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INDUSTRIAL CASE STUDIES IN PRODUCT FLEXIBILITY FOR FUTURE EVOLUTION: AN APPLICATION AND EVALUATION OF DESIGN GUIDELINES

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ABSTRACT

A product's flexibility for future evolution is its ability to be quickly and economically adapted to meet changing requirements. In previous work, a set of guidelines has been developed for designing flexible products. In this paper, two similar industrial case studies are presented to investigate the effectiveness of these guidelines for designing small-lot products with flexibility for future evolution. The systems are real products that have been designed and built by the authors, providing unrestricted insight into the design process and outcome of each project. The first product, a large testing system for high pressure seals, was designed without the aid of flexibility for future evolution guidelines. The second product, an automated welding test station, was designed with flexibility for future evolution as a specific deliverable of the final product. The flexibility of each system was measured by considering its adaptability to prototypical change modes. Of the two systems, the welding system was found to be more flexible than the seal testing system. The welding system also served as an example of integrating product flexibility guidelines throughout the development process.

1. INTRODUCTION

Product flexibility for future evolution is the capability of a product to be quickly and economically redesigned to meet changing requirements. Requirements may change due to shifting customer needs, advances in component technology, or expanding markets. Future trends are difficult to predict; so, specific future changes cannot always be anticipated. Accordingly it is desirable to create flexible or *evolvable* designs that can be modified in response to unanticipated changes in requirements. Evolvable product designs decrease the amount of design effort required to produce subsequent generations in a product line.

Designing mass produced, consumer products with evolvability can have significant cost and time saving advantages. For example, consider the two generations of the Black and Decker Lids Off jar opener shown in Figure 1. The first generation of this 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 [1]. This may have resulted in significant cost savings for Black and Decker, and the advantage of designing an evolvable product is clearly visible in this case.

In previous work, a set of guidelines have been developed for designing products with flexibility for future evolution (FFE) [1]. In this paper, the effectiveness of these guidelines is investigated by reviewing the design of two separate case studies. The case studies are representative of small-lot production systems; therefore, they serve a dual purpose of investigating the applicability of FFE guidelines to products beyond the typical, mass production domain for which they were originally derived. The term small-lot is used to refer to products that are manufactured in small quantities and often for a specific customer. The case studies presented here could further be defined as one-off systems since only one physical realization of the system is created. Lot size is an important consideration when selecting the manufacturing process for any product or system [2]. It is often more economical to manufacture small lots in job shops on general purpose machines such as vertical mills and engine lathes. However, as with any product, the needs of the customer and thus the requirements of the product are likely to change.

Figure 1: The Original Lids Off and the New Lids Off Open-It-All Center [3,4]

The two systems studied in this paper were manufactured in a manner that is typical for small-lot systems. Both of them were composed of a mix of custom machined parts and OEM components that were made, or ordered, in small quantities. Unlike mass produced products, the small production volume of small-lot products, and the corresponding lack of economies of scale, make the design costs of small-lot systems more significant relative to production costs. The purpose of this paper is to study the effectiveness of infusing the FFE guidelines into the design process of small-lot, complex systems.

2. RELATED WORK

Studies in modularity [5-8] have demonstrated a strong relationship between the modularity and flexibility of a product or system. With a modular architecture, design changes are localized to the module or modules being changed and do not propagate to the other modules and components of the system, thus reducing overall redesign efforts. However, complete modularity is not always achievable. Holtta-Otto and de Weck [9] show that products that are designed under stringent technical constraints tend to exhibit a more integral architecture. This suggests a need for specific product architecture guidelines for designing flexible products.

Robertson [10] defines a product platform as “a collection of assets that are shared by a set of products.” Product platforms provide a means for providing variety while keeping many of a product’s components common. Simpson [11] introduces a method for designing scalable product platforms and a corresponding family of products, thus increasing the variety of the product family through scalability. Martin and Ishii [12] propose a design for variety (DFV) method to minimize the design effort required for future generations of a product. This method uses generational variety and component coupling metrics to help designers focus on parts that could hinder future changes to the product.

