Principles for Designing Products with Flexibility for Future Evolution[1]

Abstract: The capability of a product design to be redesigned quickly and economically into subsequent product offerings is defined as its flexibility for future evolution. In this paper, a comprehensive set of design guidelines is created for product flexibility by merging the results of two research studies—a directed patent study of notably flexible products and an empirical product study of consumer products analyzed with a product flexibility metric. The guidelines are organized in categories that describe how and under what circumstances they increase flexibility for future evolution. The guidelines are critically evaluated by comparing them to existing literature on closely related topics, including product platforms and mass customization. Two examples are provided to illustrate how the use of the guidelines can improve a product's flexibility for future evolution.

Keywords: Flexibility for future evolution, product flexibility, design guidelines, design principles, product architecture, change propagation

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1. INTRODUCTION

Product flexibility for future evolution is defined as the ability to redesign a product quickly and inexpensively to meet changing requirements. These changing requirements may include shifting customer needs, advancing technology, or expanding markets. Since these changes are difficult to predict, product designs may need to be evolved over time in unanticipated ways. These unexpected redesign activities are referred to as future evolutions of a product, which are common in a variety of systems (Wheelright and Clark, 1992) from helicopters (Clarkson, Simons and Eckert, 2004), space systems (Siddiqi and De Weck, 2008), and aircraft (Saleh, Hastings and Newman, 2002) to sensor systems (Giffin *et al.*, 2009).

Product flexibility for future evolution can be distinguished from other product attributes such as changeability, reconfigurability, adaptability, and robustness. Changeable systems are defined as "those systems whose configurations can be changed, altered, or modified with or without external influence after the system has been deployed (Ferguson *et al.*, 2007)." Reconfigurable systems are a subset of changeable systems that are capable of specific, repeatable transformations, often involving changes of state during deployment (Ferguson *et al.*, 2007;Siddiqi and De Weck, 2008;Singh *et al.*, 2009). Similarly, adaptable systems are often defined as a specific type of reconfigurable system that is capable of changing its configuration *without* external intervention after it has been deployed (Fricke and Schulz, 2005;Ross, Rhodes and Hastings, 2008). Whereas reconfigurable systems research is generally focused on modifying the configuration of a product or system as it is being used, the research presented in this paper is focused on *redesigning* a product to meet changing needs and requirements that cannot be met in any other way. When a product is redesigned over time, it is said to evolve (Ferguson *et al.*, 2007;McManus and Hastings, 2006)—a type of change that is facilitated by flexibility or the ability of a system to be changed easily to meet new requirements or objectives (Ferguson *et al.*, 2007;McManus and Hastings, 2006;Roser and Kazmer, 1999;Ross, Rhodes and Hastings, 2008;Saleh, Hastings and Newman, 2002;Thomke, 1997)].

Product flexibility for future evolution can also be distinguished from product platform and product family design. Families of products are typically derived from a product platform "either by adding, removing, or substituting one or more modules to the platform or by scaling the platform in one or more dimensions to target specific market niches (Simpson, 2004)." Several product platform-based design strategies have been suggested, including standardization (Collier, 1981;Kota, Sethuraman and Miller, 2000;McDermott and Stock, 1994;Uzumeri and Sanderson, 1995), robustness (Rothwell and Gardiner, 1990), scalability (Farrell and Simpson, 2003;Hernandez *et al.*, 2001;Simpson, Maier and Mistree, 2001;Simpson, Seepersad and Mistree, 2001), and modularity (Dahmus, Gonzalez-Zugasti and Otto, 2001;Fujita, 2002;Gershenson, Prasad and Zhang, 2003;Holtta-Otto, Tang and Otto, 2008;Rosen, 1996;Sosa, Eppinger and Rowles, 2003;Stone, Wood and Crawford, 2000;Ulrich, 1995), along with some qualitative guides and frameworks for product family design (Fujita, 2002;Gonzalez-Zugasti, Otto and Baker, 2000;Martin and Ishii, 2002;Nelson, Parkinson and Papalambros, 2001;Tseng and Jiao, 1999). Whereas product platform design strategies are aimed at meeting a predefined set of requirements with a common product core, product flexibility research is focused on designs that can be evolved quickly and economically to meet new and unanticipated requirements.

A product that is flexible for future evolution has physical attributes that make it faster and easier to redesign it into a future product offering. The manner in which the components of the product are physically oriented relative to each other, the interfaces between them, and the form of the components themselves are important factors that determine whether a design is flexible enough for future evolution (Palani Rajan *et al.*, 2004).

This type of product redesign is particularly challenging because it often takes place after a design has been finalized and launched, and manufacturing tools and processes have been established.

To support this evolutionary process, design tools are needed for quickly and economically innovating and selecting designs that are flexible enough to accommodate unanticipated future changes. Recent research in change propagation has focused on predicting and managing the chain of design changes that often results from an initial design change (Clarkson, Simons and Eckert, 2004;Eckert, Clarkson and Zanker, 2004;Giffin *et al.*, 2009). Design structure matrices, for example, are used for modeling the interactions between components (Tilstra, Seepersad and Wood, 2009), predicting chains of change propagation, and analyzing the likelihood and risk of change for specific components (Giffin *et al.*, 2009). Based on change propagation analyses, components can be classified as change absorbers, multipliers, or carriers, depending on the relative number of changes absorbed and initiated by a specific component (Eckert, Clarkson and Zanker, 2004). Since change propagation research is focused primarily on retrospective analysis of an existing design, design tools are still needed for proactively infusing flexibility into a system during the design process.

Design guidelines and principles are often useful for informing the design process, even during the early conceptual stages of design. Fricke and Schultz (2005), for example, compiled a set of principles for design for changeability; examples include autonomy, scalability, modularity, and independence. Similarly, Simpson and coauthors (1998) proposed a set of guiding principles (modularity, mutability, and robustness) for designing open engineering systems "that are readily adaptable to changes in their environment." Although these high-level principles are useful for organizing and articulating overall design strategies or directions, it is also important for designers to have actionable tips or guidelines, such as a set of specific architectural features that typically contribute to modularity.

In this paper, a set of guidelines is presented for designing products with embedded flexibility for future evolution. The guidelines are categorized by high-level principles, but each principle is accompanied by a list of actionable guidelines intended to provide concrete advice for implementing each principle. The guidelines are derived from empirical patent and product studies, as part of the research approach described in Section 2. The design guidelines themselves are presented in Section 3, along with their relationship to existing literature. In Section 4, the guidelines are used to design representative products for future evolution and to retrospectively evaluate a commercial product that has undergone an evolution.

2. RESEARCH METHODOLOGY

The guidelines presented in this paper are the results of an ongoing research effort (Keese, 2006;Kuchinsky, 2005;Munoz, 2004;Pinyopusarerk, 2004;Qureshi, 2006;Schaefer, 2004) that focuses specifically on the goal of improving product flexibility for future evolution by establishing a set of design guidelines. A research methodology was developed for this purpose. As shown in Figure 1, the guidelines were developed by merging the results of two independent research studies: a directed patent study of notably flexible products and an empirical product study of consumer products analyzed with a product flexibility metric. Each of these studies was based on an inductive research approach. The benefits of utilizing different methodologies to develop the guidelines included more comprehensive results and greater cross-validation. The combined list of guidelines was then compared to design approaches in other product flexibility research to establish the extent of overlap with previous research.

In the directed patent study, a filtered set of over 250 patents was analyzed for characteristics related to flexibility, and the resulting insights were used to derive design guidelines. This set of filtered patents resulted from a search of over 500,000 patents carried out in parallel by five independent research assistants (Keese, 2006;Kuchinsky, 2005;Munoz, 2004;Pinyopusarerk, 2004;Qureshi, 2006;Schaefer, 2004), who systematically compared and combined their independent results. Qureshi (2006) presents a detailed description of this methodology.

Four methods of filtering were used to create the set of filtered patents: keyword searches for patents referring to the term flexibility or related synonymous terms (e.g., modifiable, adaptable, accommodating), searches for patents that have evolved using assignee names and chains of references, searches for continuation-in-part patents that become children and grandchildren of an original patent, and keyword searches for words related to hypothesized design guidelines. Over two-hundred and fifty patents, primarily in the mechanical domain, were filtered from the USPTO (US Patent and Trademark Office) database and other repositories such as “freepatentsonline” for detailed analysis and dissection. The information gathered from these patents led to insights into design characteristics associated with flexibility for future evolution. These insights were collected and organized into design guidelines, and at least five to ten independent patents were required to confirm and validate each guideline.

