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A PLATFORM-BASED METHODOLOGY FOR THE REDESIGN OF LOW VOLUME HIGHLY CUSTOMIZED PRODUCTS

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ABSTRACT

The new paradigm of mass customization has emerged in industry and is transforming markets by making product variety affordable with the ultimate goal of achieving mass production costs of individually customized goods and services. Achieving this goal requires a methodology for providing product variety without losing the commonality of parts needed to maintain the economies of scale inherent in mass production. In addition to the use of modularity, an emerging complementary approach is to develop a product platform consisting of common components and processes from which a family of variant products is generated. Although product platforms have successfully improved economies of scale and scope for large companies, it is questionable whether similar success can be achieved within small companies that produce highly customized products at low volume, and the focus of this research is to develop a product platform and design methodology for low volume, highly customized products. An additional focus is to determine if the ubiquitous World Wide Web can facilitate customization and improve the marketing of such products.

The dissertation presents a methodology that addresses research embodied by three fundamental questions: (1) in what ways can platform-based product development benefit small companies who produce highly customized products at low volumes?, (2) how should product platform design differ from current methods for such products, and what factors are important for defining the best platform design strategy?, and (3) how can the World Wide Web be used to facilitate customized product design for low volume products? The methodology addresses these questions by building upon existing research regarding product platform portfolio design utilizing so called bottom-up platform design techniques. A detailed methodology is presented for transforming an existing product line of low volume highly customized product into a virtual product platform portfolio through targeted component redesign. In addition, an algorithm is presented for implementing a virtual product platform portfolio through a web-based interface that allows the early incorporation of custom design requirements into the design process and includes strategies for designing custom features on demand through an engineer-to-order approach. Implementing a virtual product platform portfolio improves the specification of low volume highly customized product as it avoids the premature ordering of inventory yet allows for quick response to custom requests.

The design of yokes for mounting motor actuators on valves for use in the nuclear power industry is used as the example throughout the research. This example is highly representative of the type of product that is the focus of the methodology. The example is presented in detail such that all aspects of the methodology are demonstrated.

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Chapter 1

Introduction

The new paradigm of mass customization has emerged in industry and is transforming the marketplace by making product variety affordable to the masses. Pine (1993) defines mass customization as “At its limit, it is mass production of individually customized goods and services”. Mass customization developed out of the customer’s “push” for variety. Pine discusses the evolution of this push for United States markets since the early 1900’s, where evolving class distinctions and maturing markets created increasing demand for differentiation in product offerings. He describes five steps that a firm can implement to gradually shift to mass customization: (1) customize services around existing standardized products or services, (2) embed customizability into mass produced products, (3) create point-of-delivery customization, (4) provide quick response, and (5) modularize. He concludes that “It is therefore important for new products to meet customer needs more completely, to be of higher quality, and simply to be different from what is already in the marketplace”.

Today, companies realize that the modern consumer demands variety and that market share is best maintained through a wide range of product offerings. In addition, it is widely recognized that the failure to address even small market niches could give competitors opportunities to steal market share. One consumer may choose a product based on its brand, while another may be only interested in cost, while yet another may look for aesthetics.

However, variety comes at a price: mass customization techniques are being developed, used, and improved that provide cost savings through economies of scale and scope while still providing the necessary product differentiation. Commonality is recognized as an effective way to achieve economies of scale and scope, and successful implementation of mass customization involves optimizing the tradeoff between variety and commonality. In addition, methods are being developed for providing variety in derivative products that will efficiently meet future demand.

A common approach for providing variety without losing commonality is to employ a modular architecture (Baldwin and Clark 2000) where different product "chunks" (or modules) can be pieced together in various ways. Employing modules helps increase commonality, which results in economies of scale and scope, yet provides seemingly endless variety. However, a possible disadvantage to a modular architecture is that a product line could be easily copied.