Ferguson et al. [13] defined changeable systems as “those systems whose configurations can be changed, altered, or modified with or without external influence after the system has been deployed.” They also defined reconfigurable systems as a subset of changeable systems, which are systems that allow specific changes to be made repeatedly and reversibly. Katz [14] developed a set of design principles to aid designers in the development of reconfigurable machines. Reconfigurable machines are designed to accommodate specific changes that are known to the designers during the development process. The reconfiguration or adaptation is performed within the current product. The focus of flexibility for future evolution is different; it is intended to reduce the redesign effort required for addressing evolutionary changes that may not be anticipated or precisely defined during the design of the original product.

Although concepts like modularity, platform design, and design for variety have significant effects on the evolvability of a product, they are broad concepts that do not necessarily aid designers with the detailed design of evolvable products. Furthermore, associated design tools are typically aimed at meeting a *predefined* set of requirements or market segments, rather than *unanticipated* changes in requirements that prompt product evolution. Current studies in evolvability stem from the need for a comprehensive list of guidelines to help designers with architectural decision making when designing evolvable products. This effort began with several studies of US patents with obvious evolvable features to generate an initial list of 17 design guidelines [15-17]. To further expand this list, Keese et al. [1] inductively derived 14 guidelines by reverse engineering a select group of electro-mechanical consumer products. Of the sets of guidelines, 7 were common to both lists, leaving a total of 24 unique guidelines, as shown in Figure 2. Tilstra [18] demonstrates the uniqueness of the guidelines for flexibility for future evolution by showing that many of the guidelines offer suggestions that were not previously available in related design literature. This paper extends the research on product flexibility for future evolution by investigating the effectiveness of the guidelines for increasing the evolvability of a design.

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: Guidelines for Flexibility for Future Evolution [1]

3. RESEARCH APPROACH

Previous research in flexibility for future evolution was focused on empirical studies of existing products and simple design exercises. The case studies presented in this paper gave the authors the opportunity to apply this research to real products of which they were the designers and project managers. These design problems are presented in Section 4. The first system, a seal testing system, was initially being developed for use in research unrelated to product flexibility for future evolution, or product evolvability. Therefore the design of the system was not influenced by the guidelines, nor was the evolvability of the design considered as a deliverable of the project. The second system, a welding test station, was developed with the evolvability of the design as a specific deliverable of the project. The guidelines for product flexibility for future evolution were integrated into the design process from the outset to help reach that goal.

To demonstrate the usefulness of the guidelines, the systems are evaluated by considering similar prototypical change modes for each system. The ability of the design to evolve to meet the new requirements of each change mode is determined using a Change Modes and Effects Analysis (CMEA) [19]. The CMEA measures the reusability of components in the original bill of materials. The guidelines are also directly mapped to the change modes for which they are beneficial. By showing that the second system design is more easily evolved, the usefulness of the guidelines during the design process is supported.

In Section 4, the design features and intended application for each system are discussed. In Section 5, a detailed summary of the design process of each system is given. In Section 6 the final systems are presented and prototypical change modes are created. These change modes are used to analyze each system for evolvability, and the results are compared.

4. DESCRIPTION OF CASE STUDIES

Each of the systems was designed and built by the authors, who possess intimate knowledge of each system's design and functionality. Since a product's evolvability is largely determined by interactions between modules and components and their detailed design characteristics, this level of knowledge is necessary to make accurate judgments of each system's evolvability. Both systems are challenging and particularly appropriate because they are not simplified design exercises. Both were designed and built specifically to meet the needs of real customers outside of the academic department. The seal testing system is slightly more complex than the welding test station. Differences in complexity are taken into account in the subsequent CMEA analysis and comparison of system flexibility, by normalizing by the number of components.

4.1 Scaled Seal Testing System

The scaled seal testing system, shown in Figure 3, was designed and built for a customer that 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 be able to apply the pressure and simulate the movement of the pipe.