To further refine and verify the guidelines first developed from the empirical patent studies, two approaches were developed. First, as the filtered patents were studied and dissected, a convergence analysis was carried out, plotting the number of guidelines discovered versus the number of patents studied. Assuming the existence of a finite number of guidelines for product flexibility for future evolution, this plot should converge to an asymptote as the number of filtered patents increases. Such an asymptotic relationship was confirmed (Qureshi, 2006). Second, the design guidelines, when applied to inventive design problems, should result in inventions that exhibit the characteristics of product flexibility. Table 1 shows four example inventions from the research: an innovative running shoe evolution, an ambidextrous (reconfigurable) digital camera, a control device for precisely positioning a laserpointer, and a device that enables children with disabilities to play percussion instruments. The running shoe allows the direct evolution of current products to trail shoes, the digital camera is flexible for reconfiguration according to the dominate hand of the user and the development of new technologies in each module. The laserpointer control device allows the precise positioning of the laserpointer for use in forensics or concept instruction. The assistive technology percussion system allows children with severe disabilities to play and compose music through Big Mac switch interaction. New instruments may be added, or new sensory devices may be added, to the device due to its flexible design.

[TABLE 1 INSERTED HERE]

In the empirical product study, electro-mechanical consumer products of light-to-moderate complexity were reverse engineered and analyzed for flexibility using a Change Modes and Effects Analysis (CMEA) (Keese, 2006). CMEA is a tool for measuring the flexibility of a product for future evolutions based on a set of predicted change modes (Keese, Seepersad and Wood, 2009;Palani Rajan *et al.*, 2003). Before conducting a CMEA, each product was reverse engineered—a process that included gathering customer needs, functionally modeling each product, and disassembling each product. Next, concept generation sessions were conducted with mechanical engineering graduate students to predict potential change modes for each product in future design iterations. These change modes served as input to the CMEA of each product, and the resulting flexibility rating results were studied for insights into design factors influencing flexibility. Design guidelines were hypothesized, based on the results of the analysis, and then the guidelines were tested and revised with hypothetical applications.

After the patent study and the product study were completed independently, the two sets of design guidelines were compared and combined. A more detailed description of the empirical product study and the process of merging the design guidelines can be found in Keese *et al.* (2006;2007).

[FIGURE 1 INSERTED HERE]

3. A SET OF DESIGN GUIDELINES FOR FLEXIBILITY FOR FUTURE EVOLUTION

The resulting set of design guidelines for flexibility for future evolution is presented in Figure 2. The guidelines are organized into five different principles for improving flexibility. This organizational structure clarifies the purpose of each guideline and its potential effect on flexibility. The symbols indicate the research approach by which each guideline was identified. In addition, these guidelines are stated with a consistent lexicon structure. Each design guideline is described in Section 3.1, followed by a discussion of the guidelines' relationship to existing literature in Section 3.2. A more detailed description of the guidelines is presented in the appendix.

[FIGURE 2 INSERTED HERE]

3.1 Description of Individual Design Guidelines

Guidelines listed under the "Modularity Principle" are intended to assist the designer in increasing the degree of modularity in the device. These guidelines offer suggestions on how to create modules such that change propagation across components will be decreased. For example, Guideline 1 suggests using separate modules to perform separate functions so that if a change is required of a function it is constrained to a single module. Guideline 4 suggests dividing modules into multiple smaller, identical modules. For example, Dell™

Poweredge^{TM} blade servers are used in high power computing applications. Each ‘blade’ is a separate and autonomous processor and thus processor capability may be scaled by the addition or removal of the required number of blades.

[FIGURE 3 INSERTED HERE]

Guidelines based on the “Parts Reduction Principle” are beneficial to a product’s flexibility for future evolution because they reduce the number of parts requiring design and manufacturing changes. Guideline 8 suggests looking for ways to use duplicate parts. The Black and Decker HedgeHog XR Pivoting Head Hedge Trimmer, pictured in Figure 4, uses two identical blades that slide against each other to create shearing action. In the event of a design change to the blades, it is likely that the two blades can be redesigned together and remanufactured as one part. This likelihood is lower for a competing hedge trimmer that uses different components for the top and bottom blades.

[FIGURE 4 INSERTED HERE]

The “Spatial Principle” guidelines are intended to facilitate the addition of new functionality and rearrangement or scaling of parts. Evolutions of products often included added features or increased operating parameters that require larger components. Both of these changes require space; so, Guideline 9 suggests adding room around modules so that they can be changed or expanded without changing surrounding modules. Guideline 11 suggests making space available around the transmission components of a device so that future components can receive power from the prime mover. Guideline 12 suggests creating designs that are more “skeletal” in configuration, such as foldable sports chairs that have functional changes on the exterior of the chairs across the multiple product offerings. All three of these guidelines are exemplified in the Black and Decker Lids Off® Jar Opener transmission shown in Figure 5. The large chamber at the top of the product contains the transmission, which can be expanded to operate new functions, such as a can-opener as discussed in the example in Section 4.

[FIGURE 5 INSERTED HERE]

Guidelines under the “Interface Decoupling Principle” are intended to reduce connections between modules, and enable a device to function normally regardless of the orientation, location, and arrangement of its individual modules. By reducing the contact points between modules as suggested in Guideline 16, changes are less likely to propagate between modules. The water reservoir in the cappuccino maker in Figure 6 is connected to the casing at only four coplanar points. Changes can be made to the shape and size of this reservoir without propagating to surrounding parts. Furthermore, as recommended by Guideline 20, many consumer products use a framework to support interior modules, as illustrated by the Black and Decker Blower/Vac in Figure 7. The framework can absorb changes to any single module without forcing accommodating changes in other modules.

[FIGURE 6 INSERTED HERE]

[FIGURE 7 INSERTED HERE]

The “Adjustability Principle” guidelines are intended to enable the device to be adjusted for minor changes or to have the overhead to accept the change. If the adjustment can be made by the user of the device or during the assembly of the product, then a new evolution of the product may be avoided.

3.2 A Critical Review of the Guidelines in the Context of Related Literature

As described in Section 2, the flexibility guidelines were derived from empirical studies of products, rather than reviews of related literature. As a result, some of the principles and guidelines in Figure 2 overlap with design suggestions archived in the literature, but many of them have been uniquely identified and articulated as a result of this research. In this section, related literature is reviewed to investigate the extent of overlap between the guidelines in Figure 2 and similar design suggestions archived in the literature.

The general principle of modularity is the most frequently cited aspect of the guidelines in Figure 2. In their seminal work, Rothwell and Gardiner (1988;1990) cite modularity as an important strategy for realizing robust products that can be changed into a family of variants, and Ulrich (1995) describes the fundamental role of modularity in defining how a product can be changed. Numerous subsequent papers advocate the use of modularity for achieving product variety (Dahmus, Gonzalez-Zugasti and Otto, 2001;Fricke and Schulz, 2005;Fujita, 2002;Gershenson, Prasad and Zhang, 2003;Holtta-Otto, Tang and Otto, 2008;Rosen, 1996;Sosa, Eppinger and Rowles, 2003;Suh, 1990;Ulrich, 1995). The modularity-related guidelines (1-6) are mentioned *explicitly* much less frequently in the literature. Rothwell and Gardiner (1988), Robertson and Ulrich (1998), and Holtta (2004) suggest Guideline 5, and Ulrich (1995) and Stone and coauthors (2000), for example, recommend Guideline 6. Ulrich implicitly recommends Guideline 2 in his discussion of mapping function to form, as do Otto and Holtta-Otto (2007) in their discussion of complexity. Ericsson and Erixon (1999) also describe Guideline 2 in their discussion of modular product platforms and provide metrics for ratios of functions to parts that implicitly target Guidelines 1 and 3. Guideline 4 is closely aligned with the recommendations of several authors (Fricke and Schulz, 2005;Siddiqi and De Weck, 2008) who advocate the use of multiple common or identical modules, and it is closely related to the concept of scaling that is a common strategy for achieving product variety (Meyer and Lehnerd, 1997;Simpson, Maier and Mistree, 2001). Guideline 5 is implicitly recommended by Suh *et al.* (2007), who present a strategy for separating flexible or changeable components from standardized components in a product platform and utilizing design optimization under uncertainty techniques to embody the flexible components.

