower		
				Number of Non-Reusable Parts	6	
				Percentage of Non-Reusable Parts (52 total)	88%	
				Flexibility Rating	2	
				Average Readiness Rating		3.33

Table F.2.1: Beam pattern measurement system: Reusability Matrix (Part 1 of 2)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness
1	-	1	SF						
1	-	2	SF						
1	-	3	SF						
1	-	4	SF						
1	-	5	SF						
1	-	6	SF			N	5		
1	-	7	SF	N	4				
1	-	8	SF					N	4
1	-	9	SF			N	4		
1	-	10	SF			N	4		
1	-	11	SF	N	4				
1	-	12	SF			N	5		
1	-	13	SF	N	4				
1	-	14	SF			N	6		
1	-	15	SF	N	4				
2	-	1	TA			N	3		
2	-	2	TA	N	5				
2	-	3	TA					N	3
2	-	4	TA						
2	-	5	TA			N	4		
2	-	6	TA			N	4	N	4
2	-	7	TA	N	6			N	4
2	-	8	TA			N	3		
2	-	9	TA	N	3				
3	-	1	PS			N	3		
3	-	2	PS			N	3		
3	-	3	PS						
3	-	4	PS						
3	-	5	PS						
3	-	6	PS						
3	-	7	PS						
3	-	8	PS						
3	-	9	PS						
3	-	10	PS						
3	-	11	PS						
3	-	12	PS						

3	-	13	PS						
3	-	14	PS						
3	-	15	PS						
3	-	16	PS						
3	-	17	PS						
3	-	18	PS						
3	-	19	PS						
3	-	20	PS						
3	-	21	PS						
3		22	PS						
3	-	23	PS						
3	-	24	PS						
3	-	25	PS						
3	-	25	PS						
3	-	26	PS						
3	-	27	PS						
				7		11		4	
				87%		79%		92%	
				2		2		1	
					4.29		4		3.75

Table F.2.2: Beam pattern measurement system: Reusability Matrix (Part 2 of 2)

	Used	Helpful	Change Mode 1: Add controlled motion to the 2nd transducer mount	Used	Helpful	Change Mode 2: Add a gate to one end for easy access
Modularity						
1 Using separate modules to carry out functions that are not closely related	y	y	Separate motion components from frame and tank	y	n	Done but not helpful in this case
2 Confining functions to single modules	y	y	x and x' components are in separate modules	y	n	Done but not helpful in this case
3 Confining functions to as few unique components as possible	y	y	common guide rails	y	y	Standardized tank member cross section reduces redesign effort.
4 Dividing modules into multiple smaller, identical modules	n	n	Not relevant	n	n	Not relevant
5 Collecting parts which are not anticipated to change in time into separate modules	y	y	Controlled motion components are separate from non controlled	y	y	Positioning system is not anticipated to change for this change mode.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant	n	n	Not relevant
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	y	y	x-axis guide rails are shared	n	y	Tank and frame could have been integrated.
8 Using duplicate parts as much as possible without raising part count	n	y	Drivable carriages could have been used for the non-driven motion components	y	y	Many of the tank frame member are duplicates, reducing redesign effort
Spatial						

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	y	y	Unconstrained space on top of table for addition of parts and dimensions	n	n	Not relevant
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	n	n	Not relevant	n	n	Members are replaced with a gate, so no new interfaces
11 Extending the available area on the transmission components of the device	y	n	Lead screw is exposed and extensive, but cannot be used for x' because motion must be independent.	n	n	Not relevant
12 Locating those parts which are anticipated to change near the exterior of the device	y	y	All changing components are located on the exterior	n	y	Tank end is anticipated to change, but is not located near the exterior of the device.
13 Reducing nesting of parts and modules	n	n	Not relevant	n	y	Tank is nested inside the support frame
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	Standard connection between all guide rails and carriages	y	y	Standardized connectors between tank members
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant	n	n	Not relevant
16 Reducing the number of contact points between modules	n	n	Not relevant	y	n	No contact between the frame and the tank, but not helpful for this change mode.
17 Simplifying the geometry of modular interfaces	y	y	Simple interfaces between rails and supporting structures	n	n	Not relevant