Figure 3: Scaled seal testing system

The final seal testing system model is shown in Figure 4. It consists of a pressure vessel that is centrally located between two identical linear motion systems. 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 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, a closer view of one of the linear motion systems and the central pressure vessel is shown.

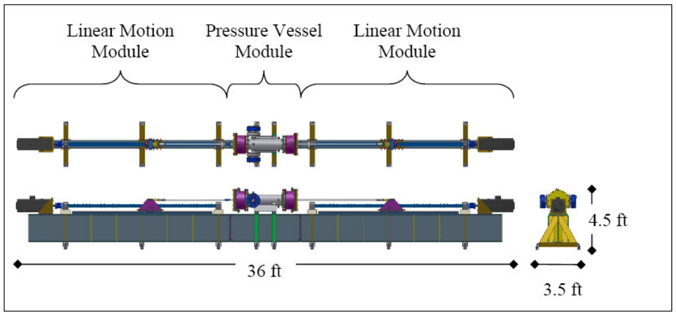

Figure 4: Seal testing system overview

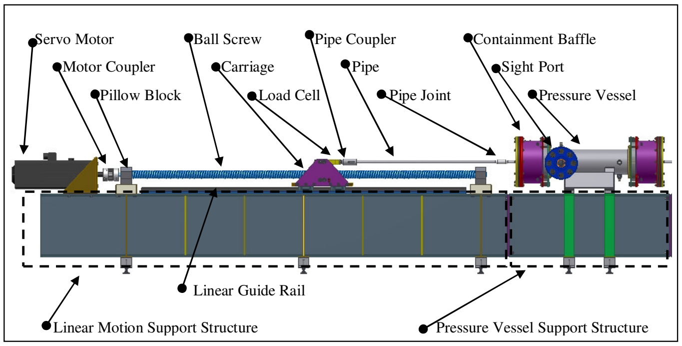

Figure 5: Seal testing system component description

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 of the seal under test or can be used to take still shots.

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. The design process is summarized in Section 5 and covered in detail by Tilstra [18].

4.2 Welding System

The welding system shown in Figure 6 was designed and built for a national laboratory that wanted to perform 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 is practically impossible to do 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 researchers.

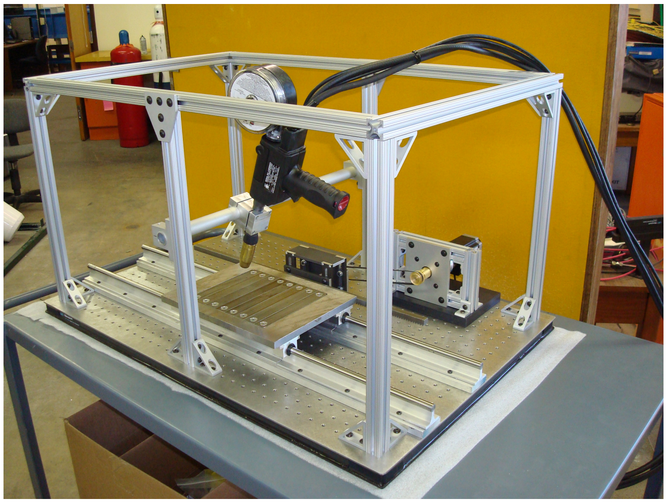

Figure 6: Welding test station

The final layout of the test station is shown in Figure 7 and 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.