Although the parts reduction principle is mentioned very generally by some authors as a means of reducing the costs of product variety and evolution (e.g., (Rothwell and Gardiner, 1988)), it is more frequently cited as a means of increasing assembly efficiency (e.g., (Boothroyd, 1980;Boothroyd, Dewhurst and Knight, 2002)) . In fact, Guidelines 7 and 8 overlap with Design for Assembly guidelines proposed as early as the 1960s (Iredale, 1964 (8 April);Tipping, 1965), but their use as explicit guidelines for enhancing product flexibility appears to be newly articulated in this research. In related work, Stone and coauthors (2000) suggest defining modules based on a dominant flow heuristic, which is stated very differently from Guideline 7 but reinforces the overall message of grouping closely related functions into a single module.

The spatial principle is relatively unique to this research. Martin and Ishii (2002) advocate increasing the “headroom” of design specifications and offer examples that reinforce Guidelines 9 and 11, which involve leaving space for expansion of various aspects of the product. Similarly, Otto and Holtta-Otto (2007) support adjustability of interfaces between standardized modules and models that are expected to change. Ulrich (1995) discusses the negative effects of nesting on modularity and product variety, thereby implicitly prescribing Guideline 13. Guideline 13 is also common in Design for Assembly guidelines (e.g., (Boothroyd, Dewhurst and Knight, 2002)) that value assembly in open space and ease of access to important components. Guidelines 10 and 12 appear to be unique to this study, but complement Guidelines 9, 11, and 13 in terms of spatially arranging parts and interfaces to facilitate new product architectures and functionality.

The interface decoupling principle has been discussed very generally by several authors, but the specific guidelines are not typically articulated. For example, Ulrich (1995) distinguishes generally between coupled and de-coupled interfaces. Martin and Ishii (2002) stress the importance of decoupling for realizing product variety and introduce a coupling index to measure it. Both Ulrich and Robertson (1998) and Whitney (1993) discuss the importance of standardized interfaces between modules, as recommended in Guideline 14, and Fricke and Schulz (2005) incorporate common interfaces and bus architectures within their principle of integrability. Fricke and Schulz also recommend reducing the number of interfaces between modules, which aligns closely with Guideline 16. Otto and Holtta-Otto (2007) advocate simplified interfaces, which aligns closely with Guideline 17. The remaining guidelines sometimes appear as implicit features of examples in the product platform and product variety-related literature, but they are rarely articulated explicitly by the authors. Many of the guidelines do overlap with Design for Assembly rules, including Guidelines 14 and 15, which explicitly correspond to DfA guidelines suggested by several authors (Boothroyd, Dewhurst and Knight, 2002;Iredale, 1964 (8 April);Tipping, 1965), and Guidelines 19 and 21, which align closely with DfA guidelines that suggest modularizing subassemblies and eliminating fasteners. The remaining guidelines appear to be newly articulated as a result of this study, although Guideline 18 is closely aligned with strategies of decentralization and nonhierarchical integration advocated by Fricke and Schulz (2005), for example.

The adjustability principle is closely aligned with robust design methodology, which advocates the use of tuning parameters to adjust performance (e.g., (Chen *et al.*, 1996;Otto and Antonsson, 1993;Phadke, 1989)). Although Guideline 24, with its emphasis on the potential for expanding energy storage or importation, appears to be unique to this study, several authors advocate reserving margins or “headroom” for accommodating larger, heavier, or more powerful future designs (Eckert, Clarkson and Zanker, 2004;Martin and Ishii, 2002).

With the abundance of research on closely related topics, such as product platforms, mass customization, and reconfigurability, it is not surprising that some of the flexibility guidelines overlap with directives and examples in previously published research. In fact, this overlap partially validates the principles by confirming that independent researchers have arrived at similar conclusions about the beneficial, change-enabling aspects of product architecture. However, several unique aspects of the flexibility guidelines expand our knowledge of product flexibility and make the guidelines valuable tools for practitioners and researchers. As mentioned throughout this section, several of the guidelines are newly or uniquely articulated in this research. Also, unique and overlapping guidelines are synthesized into a comprehensive list, which is organized hierarchically into a set of overarching principles and actionable guidelines. Previously, many of the non-unique guidelines were scattered throughout the literature, in various references on modularity, product architecture, design for assembly, and other topics. This scattered knowledge makes it difficult for a designer to quickly assemble tips or rules of thumb for analyzing her design quickly within a fast-paced product development timeline. Finally, as noted by other authors (e.g., (Gershenson, Prasad and Zhang, 2003;Simpson, 2004)), the directives often appear as high-level strategies such as modularity, tuning, or scaling, that provide little detailed guidance on how to actually implement them on an embodiment level. The principles in Figure 2 assume the same high level of detail, but the guidelines are intended to be much more actionable for a practicing designer making decisions about product architecture.

4. EXAMPLES

Two examples are presented for investigating the effectiveness of the guidelines for analyzing and designing products with flexibility for future evolution. The first example is an analysis of two generations of an evolving consumer product, the Black and Decker Lids Off® jar opener. The example explores the ease with which the product evolved and the extent to which product flexibility guidelines could have played a role in guiding its evolution. The second example compares two mechanical systems designed and built by the authors—one with the aid of flexibility guidelines and one without. This example illustrates how product flexibility guidelines can be integrated into the development process and investigates the impact of guideline use on the flexibility of the final product.

4.1 Evolution of the Black and Decker Lids Off® Jar Opener

The Black and Decker Lids Off® product family is a recent example of a product that evolved from one generation to the next. The original Lids Off® product was designed to loosen the lids of jars (Figures 5 and 8). Black and Decker later released the Lids Off® Open-It-All® Center, an evolution of the original Lids Off® that also included a can opener and a bottle opener (Figure 8). The Open-It-All® Center was intended to be a multi-functional product with increased consumer utility, relative to the counter space it occupies.

[FIGURE 8 INSERTED HERE]

Table 2 compares the parts used in both the original product and the new evolution. These numbers reflect the number of unique parts that would be listed on separate lines of the bills of materials. Around 75% of the parts in the original Lids Off® were reused in the new Open-It-All® Center. The reused parts accounted for half of the parts in the new product. Many of these parts were injection molded plastic or stamped steel. By reusing parts from the original product offering, Black and Decker did not need to redesign manufacturing processes or tooling. Some of the common parts can be seen in the side-by-side exploded views of the products in Figure 9. Since both products were sold simultaneously in the marketplace, Black and Decker leveraged economies of scale by using common parts while still offering distinct product choices to their customers.

[FIGURE 9 INSERTED HERE]

[TABLE 2 INSERTED HERE]

It is unlikely that the two products are an example of preplanned product platform design because Black and Decker does not appear to have planned for the additional features during the design of the original Lids Off® product. Twenty percent of the original parts were very similar to parts in the new product but needed to be changed in some way. Some of these changes, such as modifications to the button and portions of the casing, could have been avoided with successful platform design. For example, as documented by Sudjianto and Otto (2001), Black and Decker successfully applied platforming strategies—specifically, slot modularity—to use the same injection molded housing for both a Black and Decker cordless drill and a Firestorm cordless drill. When the two sides of the drill housing were mated, an open space remained on the top of the drill. The Firestorm drill had a dual-speed transmission selector that fit into this gap. The Black and Decker drill had a blank part to fill the gap since it did not have a dual-speed transmission. A similar slot-modularity method could have been employed in the Lids-Off® product family. As seen in the exploded view, a majority of the components for the can opener and bottle opener were mounted onto a separate front casing piece that was inserted into the top casing. If the Lids Off® Original and Open-It-All® Center had been designed as a platform, a blank insertion piece could have been used on the original in place of the can opener module. Accordingly, the top casing shell, the top, and the button could have been reused in the Open-It-All® Center.

Nevertheless, the Lids Off® Original had a significant amount of flexibility for future evolution, and Black and Decker was able to reuse a majority of the parts. For example, although the motor is reoriented and the transmission is redesigned in the Lids Off® Open-It-All®, the change propagation is mitigated by the open space preserved around the motor and transmission in the Lids Off® Original.