Another approach that is becoming popular is the development of a product platform from which a family of products can be generated (Simpson, et al. 2005). A *product family* is a group of related products that share common features, components, and subsystems yet satisfies a variety of market niches. The set of common parameters, features, or components that remain constant from product to product within a given product family is referred to as a *product platform*. The product platform provides the basis for the product family, which is derived through the addition, substitution, or exclusion of one or more modules from the platform (Dahmus, et al. 2000; Gonzalez-Zugasti and Otto 2000; Martin and Ishii 2000; Ulrich 1995; Zamirowksi and Otto 1999) or by scaling the platform in one or more dimensions (Dai and Scott 2006; Fellini, et al. 2005b; Messac, et al. 2002; Nayak, et al. 2002; Simpson, et al. 2001).

A company's product line could be based totally or in part on a *product platform portfolio*, which is a collection of product platforms. The combination of a management style centered on the mass customization paradigm with a design process centered on a product platform portfolio could result in a cost-effective product development system that can provide the variety demanded by the market. An agile manufacturing system combined with a well-designed portfolio can efficiently and proactively change to meet future demand.

1.1 The Benefits of Mass Customization and Product Families

Is the adoption of mass customization techniques and product platform development a good strategy for all products and services? Like any change, it comes with a cost, and it requires a major shift in a company's business strategy. Obviously, a payback must be foreseen before a company would implement the required changes. For many large companies, implementation of product families has already proven successful, and some examples are discussed in Section 1.2. However, many small manufacturers may be hesitant to commit resources as they do not have the "deep pockets" or "financial float" of larger firms (Maupin and Stauffer 2000). Nevertheless, there may be a huge hidden cost for not committing to change, which entails increased competition and pricing pressures from those firms who successfully adopt the new paradigm.

Can a product line require so much customization that a product family is infeasible? Heavy industrial equipment used for material processing, manufacturing, or power production are good examples of products that are highly customized. These types of products can be one of a kind and can have unique design requirements. Some attempts at designing product platforms for such products are documented in the literature. For instance, Seepersad, et al. (2000; 2002) describe absorption chillers as a highly customized product, and a product platform is developed for them to satisfy a range of customer requirements. Custom equipment is also prevalent in the highly regulated nuclear power industry, and preliminary work involved with this dissertation (Farrell and Simpson 2003, 2006; Farrell, et al. 2003) describes the development of a product platform for actuator mounting yokes on nuclear grade valves.

It can be difficult to achieve and maintain commonality for companies involved with low volume highly customized products with strict customer design requirements that may vary greatly from contract-to-contract or from piece-to-piece. When a product is unique, it results in high development and production costs that are difficult to predict, and in long and uncertain production times. A manufacturer of these products may eventually develop a quasi-standard product line, but since the line is designed one custom product at a time, the full spectrum of product offerings is rarely reviewed to ensure that it is optimal for the business (Mather 1995). Focusing on custom products can result in "a failure to embrace commonality, compatibility, or standardization" (Martin and Ishii 1997), leading to a proliferation of products and parts with increasing costs and overhead. The failure potential increases by degree for highly customized product lines and is even greater for small firms.

As expressed by Anderson and Pine (1997), some companies are able to manufacture custom products somewhat quickly, but they sacrifice cost and control in the process. This is a “reactive” approach to customization, which can be very expensive. In contrast, mass customization advocates a “proactive” approach where the challenge is to achieve timely and efficient mass customization of products. This reactive verses proactive approach is illustrated in Figure 1-1.