18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	Not relevant	n	n	No flows taking place
19 Creating detachable modules	y	y	Detachability of carriages makes for easy retrofitting	n	y	Detachable components on tank end improve reusability.
20 Using a framework for mounting multiple modules	y	y	Support frame allows for easy addition of extra lead screws and motors	n	y	Single frame could have been used to mount tank and positioning system
21 Using compliant materials	n	n	Not relevant	n	n	Not relevant
22 Simplifying the geometry of each component	n	n	Not relevant	y	y	Simple tank support members make for easy redesign
Adjustability						
23 Controlling the tuning of design parameters	y	y	2nd mount is entirely tunable and adjustable, so controls are easy to implement.	n	n	Not relevant
24 Providing the capability for excess energy storage or importation	n	n	Not relevant	n	n	Not relevant

Table F.3.1: Beam pattern measurement system: Use of Guidelines Report (Part 1 of 2)

	Used	Helpful	Change Mode 3: Lengthen the test tank	Used	Helpful	Change Mode 4: Deepen the test tank
Modularity						
1 Using separate modules to carry out functions that are not closely related	n	y	A modular support frame would reduce redesign effort of the frame	y	y	Fame legs are separate from upper components
2 Confining functions to single modules	y	n	Done but not helpful in this case	y	y	Support table is done by frame legs and support positioning system is done by upper components
3 Confining functions to as few unique components as possible	n	n	Not relevant	y	y	Identical leg members on all four corners.
4 Dividing modules into multiple smaller, identical modules	n	y	Multiple smaller tank or frame modules would have been helpful	y	y	Support frame divided in to smaller pieces with removable legs
5 Collecting parts which are not anticipated to change in time into separate modules	n	n	All modules are expected to change	y	y	Upper frame components are separate from legs.
6 Collecting parts which perform functions associated with the same energy domain into separate modules	n	n	Not relevant	n	n	Not relevant
Parts Reduction						
7 Sharing functions in a module or part if the functions are closely related	n	y	Tank and frame could have been a single module	n	n	Not relevant
8 Using duplicate parts as much as possible without raising part count	y	y	Lengthwise members are all duplicate parts	y	y	Leg and frame interface pieces are identical
Spatial						

9 Creating room on the exterior surfaces of the device, around interior modules, and around those parts which are designed to interface with humans	n	y	Oversized support frame would allow room for tank expansion	n	y	Interior space would eliminate need to raise the support frame
10 Providing free interfaces and expansive, unobstructed surfaces for new interfaces	n	n	No new interfaces	n	n	No new interfaces
11 Extending the available area on the transmission components of the device	n	n	No transmission components involved	n	n	No transmission components involved
12 Locating those parts which are anticipated to change near the exterior of the device	n	y	Tank is nested inside the support frame	n	y	Tank is nested inside the support frame
13 Reducing nesting of parts and modules	n	y	Tank is nested inside the support frame	n	y	Tank is nested inside the support frame
Interface Decoupling						
14 Standardizing or reducing the number of different connectors used between modules	y	y	Standardized connectors between tank members	y	y	Standard connectors between legs and upper support frame
15 Reducing the number of fasteners used, or eliminating them entirely	n	n	Not relevant	n	n	Not relevant
16 Reducing the number of contact points between modules	y	n	No contact between the frame and the tank, but not helpful for this change mode.	y	n	No contact between frame and tank, but not helpful
17 Simplifying the geometry of modular interfaces	n	n	Not relevant	y	y	Simple geometry between the legs and support frame
18 Routing flows of energy, information and materials so that they are able to bypass each module at need	n	n	No flows taking place	n	n	No flows taking place