4.2 A Comparison of Two Mechanical Systems

Two mechanical systems were designed and built by the authors: a seal testing system illustrated in Figure 10 and a welding test station in Figure 11. The seal testing system was designed and built by the first author before he began contributing to product flexibility research; therefore, the design process was not influenced by the product flexibility guidelines. In contrast, the welding test station was designed and built by the second author with the evolvability of the design as a specific deliverable of the project. The product flexibility guidelines were integrated throughout the design process to help reach that goal. To demonstrate the usefulness of the guidelines, the evolvability of the two systems is analyzed and compared for a set of likely change modes for each system. The guidelines are directly mapped to the change modes for which they are beneficial (or would have been beneficial if they had been applied). The example begins by describing each system and its associated design process, followed by a discussion of the relative evolvability of each system.

[INSERT FIGURE 10 HERE]

[INSERT FIGURE 11 HERE]

4.2.1 Description of Scaled Seal Testing System

The scaled seal testing system, shown in Figure 10, was designed and built for a customer who desired to perform scaled testing of a high-pressure seal. The seal was required to retain pressure while a pipe with sections of varying diameter was moved through it. Therefore, the testing system was required to apply high pressure and simulate the movement of the pipe.

The final seal testing system model is shown in Figure 12. It consists of a pressure vessel that is centrally located between two identical linear motion systems. The seal to be tested is installed on one side of the pressure vessel and the backside of the pressure vessel is sealed using a similar seal. 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 13, a closer view of one of the linear motion systems and the central pressure vessel is shown.

[FIGURE 12 INSERTED HERE]

[FIGURE 13 INSERTED HERE]

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 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. A pressure charge circuit mounted below the pressure vessel is used to maintain a consistent pressure as the pipe joint is oscillated in and out of the vessel. Without the accumulator in the charge circuit there would be an unsafe spike in pressure every time the pipe joint entered the vessel and a drop in pressure as the pipe joint left the vessel. In the event of a seal failure, a containment shell around the ends of the pressure vessel protects the surrounding equipment and technician from water spray. This feature is important to protect the ball screws from rusting.

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 or still shots of the seal during testing.

The customer had begun designing the test system but required assistance in the detailed design and integration of the final system. Based on preliminary design concepts, long lead-time items were ordered that effectively fixed the general architecture of the system. However, due to the complexity and large scale of the system, much design effort was required to integrate these components into an automated testing system.

4.2.2 Welding System

The welding system shown in Figure 11 was designed and built for a national laboratory that sought to perform repeatable gas metal arc welds on laboratory test specimens. The overall purpose of the project was 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. This task is practically impossible to perform manually, 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 researchers.

The final layout of the test station, as shown in Figure 14, is composed of five separate modules that carry out the main functions of the system. The frame/base assembly is the common platform to connect all other modules. 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 a motor assembly with a belt pulley system, moves the sliding linear weld surface with a rack and pinion drive mechanism. The motor assembly secures the motor and isolates it from the welding current during operation. The torch mount holds the welding torch in a steady position during the welding process.

[INSERT FIGURE 14]

In addition to the modules shown in Figure 14, the welding system includes motion control hardware, data acquisition hardware, and a personal computer for operating both. The motion control hardware consists of a standard motion controller/driver combination. To acquire a temperature profile, thermocouples and a block of thermocouple signal conditioning modules are used. The data acquisition and the motion controls are integrated in a LabVIEW virtual instrument that synchronizes the position of the test piece with the temperature measurements. The weld speed, number of passes, and data sampling rate are all process parameters that can be adjusted within the graphical user interface of the virtual instrument.

4.2.3 Design Process for the Mechanical Systems

The design process of the seal testing system is considered to be a ‘typical’ design process, consisting of the basic steps of project initiation, conceptual design, detailed design, manufacturing, integration, and project completion. This process is shown in Figure 15. Almost all design projects require iteration at some point to refine component or subsystem designs that are found to be incompatible with the rest of the system. In Figure 15, the iteration that was required during the design of this system is shown. However, major iteration between the high level steps of the process was avoided by clearly defining subsystem boundaries and interactions at the beginning of the project.

[INSERT FIGURE 15]

The welding test station was designed using a process similar to that of the seal testing system, but the flexibility for future evolution guidelines were used at key design and decision making steps. The shaded blocks in Figure 15 represent the steps where the flexibility for future evolution guidelines were utilized during the design of the welding test station.

To generate concepts for the welding test station, a group of graduate students was asked to participate in a 6-3-5 concept generation session (Otto and Wood, 2001). The students were given the functional requirements of the system, but were not shown the guidelines for flexibility for future evolution. The session resulted in a set of five unique concepts. To refine this set, the 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 in Figure 2, 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 distinct 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 variation. To accommodate this potential change, the surface was split into multiple, smaller pieces that are removable to accommodate specimens of different lengths, 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 flexibility for future evolution guidelines were incorporated in the design of the welding test station whenever possible, and it was hypothesized that this would result in a more evolvable product. In the next section, the evolvability of the seal testing system and the welding test station are analyzed and compared to determine the effectiveness of using the guidelines in the design process.

4.2.4 Analysis of Evolvability

The evolvability of each system is evaluated by analyzing the reusability of its components for a representative set of likely change modes. As documented in Tables 3 and 4, five change modes for each system were selected to cover the range of possible ways in which each system may evolve. Although each system's change modes are unique, an effort was made to select matching change modes that trigger equivalent types of design evolutions in each system. For example, increasing the pipe stroke length and increasing the weld pass length (the second change modes) both require processing parts of longer dimensions. For each change mode, redesign concepts are generated, and the concept that best meets the requirements of the change mode is selected and used to evaluate the flexibility of the current product. The numbers of parts that can be readily reused are counted for each change mode. This evaluation is carried out at the component level using the list of components from the product's bill of materials. The list of readily reusable parts does not include any parts requiring additional analysis to determine their reusability. The number of readily reusable parts is divided by the total number of components listed in the bill of materials (not including fasteners) to calculate the percent of readily reusable parts. This ratio compares readily reusable parts to total parts, as follows:

$$\%RR = \frac{\text{\# of readily reusable parts}}{\text{Total \# of parts}} * 100\% \tag{1}$$

[INSERT TABLE 3 HERE]

[INSERT TABLE 4 HERE]

The results of the reusability analysis are summarized in Tables 5 and 6, for the change modes listed in Tables 3 and 4. As predicted, the welding test station can be redesigned to meet its change modes with a higher fraction of reusable parts. There are several factors, however, that prevent drawing far-reaching conclusions from this quantitative analysis. The two systems have different levels of complexity (34 versus 148 parts, for example); the change modes are similar but not precisely equivalent; and reviewing only the percentage of readily reusable parts may mask the underlying complexity of the redesign (e.g., a change in prime mover versus a modular exchange of a data acquisition tool). Accordingly, the identities of the non-reusable components are investigated (cf. the final column of Tables 5 and 6), along with examples of successfully implemented guidelines and detrimentally unutilized guidelines in Tables 7 and 8. These qualitative factors are discussed in the remainder of this section.

[INSERT TABLES 5, 6, 7, AND 8 HERE]

The seal testing system was not designed using the flexibility for future evolution guidelines, but it was intentionally designed using a modular architecture. Modules helped to divide the design process into manageable subsystems that could be designed in series by a single designer. During the CMEA process it was found that the modular architecture reduced the impact of change modes to the current design. For example, the pressure vessel is mounted on a central frame unit with a simple bolted interface that attaches to the linear motion units on either side. Significant changes can be made to the linear motion systems that pull the pipe through the pressure vessel without requiring any design changes to the central pressure vessel module. Modularity is in fact one of the general principles that are suggested by the flexibility for future evolution guidelines. However, there are many other ways in which other guidelines could have increased the system's flexibility for the selected change modes. As stated in Tables 3 and 5, many of the change modes would require significant changes to the current design. In fact, four of the five change modes will require a complete redesign of the linear motion systems, which constitute over 70% of the total component cost of the testing system and represent a significant investment of design effort. This is unavoidable because the ball screws, which provided the linear force to pull the pipe through the pressure vessel, are being used near the limits of their capability for stroke length, force, and speed. Table 7 lists just a few examples of how using the guidelines during the design process could have improved the system’s flexibility for future evolutions. A more complete table can be found in Tilstra [18].

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 16, the overall layout of the system is shown with its evolvable features and corresponding guidelines labeled.