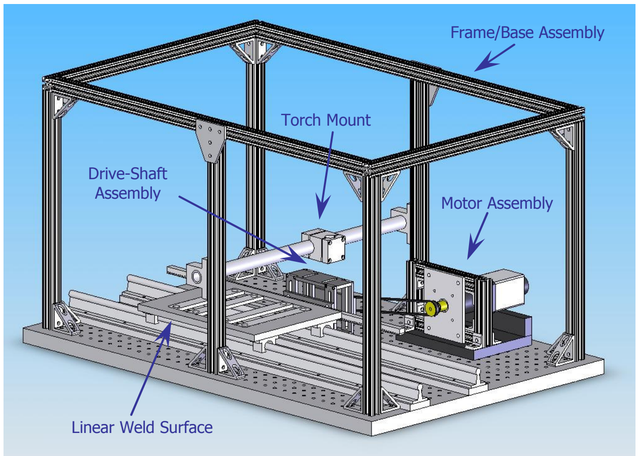

Figure 7: Final test station layout

In addition to the modules shown in Figure 7, 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 the data sampling rate are all process parameters that can be adjusted within the graphical user interface of the virtual instrument.

5. DESIGN PROCESS

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 8. 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 8, 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.

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. In Figure 8, the shaded blocks 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 [20]. 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 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 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 Section 6, 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.

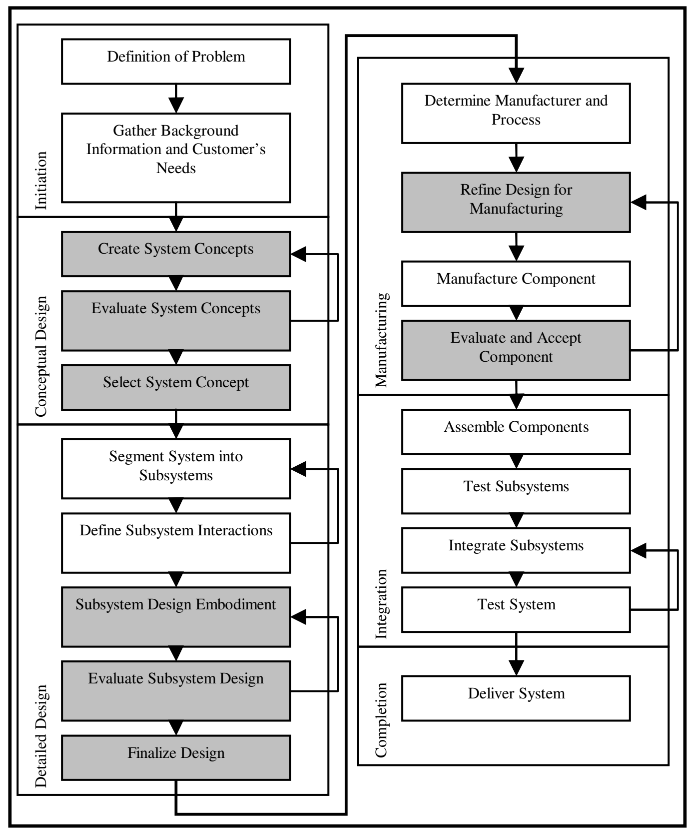

Figure 8: Design process of case studies with steps where flexibility guidelines were used shaded in gray (Welding station only)

6. ANALYSIS OF EVOLVABILITY

The evolvability of a system is evaluated by determining its change potential number (CPN) to a prototypical set of change modes using a Change Modes and Effects Analysis (CMEA) table. The CMEA is similar to that used for mass produced products, as described in [21], but has been modified for application to small-lot products as described in [18]. The CPN is a function of the design's flexibility for a specific evolution, the likelihood that the change will occur, and the readiness of the firm to adapt for that change. These ratings are determined by the process described in this section and recorded in a CMEA table (Table 1). Although the entire CMEA table is created for each case study, the focus for the purpose of this paper is on the Design Flexibility rating. The Design Flexibility rating is directly affected by decisions made during the design of the original, or parent, product. Therefore benefits from using the guidelines for evolvable products will be seen in this rating.

In Figure 9, the process chart for performing the Change Modes and Effects Analysis is shown. The deliverables are intended to record the assumptions and decisions made by the person or team doing the analysis. These files are added to the product's project folder so that the information can be reviewed in the future if an evolution of the product is required. In the following sections, the details of each step are discussed and examples are provided. Due to the large number of parts in the systems, not all deliverables are included in this paper. Examples of the complete deliverables can be found in the detailed analysis by Tilstra [18].