19 Creating detachable modules	n	n	Not relevant	y	y	Detachable table legs
20 Using a framework for mounting multiple modules	n	y	Single frame could have been used to mount tank and positioning system	n	y	Single frame for tank and support would have reduced non-reusability
21 Using compliant materials	n	n	Not relevant	n	n	Not relevant
22 Simplifying the geometry of each component	y	y	Simple tank members made for easy redesign	y	y	Simple frame legs allow for easy redesign
Adjustability						
23 Controlling the tuning of design parameters	n	y	Slotted or telescoping tank frame members and sliding panel ends would have enabled adjustability.	n	y	Adjustable length table legs and sliding height tank panels could have been used.
24 Providing the capability for excess energy storage or importation	n	n	Not relevant	n	n	Not relevant

Table F.3.2: Beam pattern measurement system: Use of Guidelines Report (Part 2 of 2)

Change Mode		Evolution Response	Readiness
1	Add controlled motion to the second TD mount	Motors and lead screws are added to the existing carriages. Upper frame surface is fitted with new x-axis motor.	All of the relevant components are standard motion control hardware and can be supplied by the current vendor.
2	Add a gate to one end of the tank for easy access	Tank and frame end components are removed and replaced with a locking gate. Gate must have a smooth, featureless inner surface and create a seal with the adjacent side panels.	Current frame and tank vendors can implement the change with significant effort.
3	Lengthen the test tank	X-axis guide rails are replaced with longer ones.	Current motion component vendor can supply longer guide rails.
4	Deepen the test tank	No change needed. Design can be adjusted and reconfigured to meet this change mode.	Change can be made in-house.

Table F.4: Beam pattern measurement system redesign: Evolution Response Table

Module	Change Mode 1: Add controlled motion to second TD mount	Change Mode 2: Add a gate to one end for tank access
Support Frame / Tank Assembly (SFT)	Change	Change
Positioning System (PS)	Change	No Change
Change Effect	Motors and lead screws are added to the existing carriages. Upper frame surface is fitted with new x-axis motor.	Tank and frame end components are removed and replaced with a locking gate. Gate must have a smooth, featureless inner surface and create a seal with the adjacent side panels.

Table F.5.1: Beam pattern measurement redesign: Module Change Report (Part 1 of 2)

Module	Change Mode 3: Lengthen the test tank	Change Mode 4: Deepen the test tank
Support Frame / Tank Assembly (SFT)	Change	No Change
Positioning System (PS)	No Change	No Change
Change Effect	X-axis guide rails are replaced with longer ones	No change needed. Design can be adjusted and reconfigured to meet this change mode.

Table F.5.2: Beam pattern measurement redesign: Module Change Report (Part 2 of 2)

Item - Sub#	Module	Part Name	CM 1	Readiness
1 - 1	SFT	Leg Support Block, Aluminum 1" Thick, 4"x4"		
1 - 2	SFT	Leg Dampener Block, Plastic, 1" Thick, 4"x4"		
1 - 3	SFT	Leg end interface plate		
1 - 4	SFT	Leg, 4"x4" L-cross section, 0.25" thick		
1 - 5	SFT	Support frame leg interface plate		
1 - 6	SFT	Lengthwise support frame lower horizontal beam		
1 - 7	SFT	Widthwise support frame lower horizontal beam		
1 - 8	SFT	Support frame leg		
1 - 9	SFT	Lengthwise diagonal, 45 degree		
1 - 10	SFT	Lengthwise diagonal, 30 degree		
1 - 11	SFT	Widthwise diagonal, 45 degree		
1 - 12	SFT	Lengthwise upper horizontal channel beam - outer slotted		
1 13	SFT	Lengthwise inner horizontal channel beam - inner slotted		
1 - 14	SFT	Widthwise upper horizontal channel beam		
1 - 15	SFT	Lengthwise precision cross slide support surface	N	3
1 - 16	SFT	Widthwise precision cross slide support surface	N	3
1 - 17	SFT	Tank base surface		
1 - 18	SFT	Lengthwise side panel		
1 - 19	SFT	Widthwise side panel		
1 - 20	SFT	Lengthwise upper decorative trim		
1 - 21	SFT	Widthwise upper decorative trim		
2 - 1	PS	x-axis cross slide rails		
2 - 2	PS	x-axis lead screw		
2 - 3	PS	x-axis motor		
2 - 5	PS	x-axis carriage, with lead screw		
2 - 6	PS	x-axis lead screw bearing support bracket		
2 - 7	PS	x-axis lead screw motor support bracket		
2 - 8	PS	y-axis guide rail support plate		
2 - 10	PS	y-axis cross slide rails		
2 - 11	PS	y'-axis cross slide rails (non-motorized)		
2 - 12	PS	y-axis lead screw		
2 - 13	PS	y-axis lead screw bearing support bracket		
2 - 14	PS	y-axis lead screw motor support bracket		
2 - 15	PS	y-axis motor		
2 - 16	PS	y-axis carriage pillow blocks		
2 - 17	PS	theta-axis rotary table (motor controlled)		
2 - 18	PS	theta-axis rotary table support (motor controlled)		
2 - 21	PS	theta-axis motor		