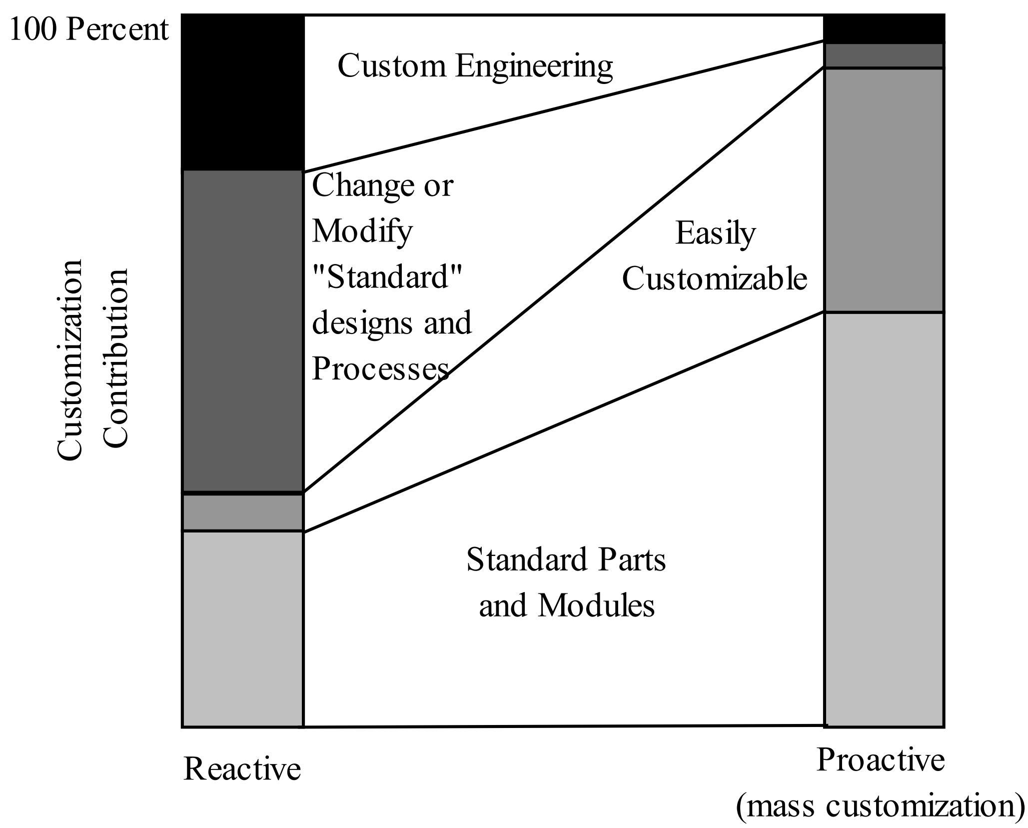


Figure 1-1: Customization Contribution for Reactive and Proactive Modes, Adapted from Anderson and Pine (1997)

1.2 Product Family Approaches and Examples

There are two recognized approaches to product line design using product platforms: *top-down* and *bottom-up*. With the top-down approach, a company starts with a 'clean slate' and strategically manages and develops a family of products based on a product platform and its derivatives. In the 1990's for instance, Sony strategically managed the development of their Walkman® products using carefully designed product platforms and derivatives (Sanderson and Uzumeri 1997). Meanwhile, with the bottom-up approach, a company redesigns or consolidates a group of distinct products to standardize components to improve economies of scale. As an example, after working with customers to individually develop over 100 lighting control products, Lutron redesigned its product line around 15 to 20 standard components that can be configured into the same over 100 models from which customers could initially choose (Pessina and Renner 1998). Another bottom-up example in the literature is the redesigned hydraulic cylinders at John Deere (Shirley 1990). Product line redesign is a major motivation for this research, and the cost savings benefits of employing the bottom-up product platform approach are investigated in detail.

Product platforms exhibit two common types of architecture. The most prominent is a *module-based* family where family members result from adding, substituting, and/or removing one or more modules from the platform. For example, Hewlett Packard successfully developed several of their ink jet and laser jet printers around modular components to gain benefits of postponing the point of differentiation in their manufacturing and assembly processes (Feitzinger and Lee 1997). An alternative architecture is with a *scale-based* product family where one or more scaling variables are used to "stretch" or "shrink" the platform in one or more dimensions to satisfy a variety of market niches. For instance, Boeing developed many of its commercial airplanes by "stretching" the aircraft to accommodate more passengers, carry more cargo, and/or increase flight range (Sabbagh 1996).