Table 1: Blank CMEA Table for the analysis of small-lot systems

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

In order to judge the evolvability of the designs in general, it is necessary to consider a selection of prototypical change modes that could potentially be required of a future evolution of the system. Prototypical change modes can be recalled from needs identified in customer interviews that are not met in the current generation of the product. In small-lot products such as the case studies in this paper, the customer may also express additional needs as the project progresses. General improvements in specifications may also be used to form change modes. Change modes from all of these sources must be gathered and organized into a list of prototypical change modes. The purpose is not to predict every instance of the product that could occur in the future, but rather to produce a prototypical set of change modes that adequately covers the design space of reasonable future evolutions of the product. The goal of this paper is to investigate whether using the flexibility for future evolution guidelines during the design process improves the evolvability of the final design.

Five change modes for each product were selected that cover the range of possible ways in which the products may evolve. In Tables 2 and 3, the five selected change modes for each system are recorded. To remain consistent with previous research on product flexibility for future evolution, the change modes are applied to the original design of the system, with the intention of building a second generation of the product. Although each system has some unique change modes, an effort was made to select corresponding change modes that cover an equivalent range of possible evolutions. Differences in the complexity of each system are considered by normalizing design flexibility ratings. Also, the CMEA accounts for differences in the likelihood of change modes by including an occurrence rating along with the design flexibility and readiness ratings.

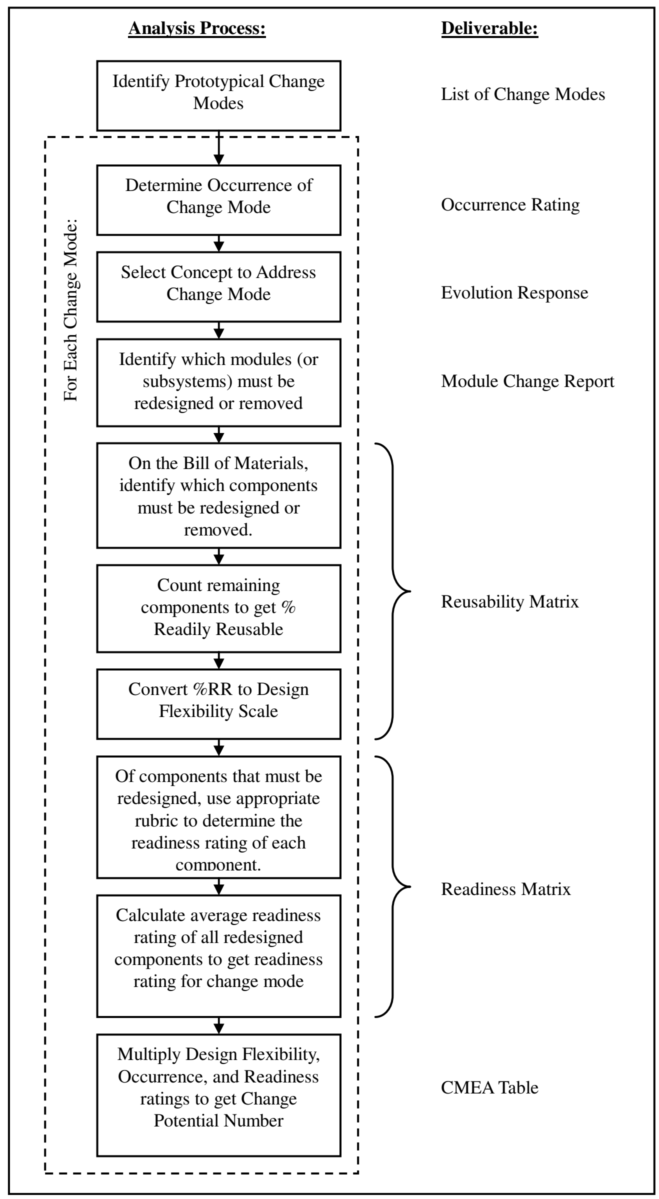

Figure 9: CMEA process and deliverables

Table 2: 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 3: 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.