2 22	PS	z-axis motor		
2 - 23	PS	z-axis support tube		
2 - 24	PS	z-axis support tube flange		
2 - 25	PS	z'-axis positioning rod		
2 - 26	PS	Transducer tube rod, upper		
2 - 27	PS	Transducer rod connector		
2 - 28	PS	Transducer tube rod, lower		
		Number of Non-Reusable Parts	2	
		Percentage of Non-Reusable Parts (45 total)	96%	
		Flexibility Rating	1	
		Average Readiness Rating		3

Table F.6.1: Beam pattern measurement redesign: Reusability Matrix (Part 1 of 2)

Item	-	Sub#	Module	CM 2	Readiness	CM 3	Readiness	CM 4	Readiness
1	-	1	SFT						
1	-	2	SFT						
1	-	3	SFT						
1	-	4	SFT						
1	-	5	SFT						
1	-	6	SFT						
1	-	7	SFT	N	4				
1	-	8	SFT						
1	-	9	SFT						
1	-	10	SFT						
1	-	11	SFT	N	4				
1	-	12	SFT						
1		13	SFT						
1	-	14	SFT	N	4				
1	-	15	SFT						
1	-	16	SFT	N	5				
1	-	17	SFT						
1	-	18	SFT						
1	-	19	SFT	N	6				
1	-	20	SFT						
1	-	21	SFT	N	3				
2	-	1	PS			N	4		
2	-	2	PS			N	4		
2	-	3	PS						
2	-	5	PS						
2	-	6	PS						
2	-	7	PS						
2	-	8	PS						
2	-	10	PS						
2	-	11	PS						
2	-	12	PS						
2	-	13	PS						
2	-	14	PS						
2	-	15	PS						
2	-	16	PS						
2	-	17	PS						

2	-	18	PS						
2	-	21	PS						
2		22	PS						
2	-	23	PS						
2	-	24	PS						
2	-	25	PS						
2	-	26	PS						
2	-	27	PS						
2	-	28	PS						
				6		2		0	
				87%		96%		100%	
				2		1		1	
					4.33		4		1

Table F.6.2: Beam pattern measurement redesign: Reusability Matrix (Part 2 of 2)

References

1. Keese, D. A., N. P. Takawale, C. C. Seepersad and K. L. Wood, 2006, "An enhanced change modes and effects analysis (CMEA) tool for measuring product flexibility with applications to consumer products," *ASME DETC*, Philadelphia, Pennsylvania.

2. Robertson, D. and K. Ulrich, 1998, "Planning for product platforms," *Sloan Management Review*, pp. 19-31.

3. Wie, M. V., R. B. Stone, H. Thevenot and T. Simpson, 2007, "Examination of platform and differentiating elements in product family design," *Journal of Intellegent Manufacturing*, Vol. 18, pp. 77-96.

4. deWeck, O. and E. S. Suh, 2006, "Flexible Product Platforms: Framework and Case Study," *DETC/CIE Design Automation Conference*, Philadelphia, PA, Paper Number: DETC2006-99163.

5. Suh, E. S., O. deWeck, I. Y. Kim and D. Chang, 2007, "Flexible platform component design under uncertainty," *Journal of Intelligent Manufacturing*, Vol. 18, pp. 115-126.