[INSERT FIGURE 16]

As shown in Tables 6 and 8, almost all of the welding station components can be reused for Change Modes 4 and 5. As a result of implementing Guideline 9, for example, the mounting frame is taller than necessary for immediate project needs. This feature creates excess space inside the work envelope, enabling the weld surface to be raised without affecting other components. Implementation of Guidelines 10 and 20, in the form of a framework surrounding the work area, enables easy addition of a glass shield. The only potential change to the existing system is the replacement of the 5-hole T-brackets that join the upper lengthwise frame members to the middle support columns with inside corner brackets. Inside corner brackets would create 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 Modes 1, 2, and 3 exhibit less reusability than 4 and 5, but they still benefit from the implementation of flexibility guidelines. For Change Mode 3, for example, the pinion gear that drives the rack on the linear motion table must be replaced with a larger diameter gear. A larger gear increases the top speed given the rotational speed range of the existing motor. As suggested by Guideline 13, however, the pinion gear on the drive shaft is not nested inside the drive shaft assembly, which avoids redesigning or replacing components in that assembly. Change Mode 2 requires lengthening the linear motion components, including the linear bearing guide rails, the rack gear on the linear motion table, the base table, and the horizontal frame rails. Also, Change Mode 1 requires replacing the linear motion table with a radial fixture. However, unlike the seal testing system, none of the change modes require replacement of the motor and drive gear due to the modular nature of the architecture. This reusability can be attributed to the implementation of several guidelines, as illustrated in Figure 16. An example is the use of Guidelines 1 and 2 to create separate modules for the motor, drive shaft, and specimen motion, allowing for the reuse of the motor and drive shaft assemblies when the linear motion table is exchanged for a radial fixture to be mounted on the drive gear.

5. Conclusions and Future Work

Product flexibility for future evolution promises to have a profound impact on contemporary design practice. The ability to design features into products that accommodate future, yet unknown, evolutions has tremendous industrial potential and interest. We pursue the development of design principles and guidelines as a theoretical foundation for this research area. The intent of these principles and guidelines is to create a framework by which design methods may be developed and tested. It is also the intent to enhance, significantly, the innate innovative skills of designers by providing them with ideation paths that are outside and beyond their intuition, focusing on product flexibility for future evolutions that are not predicted *a priori*.

The set of principles and guidelines presented in this paper has been created by an inductive study of patents and consumer products that are known to be flexible. By comparing the guidelines developed for product flexibility for future evolution to literature on other topics of product flexibility, it is shown that the product flexibility for future evolution research has made a unique contribution to the product flexibility field. The uniqueness of this contribution is characterized by the level of detail at which the guidelines offer suggestions that will aid a designer who seeks to build flexibility for future evolution into a design. This more detailed approach brings the ability and responsibility of designing flexible products to the engineers and designers who are inventing the next generation of products and making a majority of the detailed decisions during the design process; whereas most research on product flexibility to date has focused on the planning and management level of design.

The guidelines are demonstrated using examples of consumer products that exhibit the features of the guidelines. We build upon these examples with the development of two new systems: a welding test station and a seal testing system. These exemplar product designs show, at least at a basic level, the potential of the guidelines. However, the guidelines are used as mere additions to common ideation techniques and are successful in part due to the researcher's familiarity with the guidelines. It would be useful in future work to formally implement the guidelines for product flexibility for future evolution into a systematic design methodology and supporting design methods. As part of this methodology, it would be helpful to provide methods for resolving tradeoffs associated with some of the guidelines, such as the mass- and volume-related overhead often associated with the modularity and spatial principles.

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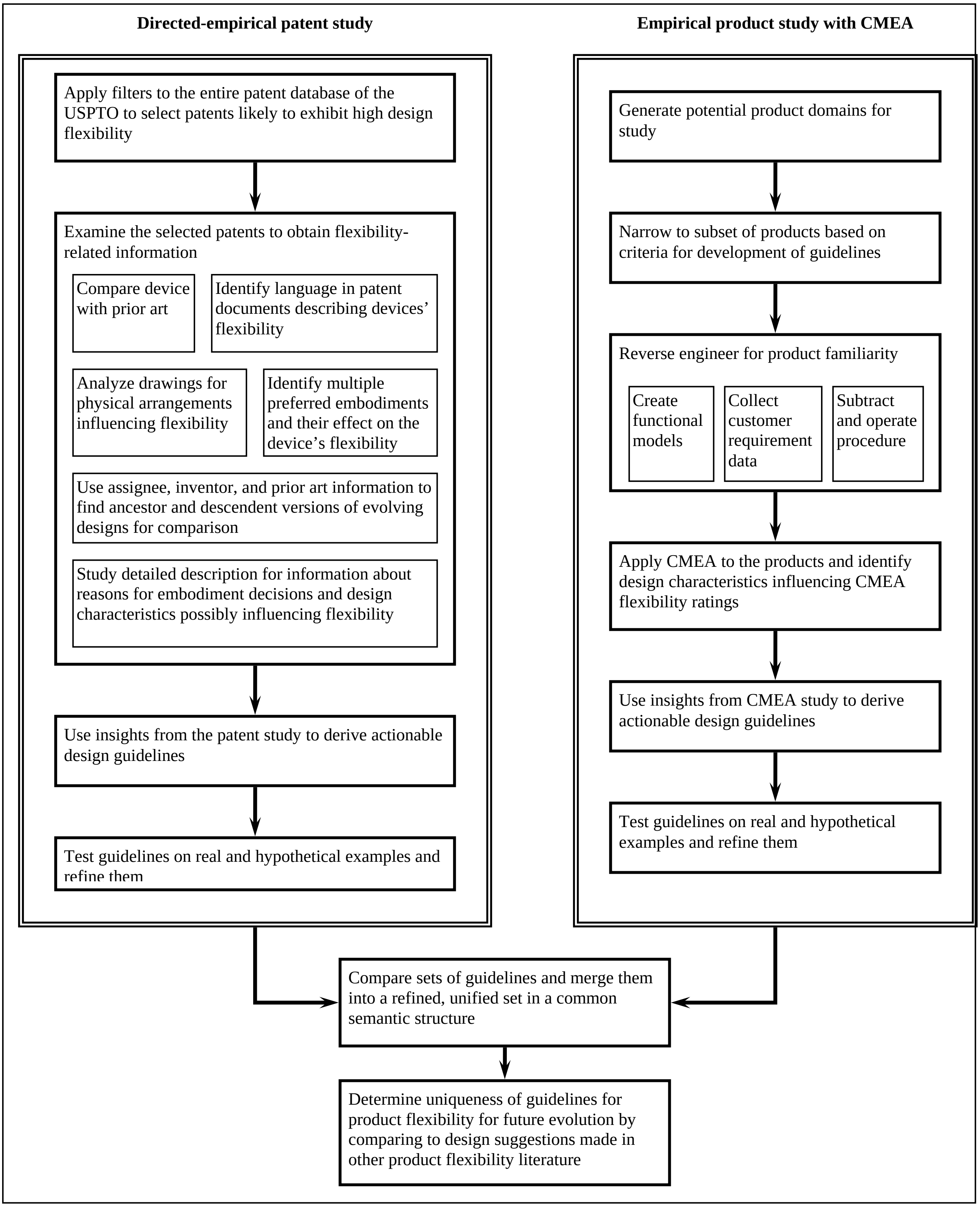


Figure 1: Research methodology

Modularity Principle

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 Principle

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 Principle

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 Principle

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 Principle

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. [†]

[*] *Discovered through the directed patent study*
[†] *Discovered through the empirical product study*

Figure 2: Guidelines for product flexibility for future evolution

Figure 3: Dell Blade Server (www.dell.com/Blades)