1.3 Research Objectives

Today's consumers are demanding increased variety in the products and services that they buy, and platform-based product development is essential to provide that variety in a cost-effective way. By means of product platforms, companies are able to strategically implement mass customization and plan future product offerings. As this trend continues, there may be huge hidden costs for firms that do not adopt the new product platform paradigm, especially those involved with high volume sales (Simpson, et al. 2006). If companies refuse to adapt, they may lose market share to firms that can and that have successfully reduced costs while providing the variety that market niches demand.

However, what about small firms and especially those who produce highly customized products at low volumes? In what ways can this new design approach benefit such a firm? Is there a danger of losing market share to larger firms who have learned how to meet custom requirements more efficiently? Assuming implementing product platforms for such firms is important, how should their approach be different from that of larger firms? It is generally assumed that commonality translates into cost savings through economies of scale and scope, but is this achievable with low volume products?

Consequently, two primary questions are addressed in this research:

1. *In what ways can platform-based product development benefit small companies who produce highly customized products at low volumes?*
2. *How should product platform design differ from current methods for such products, and what factors are important for defining the best platform design strategy?*

Assuming limited resources, as with many small companies, the bottom-up platform design approach is advocated in this research. Thus, a more focused research question is "How should the bottom-up platform design approach for a small company differ from that for a large company?" The goal of product platform design is an optimal tradeoff between production cost, product performance, and customer perceived variety. However, the optimal tradeoff can be uncertain, especially with low volume products, because of uncertain future demand, unknown customer requirements, and/or inaccurate cost modeling. The major task in the proposed research is to address this uncertainty with the development of a strategic platform design methodology that realistically captures future demand, customer requirements, and production costs through the use of appropriate metrics. The major research goal is to *develop a systematic approach for designing and maintaining a product platform portfolio that is optimal for a low volume highly custom product line*.

For low volume products, it is often uncertain what products will be demanded next, and an important aspect of platform portfolio implementation is to properly incorporate the voice of the customer into the process as early as possible. The research proposes using the World Wide Web to facilitate customer interaction. Then, a third research question is *"how can the Web be used to facilitate customized product design for low volume products?"*

The following section gives an overview of the methodology that was developed in response to the three motivating questions given above, and Table 1-1 summarizes these research questions and correspondingly motivated objectives. The methodology employs a bottom-up product platform design strategy to redesign an existing product line with the goal of improving cost through the introduction of design commonality. In addition, a strategy is presented for incorporating custom requirements early into the design process and strategically transforming an existing product line into a product platform that facilitates on-demand design, if necessary, and an algorithm is presented for implementing the strategy through the World-Wide-Web.

Table 1-1: Research Questions and Objectives Summary

Research Question	Research Objective
How can product platforms benefit the design of low volume highly customized products?	Develop a platform design methodology based on the bottom-up approach (see Chapter 3).
How should product platform design differ from current research, and what factors are important?	Develop a methodology to design, optimize, and maintain a portfolio of low volume custom product (see Chapter 4).
How can the Web be used to facilitate product platform portfolio implementation?	Develop an algorithm for early customizable portfolio implementation (see Chapter 5).

1.4 Overview of Dissertation

The methodology presented in this dissertation is motivated by the need to improve commonality in a highly customized low volume product line whose members were originally developed one-at-a-time to meet specific customer requirements, as it can be difficult to achieve and maintain commonality under this scenario. Redesign of a 'one-at-a-time' product line can be cost prohibitive, especially for a small firm. However, what may be justifiable is a strategic redesign of a limited set of component parts that have the highest potential for cost saving. A component part redesign effort can employ the product platform approach, and when applied across the market segment, a *component-based product platform portfolio* results.

A methodology is presented for optimizing the cost of implementing a product platform portfolio through the introduction of common design features to address the demands of a given market. It assumes that a product line already exists and that the objective is to redesign individual components that are common to all members of the product line but lack commonality between the members. The goal is to minimize manufacturing cost by minimizing the number of component product platforms required to address the market without sacrificing product performance or customer perceived variety, but this can be challenging because it involves a tradeoff between minimum cost and maximum performance. In order to incorporate custom design requirements early into the design process, the methodology proposes implementing any resulting product platform portfolios through a web-based user interface. What results is a web-based interface that implements a *virtual product platform portfolio* in that inventory is not stocked but the product is designed and produced on-demand in response to custom requests.