6. Simpson, T. W., J. R. A. Maier and F. Mistree, 2001, "Product platform design: method and application," *Research in Engineering Design*, Vol. 13, pp. 2-22.

7. Ironman Slides,AGSlides, http://www.agslides.com/agProductDetails.jsp?goTo=9, 2/25/08

8. Sanderson, S. and M. Uzumeri, 1995, "Managing Product Families: The Case of the Sony Walkman," *Research Policy*, Vol. 24, pp. 761-782.

9. Martin, M. V. and K. Ishii, 2002, "Design for variety: developing standardized and modularized product platform architectures," *Research in Engineering Design*, Vol. 13, No. 4, pp. 213-235.

10. Otto, K. N. and K. L. Wood, 2001, "Chapter 8: Product Portfolios and Portfolio Architecture," *Product Design - Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Inc., Upper Saddle River, NJ.

11. Pine, B. J., II, 1993, "Mass Customzation: The New Frontier in Business Competition," *Harvard Business School Press*.

12. Lau, R. S. M., 1995, "Mass Customization: The Next Industrial Revolution," *Industrial Management,* Vol. 37, No. 5, pp. 18-19.

13. U Build It Action Figure,Vicale, http://www.vicale.com/maleondemand/, 2/22/2008

14. Jiao, J. and M. M. Tseng, 1999, "A methodology of developing product family architecture for mass customization," *Journal of Intelligent Manufacturing,* Vol. 10, pp. 3-20.

15. Feitzinger, E. and H. L. Lee,1997, *Mass Customization at Hewlett-Packard: The Power of Postponement*. Harvard Business Review**:** 116-121.

16. Ulrich, K., 1995, "The Role of Product Architecture in the Manufacturing Firm," *Research Policy,* Vol. 24, No. 3, pp. 419-440.

17. Gershenson, J. K., G. J. Prasad and Y. Zhang, 2003, "Product modularity: definitions and benefits," *Journal of Engineering Design,* Vol. 14, No. 3, pp. 295-313.

18. Ulrich, K. and K. Tung, 1991, "Fundamentals of product modularity," *ASME DETC - Conference on Design/Manufacture Integration*, Miami, FL.

19. Dahmus, J. B., J. P. Gonzalez-Zugasti and K. N. Otto, 2001, "Modular product architecture," *Design Studies,* Vol. 22, pp. 409-424.

20. Holtta-Otto, K. and O. deWeck, 2007, Degree of Modularity in Engineering Systems and Products with Technical and Business Constraints, *Concurrent Engineering: Research and Applications,* Vol. 15, No. 2, pp. 113-126.

21. Mini Work Tool,BCB, http://www.bcbsurvivalusa.com, 2/12/08

22. Fieldmaster,Victorinox, http://www.swissarmy.com, 2/12/08

23. Ferguson, S., A. Siddiqi, K. Lewis and O. De Weck, 2007, "Flexible and Reconfigurable Systems: Nomenclature and Review," *IDETC&CIE,* Las Vegas, Nevada.

24. Katz, R., 2006, "Design Principles of Reconfigurable Machines," *Int J Adv Manuf Technol,* Vol. Volume 34, Numbers 5-6, pp. 430-439.

25. Siddiqi, A., O. L. deWeck and K. Iagnemma, 2006, "Reconfigurability in Interplanetary Space Vehicles: Modeling Approaches and Case Study," *Journal of the British Interplanetary Society,* Vol. 59.

26. Landers, R., B. Min and Y. Koren, 2001, "Reconfigurable Machine Tools," *Ann CIRP*, No. 50, pp. 269-274.

27. Singh, V., B. Walther, J. Krager, N. Putnam, B. Koraishy, K. L. Wood and D. Jensen, 2007, "Design for Transformation: Theory, Method and Application," *ASME DETC/CIE Design Theory and Methodology Conference*, Las Vegas, NV, Paper Number DETC2007-34876.

28. Singh, V., S. Skiles, J. Krager, K. L. Wood and D. D. Jensen, 2006, "Innovations in Design through Transformation: A Fundamental Study of Transformation Principles," *ASME DETC/CIE Design Theory and Methodology Conference*, Philadelphia, PA, Paper Number DETC2006-99575.