Occurrence Metric

The Occurrence rating for each change mode is determined using the rubric shown in Table 4. This is similar to the rubric suggested by Rajan et al. [19]. The probability of occurrence was based on knowledge of the system and an understanding of what changes are important to the industrial partner.

Table 4: Occurrence rating metric

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

Design Flexibility Metric

For each change mode, a concept that best meets the requirements of the change mode is selected and used to evaluate the Design Flexibility and Readiness of the current product. This evaluation is carried out on the component level using the list of components from the product's bill of materials to create reusability and readiness matrices. Since the systems considered in this study have a large number of components organized in distinct modules or subsystems, it is beneficial to do this in a two step process. First, the general effect on the modules of the system is considered for each change mode, and then the individual parts in each affected module are evaluated. Any additional modules or parts needed for the evolution response are not considered in this analysis because they were not required in the original product.

The numbers of parts that can readily be reused for a specific change mode are counted. This does not include any parts requiring additional analysis to determine their reusability. This number 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:

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

The percent reusability of a design can be easily interpreted by any designer, even those not familiar with the product being discussed or the design for future flexibility research. To convert the percent readily reusable term into a Design Flexibility rating on a scale of 1 to 10, consistent with the CMEA table, the following simple conversion can be used:

$$F = \text{int}(10 - 9 * \%RR) \qquad (2)$$

If one hundred percent of the parts are reusable for a given change mode then the design is very evolvable to that change. If zero percent of the parts are reusable for a given change mode then the design is obviously not evolvable to that change. For consistency of application, the following recommendations are made. The number of total parts represents the number of lines on the bill of materials and is therefore a count of the unique parts. To prevent diluting the results, fasteners are not considered in this analysis. Fasteners are selected in conjunction with the design of the two joining parts. Therefore, the required redesign effort to replace a fastener is captured in the redesign of the parts. For the purpose of this analysis, if there is any doubt whether a component or module is reusable, it should not be considered reusable. The purpose is to make a judgment on the evolvability of the design, not to completely redesign the product. So a component is only considered readily reusable if it does not require analysis. For example, if a change mode is to significantly increase the operating loads in a system and there is some doubt as to whether a bracket will safely handle the increased loading, the bracket should not be considered a readily reusable component because it will require analysis.

Readiness Metric

The Readiness rating is meant to reflect how easily a company can implement a change in the manufacturing chain. Table 5 is similar to the rubric presented by Rajan et al. [19] although it has been inverted so that lower numbers are more desirable as suggested by Keese et al. [22]. For the small-lot products presented in the case study, much of the manufacturing of components was completed by outside companies. The time required to find and form a relationship with a vendor for the production of components can be significant. Therefore, the rubric has been adapted to be based on the relative capabilities of the vendors. Since the industrial partners have dedicated machine shops, the best Readiness rating corresponds to being able to create the redesigned part in house. The worst rating is reserved for a situation in which it is difficult to find a vendor capable of producing the requested part.

Applying the metric at the system level was too general since many different vendors were used for each system, in addition to in-house manufacturing. Instead, the bill of materials was used to record the readiness of each component marked for redesign in the Design Flexibility analysis. The individual component readiness ratings were averaged to get the overall Readiness rating for the system to the considered change mode. If a part was expected to be completely removed, and could not be adapted for use in the future evolution, it was not considered in the Readiness ranking.

Table 5: Readiness rating rubric

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

Change Potential Number

The Change Potential Number (CPN) is calculated by multiplying the Design Flexibility rating, Occurrence rating, and Readiness rating for each change mode. For this case study, the CPN has been calculated using the alternative Design Flexibility rating based on the reusability of components. Similar to the Risk Potential Number in an FMEA, the Change Potential Number can be used to rank the potential change modes in order of flexibility to future change.

7. RESULTS AND DISCUSSION

In Tables 6 and 7, the results of the CMEA for the five change modes summarized in Tables 2 and 3 are shown.