Chapter 2 gives an overview of existing research that forms the technology base upon which the proposed methodology is built. The developed methodology focus is a bottom-up product line redesign strategy for low volume custom products and is based on product platform design techniques. With inspiration from existing research on collaborative design using the World Wide Web as an interface, the methodology advocates a web-based implementation of any developed product platform portfolio to quickly respond to custom requests without the need to stock inventory.

In Chapter 3, this methodology is presented in detail for redesigning an existing line of low volume custom product using a bottom-up component redesign strategy and using product platforms, and the components targeted for redesign are those with the highest potential for cost savings. The steps of the methodology are outlined in detail, and the process is described by three phases of design activity including (1) collecting knowledge of the existing product line that is needed throughout the redesign process, (2) building a baseline standard product line with which to compare any redesign effort, and (3) the development of *component classes* that are instantiated to yield candidate component platforms. The resulting product platform portfolio is created using a subset of the candidate component platforms.

Applying the methodology described in Chapter 3 results in a set of candidate component platforms from which a product platform portfolio is created, and a process is required to create a platform portfolio that is the most cost effective to implement. Chapter 4 presents an optimization process that yields the most cost effective portfolio from a subset of the candidate component platforms. The process goal is to minimize manufacturing cost without sacrificing product performance or customer perceived variety.

In Chapter 5, an algorithm is presented for strategically transforming an existing product line into a virtual product platform that is instantiated on demand in response to custom specification requests. In addition, a strategy for implementing *engineer-to-order* customization is included where key design features are engineered on-demand. The algorithm also includes a strategy for inviting a user to consider a performance compromise in exchange for cost and/or lead-time savings, which further adds to design flexibility. As a result, custom design requirements are addressed early, the potential for overlooked requirements and misunderstandings is greatly reduced, and the design process is improved overall.

A single example problem is employed throughout the dissertation regarding the design of yokes for mounting motor actuators on valves for use in the nuclear power industry. The example is very representative of a low volume highly customized product line, and it is presented in much detail to demonstrate implementation of the important aspects of the proposed methodology. In Chapter 3, a yoke component class is created and instantiated to yield a set of candidate yoke component platforms. In Chapter 4, a valve product platform portfolio is created from a subset of the candidate yoke component platforms. In Chapter 5, a web-based interface is described that implements a virtual valve product platform portfolio that allows a user or sales engineer to provide a custom design specification, compromise design requirements in exchange for cost or lead-time savings, and design yoke ribs on-demand if necessary. The web-based interface demonstrates the potential for early inclusion of custom requirements into the design process, and the implementation of a virtual product family that provides true engineer-to-order customization.

The dissertation is concluded in Chapter 6 with an overall summary of the developed methodology and the contributions to the research community. In addition, the methodology's limitations are discussed along with potential opportunities for further work.

Chapter 2

Literature Review

To determine how best to design low volume, highly customized products, the following areas of research are investigated: modularity, product platform design and related metrics, and collaborative design using the Word Wide Web. The first two topics are a precursor to the focus on product platform design and web-based collaboration. These topics form a technology base for addressing the proposed three basic areas of study: (1) the bottom-up product platform design approach, (2) optimal platform portfolio design, and (3) the use of the Word Wide Web as a design interface tool.

2.1 Modular Product Architecture

The most popular approach in the literature for implementing mass customization is through modular product architectures. A well-designed modular architecture is considered an effective way to achieve economies of scale and scope, and considerable research has focused on defining and improving the architecture. Ulrich (1995) defines a modular architecture as one that "includes a one-to-one mapping from functional elements in the function structure to the physical components of the product, and specifies de-coupled interfaces between components".