29. Skiles, S., V. Singh, J. Krager, C. C. Seepersad, K. L. Wood and D. D. Jensen, 2006, "Adapted Concept Generation and Computational Techniques for the Application of a Transformer Design Theory," *ASME DETC/CIE Design Automation Conference*, Philadelphia, PA, Paper Number DETC2006-99584.

30. Lamplight™ LED Flashlight and Lantern,Brunton, http://www.brunton.com/product.php?id=247, 02/25/08

31. Keese, D., A. H. Tilstra, C. C. Seepersad and K. L. Wood, 2007, "Emprically-Derived Principles for Designing Products with Flexibility for Future Evolution," *ASME DETC/CIE Design Theory and Methodology Conference*, Las Vegas, Nevada, Paper Number DETC2007-35695.

32. Torchmate™ CNC Cutting Systems,CNCRetro, http://www.cncretro.com/electronics.htm, 2/25/08

33. Otto, K. N. and K. L. Wood, 2001, *Product Design,* Prentice Hall, Upper Saddle River, NJ.

34. Brannan, B., 1991, "Six Sigma Quality and DFMA," *DFMA Insight,* Vol. 2, No. 1, pp. 1-3.

35. Boothroyd, G., P. Dewhurst and W. Knight, 2002, *Product Design for Manufacture and Assembly,* Marcel Dekker, New York.

36. Telenko, C., C. C. Seepersad and M. E. Webber, 2008, "A Compilation of Design for Environment Principles and Guidelines," *ASME Design Engineering Technical Conferences (DETC) 2008*, New York, New York, Paper Number DETC2008/49651.

37. Fricke, E. and A. P. Schulz, 2005, "Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle," *Systems Engineering*, Vol. 8, No. 4, pp. 342-359.

38. Palani Rajan, P. K., 2003, "Design for Flexibility - Measures and Guidelines," Mechanical Engineering, University of Texas, Austin, TX.

39. Pinyopusarerk, C., 2004, "Empirical Study of Product Flexibility Fundamentals," Mechanical Engineering, University of Texas, Austin, TX.

40. Schaefer, T. W., 2004, "Extraction of Product Flexibility Design Principles from Patent Literature and Their Application in the Design Process," Mechanical Engineering, University of Texas, Austin, TX.

41. Kuchinsky, B., 2005, "Development of Product Flexibility Principles for Engineering Design," Mechanical Engineering, University of Texas, Austin, TX.

42. Qureshi, A. M., 2006, "Flexibility: Design for Evolution," Mechanical Engineering, University of Texas, Austin, TX.

43. Qureshi, A. M., J. T. Murphy, B. Kuchinsky, C. C. Seepersad, K. L. Wood and D. D. Jensen, 2006, "Principles of Product Flexibility," *ASME DETC*, Philadelphia, Pennsylvania.

44. Keese, D. A., 2006, "Flexibility for Future Design Evolution: Guidelines and Measurement," Mechanical Engineering, University of Texas, Austin, TX.

45. Tilstra, A. H., 2007, "Review and Application of Research in Product Flexibility for Future Evolution," Mechanical Engineering, University of Texas, Austin, TX.

46. Shewchuk, J. P., 1999, "A set of generic flexibility measures for manufacturing applications," *International journal of production research*, Vol. 37, No. 13, pp. 3017-3042.

47. Jiao, J. and M. M. Tseng, 2000, "Understanding product family for mass customization by developing commonality indices," *Journal of Engineering Design*, Vol. 11, No. 3, pp. 225-243.

48. Kota, S., K. Sethuraman and R. Miller, 2000, "A Metric for Evaluating Design Commonality in Product Families," *Journal of Mechanical Design*, Vol. 122, No. 4, pp. 403-410.

49. Thevenot, H. J. and T. J. Simpson, 2004, "A comparison of commonality indices for product family design," *ASME Design Engineering Technical Conferences,* Salt Lake City, Utah.