Figure 4: The Black and Decker HedgeHog XR Pivoting Head Hedge Trimmer

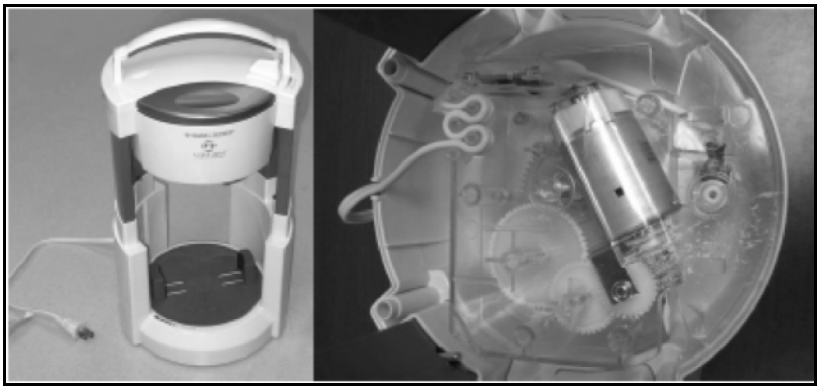


Figure 5: Black and Decker Lids Off® Jar Opener

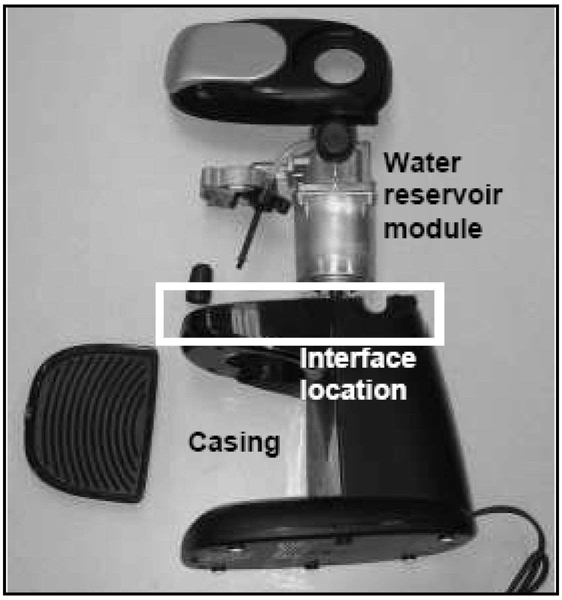


Figure 6: DeLonghi Espresso/ Cappuccino Maker

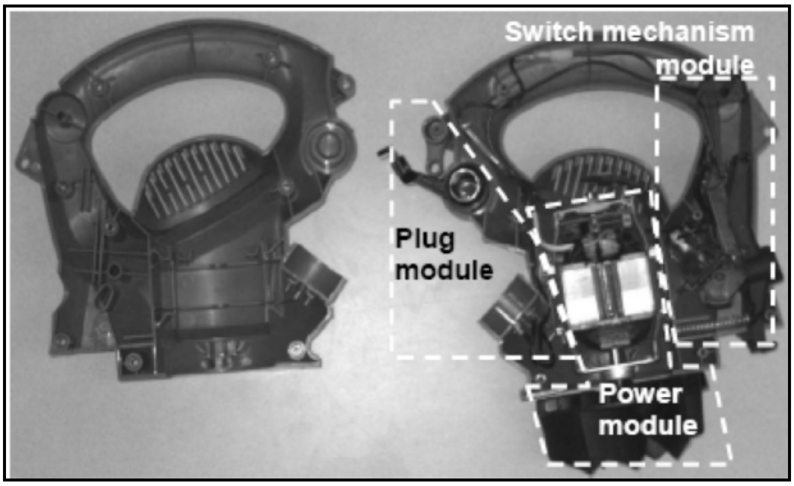


Figure 7: Black and Decker Blower/ Vac

Figure 8: The Black and Decker Lids Off® Original and Open-It-All® Center

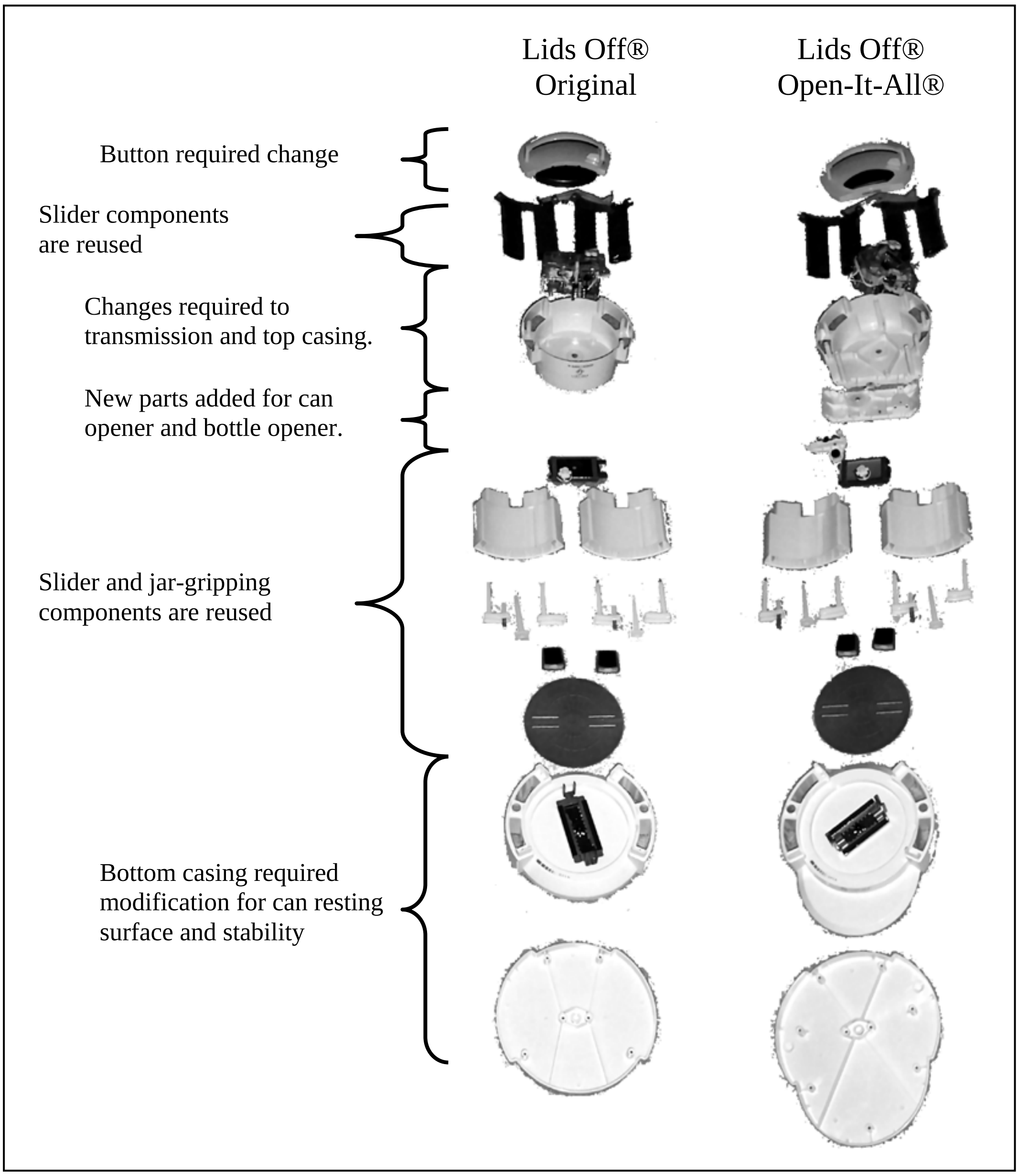


Figure 9: Exploded view of Lids Off® Original and Open-It-All® Center