Zamirowksi and Otto (1999) describe *function structure diagrams* and how a monolithic function structure, which is one that includes all members of a family of products, can be used to identify a product platform and potential modules. Dahmus, et al. (2000) present an approach for architecting a new family of products that advocates creating a generalized *function structure* for each product in a family, after which a *modularity matrix* is constructed, and then the matrix is used to identify potential modules and platforms. Siddique and Rosen (2000) propose using design spaces that model connectivity, functionality, and assemblability; consider common constraints and different viewpoints (i.e., intent, assembly, connections); and make use of the *constrained Cartesian product* to evaluate the modularity scheme.

Blackenfelt and Sellgren (2000) propose that the connecting interface between modules should be specified early to allow for parallel design activities. Their proposed approach starts with an expanded physical feasible region between interfaces, and later when more information is known, topological and shape optimization are employed to "shrink" the feasible region. The shape optimization is complemented with Robust Design techniques.

Baldwin and Clark (2000) give a thorough overview of modular design. They give a widely used definition of a module as "a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units". They look at design as an evolutionary process, describing the objects that result from design as *artifacts*, and the design process as a type of *complex adaptive system.* A set of six modular operators are defined: *splitting*, *substituting, augmenting, excluding, inverting, and porting*. Splitting is the most fundamental operator as it considers the splitting apart of an integrated design into modules or the further splitting of an existing module into sub-modules. Once a modular structure exists the other operations can be performed. Substituting, augmenting, and excluding denote the various switching that is possible with an existing modular architecture to create design variants. The last two usually occur as a design evolves. Inversion involves creating a single new module that performs a function that was previously performed internally by several modules. Porting is when a module is designed to function in two or more systems that are incompatible among themselves. The discussion focuses on the computer industry, and on the specific example of the IBM System 360 design architecture. It is shown how the structure of individual enterprises and ultimately the entire computer industry is shaped by the modular architecture of the computer artifact.

Baldwin and Clark (2000) demonstrate the use of the closely related *design structure matrix* (DSM) and *task structure matrix* (TSM). The DSM characterizes both component hierarchical dependencies and design parameter interdependencies within a design. Whereas the DSM deals with the topology of the design, the TSM characterizes the design process as it focuses on the tasks and resources involved in creating the design. Figure 2-1 gives an example DSM that addresses a portion of the parameters associated with a mug design.

Design Parameter		1	2	3	4	5	6	7	8	9	10
Material	1	o	x	x			x	x	x		x
Tolerance	2	x	o	x			x	x	x	x	x
Mfr. Process	3	x	x	o			x	x	x	x	x
Height	4			x	o	x			x		x
Vessel Diameter	5		x	x	x	o	x	x	x		
Width of Walls	6	x	x	x	x	x	o	x	x		
Type of Walls	7	x	x	x		x	x	o	x	x	
Weight	8	x		x	x	x	x	x	o	x	
Handle Material	9	x	x	x				x	x	o	x
Handle Shape	10	x	x	x	x					x	o

Figure 2-1: DSM Portion for a Mug Design (Baldwin and Clark, 2000)

Ericsson and Erixon (1999) give practical aspects of applying modularity to a product platform. They define the modular function deployment (MFD) approach, and Figure 2-2 illustrates its five major steps. The approach involves common methods and tools such as quality function deployment (QFD), design for manufacture and assembly (DFMA), and the use of a Pugh matrix, a functions and means tree, a module indication matrix (MIM), and a interface matrix. In addition, many metrics and rules are discussed that involve aspects of the design such as costs, lead time, quality, and flexibility. The input to the MFD is an infinite number of product possibilities, and the output is a modular product. Several industry examples of applying MFD are discussed, and the companies involved include Volvo Car Corporation, Atlas Copco Controls, VGG (manufacturer of the "fifth wheel" that connects to the kingpin of a semi-trailer), and Sepson (manufacturer of small winches).