50. Thevenot, H. J. and T. W. Simpson, 2006, "A Comprehensive Metric for Evaluating Commonality in a Product Family," *DETC/CIE Design Automation Conference*, Philadelphia, PA, Paper Number DETC2006-99268.

51. Palani Rajan, P. K., M. V. Wie, M. I. Campbell, K. N. Otto and K. L. Wood, 2003, "Design for Flexibility - Measures and Guidelines," *International Conference on Engineering Design*, Stackholm, Sweden.

52. Pahl, G. and W. Beitz, 1996, *Engineering Design: A Systematic Approach*, Springer, London.

53. Takawale, N. P., 2007, "A Methodology for Assigning a Readiness Rating in Change Modes and Effects Analysis," Mechanical Engineering, University of Texas, Austin, TX.

54. Tilstra, A. H., P. B. Backlund, C. C. Seepersad and K. L. Wood, 2008, "Industrial Case Studies in Product Flexibility for Future Evolution: An Application and Evaluation of Design Guidelines," *ASME DETC - Design Theory and Methodology Conference*, New York, NY, Paper Number 2008/49370.

55. Otto, K. N. and K. L. Wood, 1998, "Product Evolution: A Reverse Engineering and Redesign Methodology," *Research in Engineering Design,* Vol. 10, No. 4, pp. 226-243.

56. Karadeniz, E., U. Ozsarac and C. Yildiz, 2007, "The effect of process parameters on penetration in gas metal arc welding proceses," *Journal of Materials and Design,* Vol. 28, pp. 649-656.

57. Kim, I. S., C. E. Park and P. Yarlgadda, 2003, "A study on the prediction of process parameters in gas metal arc welding of mild steel using Taguchi method," *Materials Science Forum,* Vol. 437-438, pp. 285-288.

58. Siddique, M., M. Abid, H. F. Junejo and R. A. Mufti, 2005, "3-D Finite element simulation of welding residual stresses in pipe-flange joints: effect of welding parameters," *Materials Science Forum,* Vol. 490-491, pp. 79-84.

59. Teng, T. L. and C. C. Lin, 1998, "Effect of welding conditions on residual stress due to butt welds," *International Journal of Pressure Vessels and Piping,* Vol. 75, pp. 857-864.

60. Kim, I. S., Y. J. Jeong, I. J. Son, I. J. Kim, J. Y. Kim, I. K. Kim and P. Y. K. V. Yaragada, 2003, "Sensitivity analysis for process parameters influencing weld quality on robotic GMA welding process," *Journal of Materials Processing Technology,* Vol. 140, No. 676-681.

61. Kim, I. S., K. J. Son, Y. S. Yang and P. K. D. V. Yaragada, 2003, "Sensitivity analysis for process parameters in GMA welding processes using factorial design method," *International Journal of Machine Tools & Manufacture*, Vol. 43, pp. 763-769.

62. Palani, P. K. and N. Murugan, 2006, "Selection of parameters of pulsed current gas metal arc welding," *Journal of Materials Processing Technology,* Vol. 172, pp. 1-10.

63. Ghosh, P. K. and A. K. Ghosh, 2004, "Control of residual stresses affecting fatigue life of pulsed current Gas-Metal-Arc weld of high strength aluminum alloy," *Mettalurgical and Materials Transactions,* Vol. 35A, pp. 2439-2444.

64. Iordachescu, D., L. Guintino, R. Miranda and G. Pimenta, 2006, "Influence of shielding gases and process parameters on metal transfer and bead shape in MIG brazed joints of thin zinc coated steel plates," *Journal of Materials and Design,* Vol. 27, pp. 381-390.

65. Moller, R. V., 2008, "Design and Fabrication of an Instrument to Test the Mechanical Behavior of Aluminum Alloy Sheets During High-Temperature Gas-Pressure Blow-Forming," Mechanical Engineering, University of Texas, Austin.

66. Cate, J. A. T., 1992, "Scattering of Sound by Sound: Nonlinear Interaction of Collinear and Noncollinear Sound Beams," Mechanical Engineering, University if Texas, Austin.

67. Two Timer,Topeak, http://www.topeak.com/products/Mini-Pumps/TwoTimer, 7/16/08

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