Table 6: Seal testing system CMEA

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Design Flexibility (F)	Occurrence (O)	Readiness (R)	CPN	Description
CM 1	2	148	99%	1	2	2	4	More Tool Joints
CM 2	35	148	76%	3	4	2	24	Longer Stroke
CM 3	25	148	83%	2	2	3	12	Increase Speed
CM 4	65	148	56%	4	4	4	64	Increase Scaling Factor
CM 5	31	148	79%	2	6	3	36	Run Tests Outside
				2.4			28	Average

Table 7: Welding test station CMEA

Potential Change Mode	Removed or Redesigned	Total Minus Fasteners	% Readily Reusable	Design Flexibility (F)	Occurrence (O)	Readiness (R)	CPN	Description
CM 1	9	34	74%	3	8	1	24	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
				1.8			17	Average

Noting that the Design Flexibility, Occurrence, and Readiness ratings are based on a scale of 1 to 10, with lower numbers preferred, the change modes for both systems have all received favorable ratings for Design Flexibility. However, the Design Flexibility ratings for the welding test station are lower on average than those of the seal testing system. This result suggests that using the flexibility for future evolution guidelines, as was done for the design of the welding station, improves the ability of a design to be evolved to meet future requirements. The average CPN for the welding test station is also lower than that of the seal testing system. Since the CPN includes the Occurrence rating, this result indicates that the welding test station is more flexible than the seal testing station, even when differences in the likelihood of the change modes are taken into account. It is interesting to relate these results to the use or violation of the FFE guidelines in each system.

Although the seal testing system was not designed using the flexibility for future evolution guidelines, 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. 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 Table 2, many of the change modes would require significant changes to the current design. Table 8 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].

Table 8: 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.

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

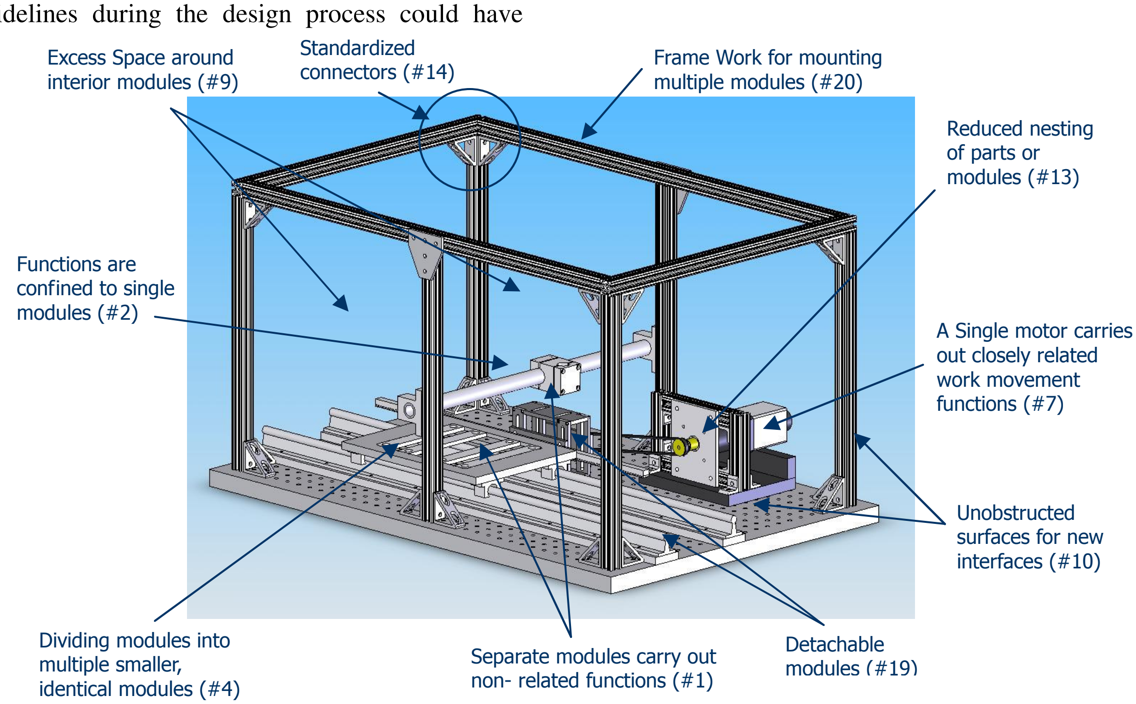

Figure 10: Welding test station with evolvable features and corresponding guidelines