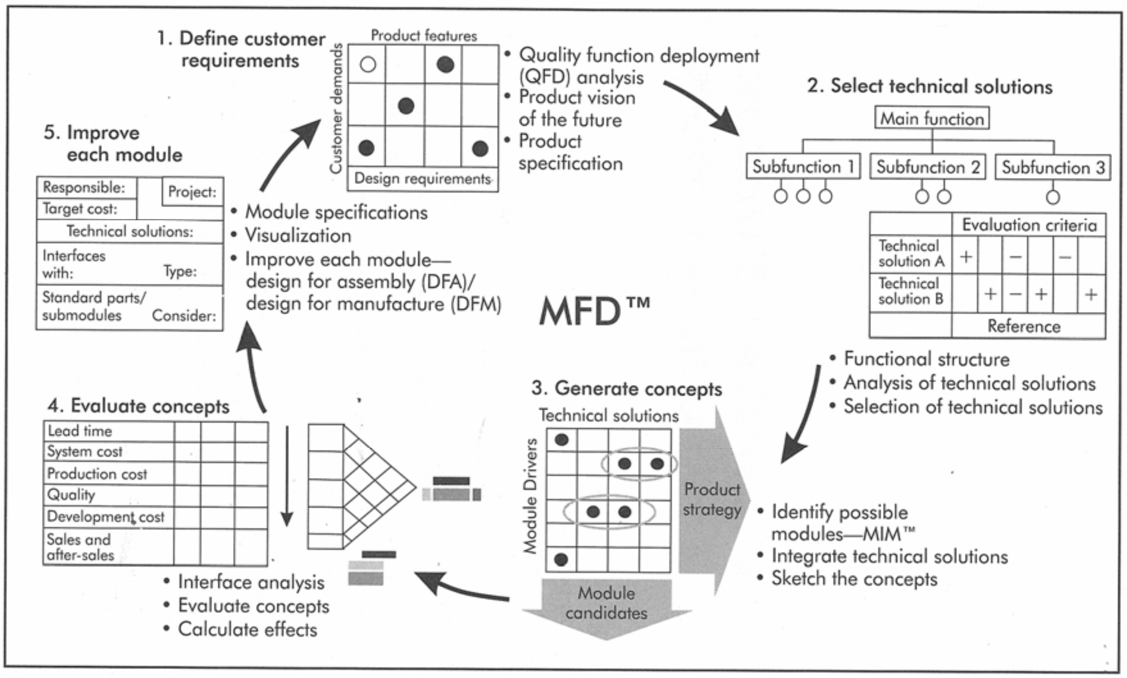


Figure 2-2: Modular Function Deployment (Ericsson and Erixon, 1999)

Gu and Watson (2001) present a modular design method called the House of Modular Enhancement (HOME) for product redesign with the goal of enhancing modularity. The method consists of three main phases: (1) generate a modular design information matrix, (2) create modules, and (3) analyze the module design. Input includes life cycle characteristics, product architecture, and function structure, and employment of a modular grouping algorithm results in the enhanced modularity.

Lipson, et al. (2001) promote modularity in evolutionary design. They define modularity as “the separability of a design into units that perform independently”, they propose that designs that exhibit modularity have higher adaptabilty and consequently have better survival rates under changing requirements, and they quantify modularity as inversely proportional to the amount of coupling in the system.

Also regarding evolutionary modular design, Allada and Lan (2002) employ a dynamic programming method for planning the launch of new modules in an evolving product family. The goal of this method is to determine (1) when to replace the modules in a product family, (2) what modules need to be replaced, and (3) what modules will serve as replacements. Both deterministic and stochastic model formulations are presented.

Ishii, et al. (2003) present results of a survey of international companies regarding their perception, definition, and use of modularity. Modularity practice in various industries is benchmarked, and it is concluded that “the form and the extent of modularity practice depend on industry specific drivers, which are largely affected by strategic preference, external uncertainties and tactical alternatives.

Similar to the focus of the proposed research, Berti, et al. (2001) advocate that small- and medium-sized enterprises employ modular design methodology in order to improve their competitiveness in global markets. They employ commercially available software to provide a flexible, inexpensive and easy to handle framework for the design of product families.

2.2 Product Platform Design

Product platform and portfolio design is the main focus of the proposed research. As discussed previously, there are two basic approaches to product family design in the literature, the top-down and bottom-up approaches; however, most research deals with the top-down approach.