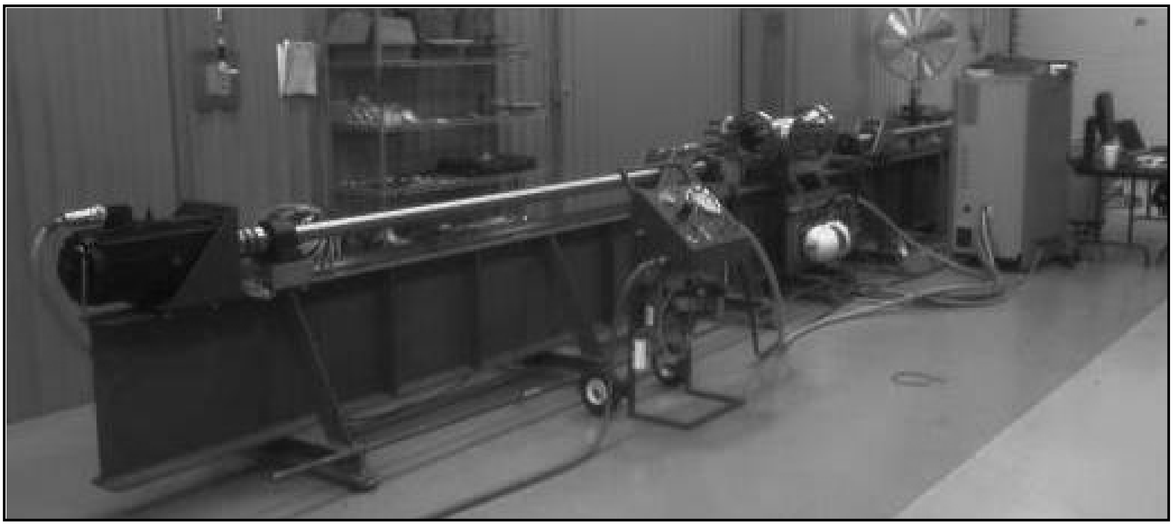


Figure 10: Seal testing system

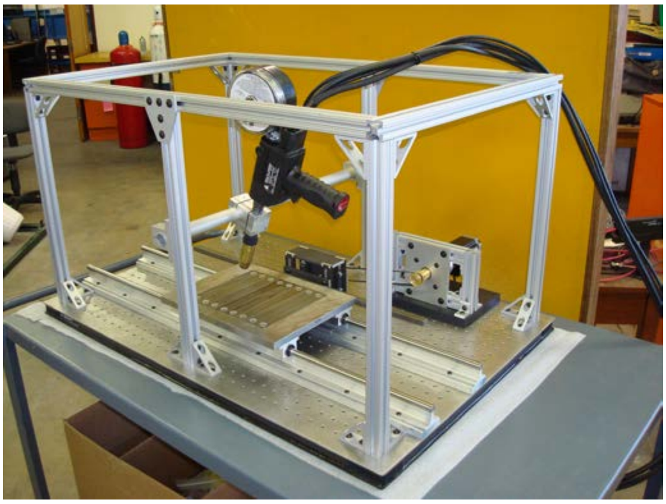


Figure 11: Welding test station

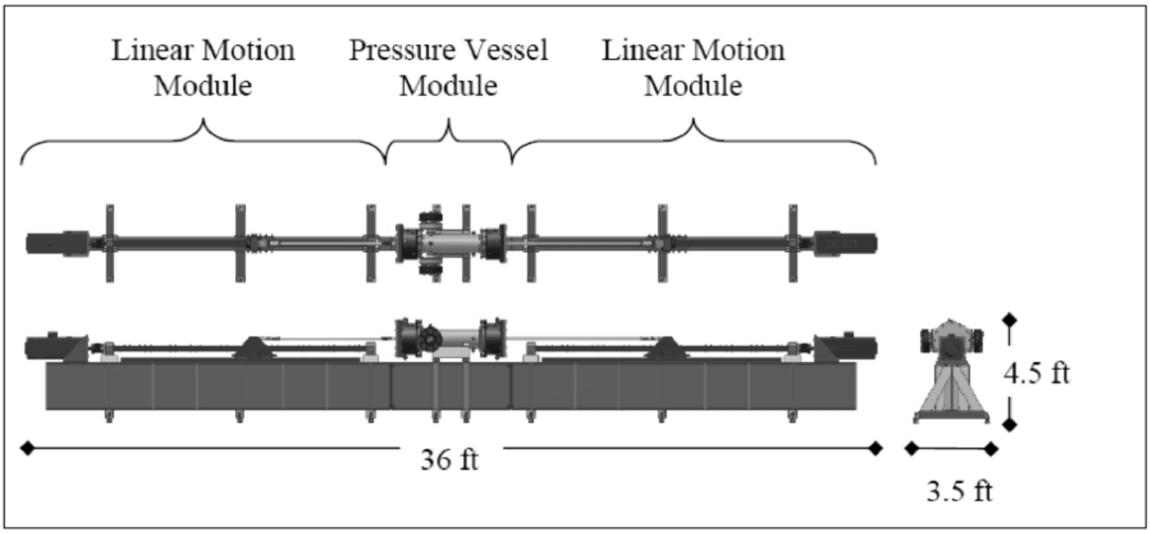


Figure 12: Overview of seal testing system

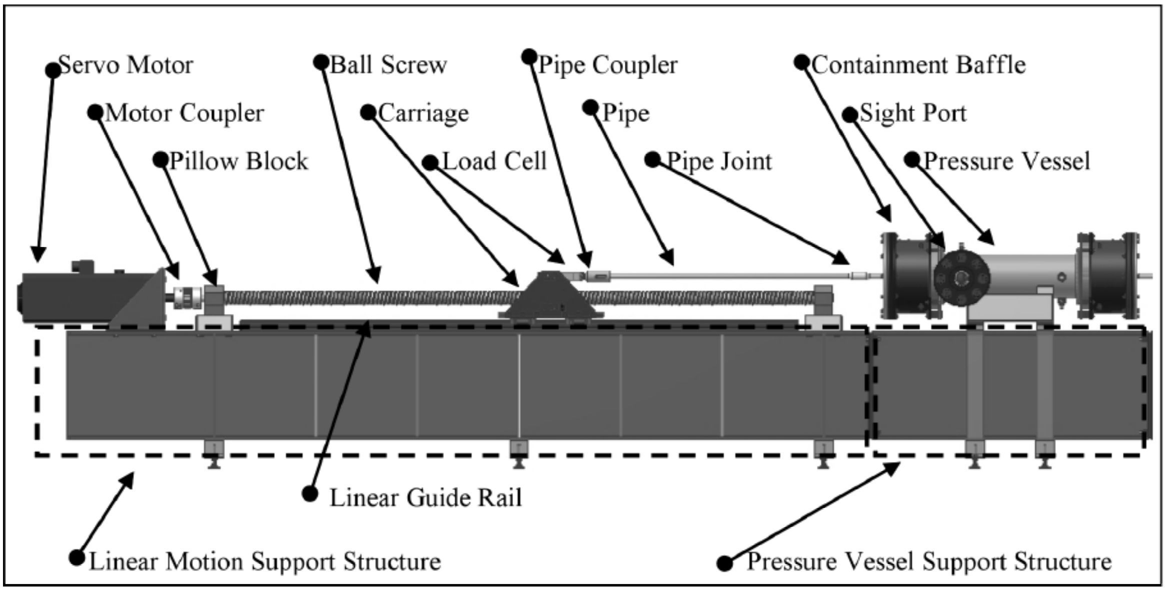


Figure 13: Linear motion system

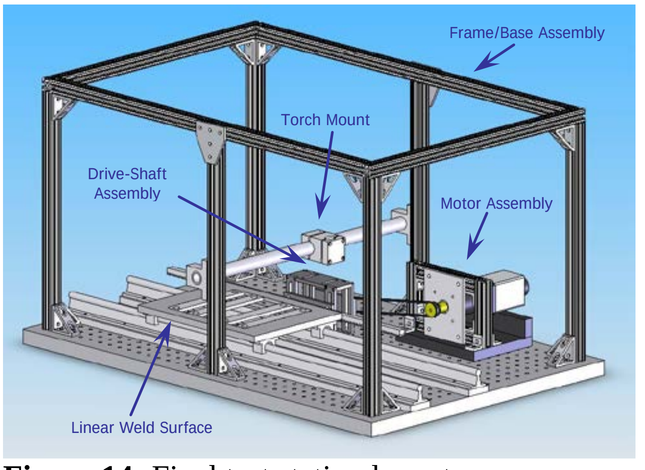


Figure 14: Final test station layout

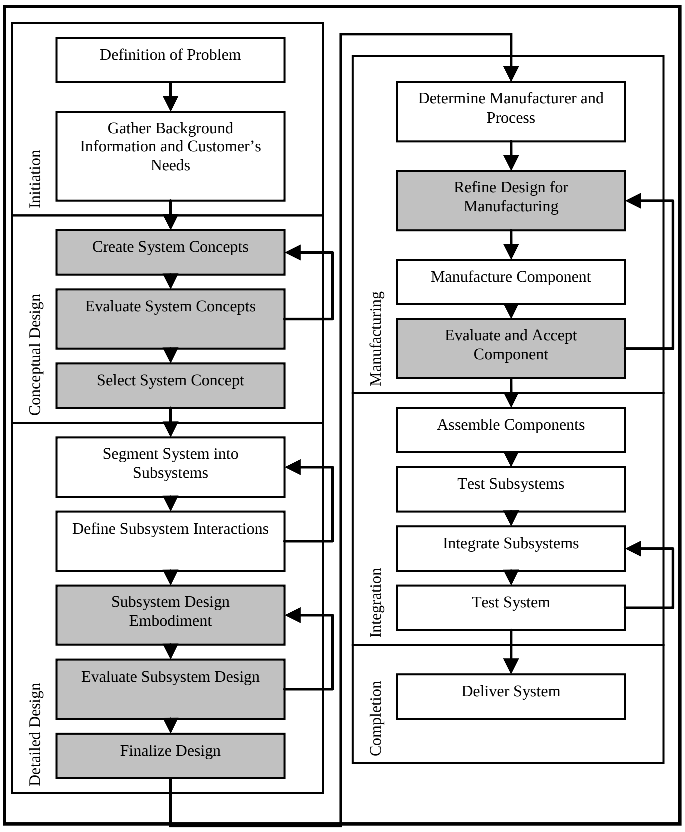


Figure 15: Design process of case studies with steps where flexibility guidelines were used shaded in gray (Welding station only)