The linear motion table provides a moving surface to which the test specimens can be mounted. One of the challenges faced when designing the welding surface is that it must accommodate various specimen shapes and sizes. Also, the specimens must 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 utilization of the guidelines in the design of the welding test station had significant effects on the flexibility metrics of each change mode in the CMEA table. In Table 9, some examples of how the use of certain guidelines affected the flexibility ratings of select change modes are shown.

Table 9: 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.

This analysis was performed with the intention of building an additional system to address a change mode if it occurs in the future, which is consistent with prior research on product flexibility for mass produced products. However, if the customer no longer needs the current generation of the system it can be physically updated to meet future needs. Therefore, the guidelines for flexibility for future evolution have created an evolvable design that can be used to produce not only additional systems in the future but also a system that is updateable.

8. CONCLUSION

In the previous section, many ways were identified in which the use of flexibility for future evolution guidelines (Figure 2) could have improved the evolvability of the seal testing system and did improve the evolvability of the welding test station. The analysis suggests that using the flexibility for future evolution guidelines during the design process does improve the evolvability of the final design. Further evidence is provided by the results of the Change Modes and Effects Analysis of each system. The Design Flexibility rating for the welding test station (for which the guidelines were used during the design process) is better, on average, than that for the seal testing system.

The decision to improve the evolvability of a product or system requires careful consideration of the tradeoffs between costs and benefits. For example, for the seal testing system, the guidelines would have suggested increasing the size of the pressure vessel. Although this change would have increased costs slightly, there would have been additional benefits, such as increased visibility of the seal being tested. For the linear motion systems, use of the guidelines would have suggested that a cable and winch or hydraulic system be used instead of the motor and ball screw. This change not only would have increased the evolvability of the system, but it also may have *decreased* the cost of the linear motion system.

There were also several tradeoffs for the welding test station. For example, splitting the linear motion table into multiple smaller segments added materials cost and machining time to the fabrication process. Another tradeoff involved the use of a framework for mounting multiple modules. The current system has only one module (torch mount) mounted to the frame. It would have been less time consuming and less expensive to make just enough structural material for the torch mount and none for anything else. However, the framework would not have been available for mounting subsequent data acquisition devices. In general, due to the low number of systems being fabricated, and to the high potential for change to occur, it is most likely that the benefits of implementing the flexibility for future evolution guidelines outweigh the costs.

The case studies presented in this research were a unique opportunity to apply product flexibility research to applied design problems. Although this comparison is a valuable data point for the validation of this research, it would be helpful to increase the number of systems studied in future work. Also, it would be interesting to assign multiple design teams to the same design problem with one team tasked with applying the flexibility guidelines and the other team isolated from the guidelines. However, it would be difficult to perform this experiment on the types of in-depth case studies presented in this paper because of the costs of duplicate efforts. Although every effort was made to objectively compare the case studies presented in this paper and to account for differences in complexity and change modes in the CMEA, a multiple design team experiment would be an excellent opportunity to evaluate the effectiveness of the flexibility guidelines more rigorously.

Further work also is planned to create a list of general prototypical change modes to allow non-similar products to be compared for evolvability. Lastly, a structured method for infusing flexibility into the design process would be beneficial. While the method used for the welding case study in this paper proved to be effective at increasing the evolvability of the final design, the flexibility for future evolution guidelines were used in an organic manner, and a more structured strategy for using the guidelines is needed.

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