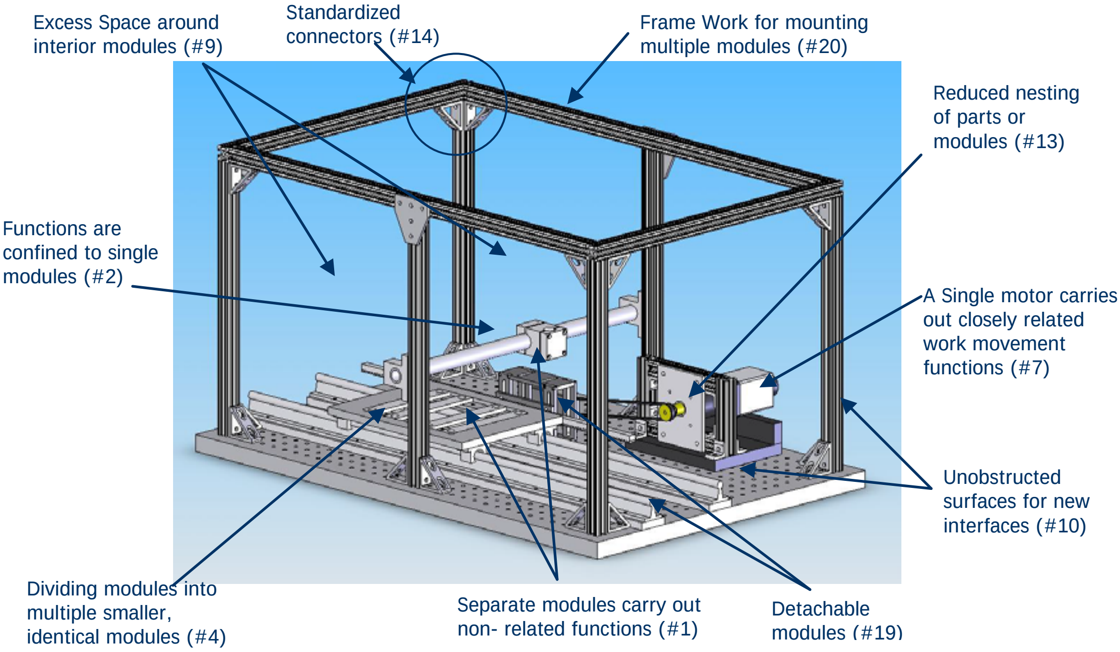


Figure 16: Welding test station with evolvable features and corresponding guidelines

List of Tables

Table 1: Validation step of flexibility design guidelines though the application to inventive problems

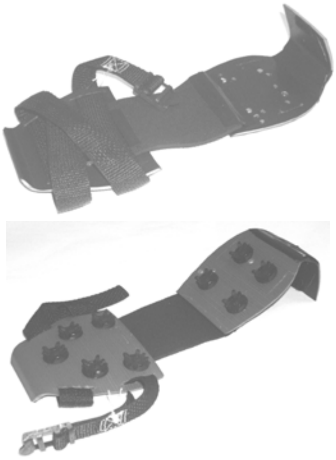
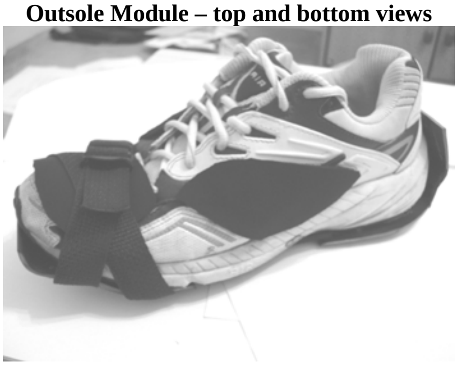
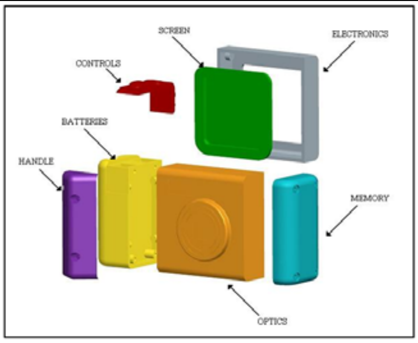
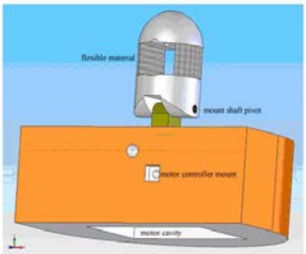
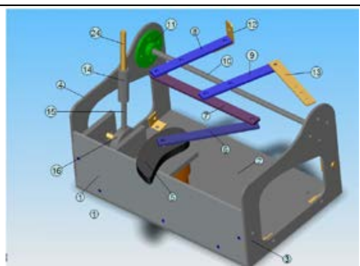
 **Outsole Module – top and bottom views**  **(a) Flexible training and trail shoe**	 **Modules of reconfigurable camera**  **(b) Ambidextrous Digital Camera (prototype)**
  **(c) LaserPointer Control Device**	  **(d) Percussion Instruments for Children w/Disabilities**

Table 2: Comparison of parts used in future evolution of Lids Off® product

Parts In Original Lids Off®				Parts In New Lids Off® Open-It-All®
3	Parts Not Reused			
14	Similar Parts	↔	14	Similar Parts
53	Reused Parts	↔	53	Reused Parts
			43	New Parts
70	Parts		110	Parts

Table 3: Change modes and evolution responses for the seal testing system

Change Mode	Evolution Response	Readiness
1 Increase number of pipe 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.
2 Increase pipe stroke length	The ball screw used cannot be made any longer. 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.
3 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.
4 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.
5 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.

Table 4: Change modes and evolution responses for the welding test station

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 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 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 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.

Table 5: Seal testing system evolvability analysis

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Description	Non-reusable components
CM 1	2	148	99%	More Tool Joints	Test pipe; Pressure vessel end cap and seal
CM 2	35	148	76%	Longer Stroke	Linear motion assembly; Motors and motor controllers; Frame; Test pipe
CM 3	25	148	83%	Increase Speed	Linear motion assembly; Motors and motor controllers; Frame
CM 4	65	148	56%	Increase Scaling Factor	Linear motion assembly; Pressure vessel; Pressure vessel supports; Motors and motor controllers; Frame; Test pipe
CM 5	31	148	79%	Run Tests Outside	Linear motion assembly; Motors and motor controllers; Frame
			79%	Average	

Table 6: Welding test station evolvability analysis

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Description	Non-reusable components
CM 1	9	34	74%	Radial Welds	Linear bearing guide rails, linear motion table
CM 2	6	34	82%	Weld Pass Length	Linear bearing guide rails, rack, base table, horizontal frame rails
CM 3	5	34	85%	Weld Speed Range	Pinion gear, drive shaft, drive shaft mounting plate
CM 4	2	34	94%	Raise Weld Surface	Linear guide rail support bars, drive shaft assembly vertical bars
CM 5	1	34	97%	Glass Shield	T brackets
			86%	Average	

Table 7: Unutilized Guidelines in Seal Testing System

Change Mode	Guidelines NOT Used	Potential Effect on Flexibility Rating
2 Increase pipe stroke length	4, 11	Use of these guidelines may have promoted the use of a cable winch system that could easily be scaled by adding multiple sections of track between the pressure vessel and the winch.
4 Increase test scaling factor	9	Use of this guideline would have resulted in a larger pressure vessel that would not need to be redesigned if the scaling factor of future evolutions was increased.

Table 8: Utilized guidelines and effects on flexibility

Change Mode		Guidelines Used	Effect on Flexibility Rating
1	Perform radial welds on circular specimens	1, 2	Separate modules for the motor, drive shaft, and specimen motion allow for the reuse of the motor and driveshaft assemblies.
4	Raise sliding weld surface	9	Excess space around the linear motion module allows it to be raised without interference.
5	Add a protective glass shield	10	Free interfaces provide exposed connection points.
		20	The framework allows for the easy addition of a glass shield.