Gonzalez-Zugasti, et al. (1998) present a basic platform design approach where the platform is designed from a performance valuation and team re-negotiation heuristic. A follow-up paper discusses when to introduce future platform variations based on 'real options' in lieu of traditional discounted cash flow or net present value functions (Gonzalez-Zugasti, et al. 1999).

Product platform design typically involves an attempt to optimize performance based on an objective function, and some specific examples follow. In Gu, et al. (2000), the platform problem is decomposed into business and engineering decisions, and a technique is given to minimize the deviation from system goals rather than optimize performance per se. Gonzalez-Zugasti and Otto (2000) give a method for optimizing a family with a known modular architecture using a Genetic Algorithm (GA). Siddique and Rosen (1998) use a weighted-sum of commonality indices as an objective function, and for products that are completely modular, they use the constrained Cartesian product to generate potential family members (Siddique and Rosen 2000). Farrell and Simpson (2003) attempt a bottom-up approach using the traditional Generalized Reduced Gradient method as an optimizer in conjunction with the Product Platform Concept Exploration Method to design a platform.

Simpson (2004) discusses the status of research on product platform design and optimization. He categorizes several research papers in terms of their formulation of the optimization problem (i.e., are resulting product families module-based or scale-based, is the objective function single or multiple objective, what kind of cost model is used, etc.), number of solution stages, and optimization algorithm (e.g., Sequential Linear Programming, Non-Linear Programming, Genetic Algorithms, etc.).

Sanderson and Uzumeri (1997) discuss how proper management of product families can make product evolution smooth and efficient. The concept of a *virtual product platform* is presented, which is defined as "a representation of the product that is common to a family of different models and common to a series of successive changes in their functionality."

2.3 Commonality, Variety, and Other metrics

Product family design is best achieved through a strategic tradeoff between commonality and customer perceived variety, and researchers have attempted to measure this tradeoff by means of indices. For instance, Martin and Ishii (1997; 2000) define three indices involved with design for variety, commonality, setup, generation variety, and module coupling. Maupin and Stauffer (2000) define simplicity, standardization, direct cost, and differentiation indices. Zamirowksi and Otto (1999) combine product variety heuristics with function structures to yield potential modules.

Delayed differentiation is a concept closely related to the commonality-variety tradeoff. Siddique and Rosen (1998) propose that cost savings can be achieved by delaying distinguishing features between closely related products until a late as possible into the manufacturing process. Maupin and Stauffer (2000) give simplified techniques that could be useful for small firms to reengineer a product family; delayed differentiation is advocated, and a delayed differentiation graph is defined.

Robertson and Ulrich (1998) stress the need to balance product distinguishing attributes with commonality and define metrics to measure improvement in customer satisfaction and flexibility. Measurements can help management decide on future change. However, once given a direction, a company must be committed to change for the better, but it is often a challenge to overcome long instilled paradigms that impose great inertia. A company committing to change can be like a person committing to a diet, where only a small percentage find the discipline to succeed.

Another important factor to consider in product platform design is production costs, and several recent works directly address the topic (Fujita, et al. 1999; Fujita, et al. 1998; Fujita and Yoshida 2001; Hernandez, et al. 2001; Park 2003; Seepersad, et al. 2000). Rather than rely on the traditional material, labor, and overhead model to estimate production costs, these works advocate the use of Activity-Based Costing (ABC) models that associate production cost to a set of production activities and how resources are consumed by these activities. A significant problem with the traditional costing approach is that overhead cost is allocated to all products equally, usually by a percentage markup, which can mask production inefficiencies, making it difficult to see the need for improvement because it is difficult to link overhead cost with critical design variables. The goal of the ABC approach is to capture the true production cost for individual products, for instance, Park and Simpson (2003) propose a production cost model based on a production cost framework associated with manufacturing activities that can be easily integrated within an optimization framework because production costs are properly linked with critical design variables. In addition, Anderson and Pine (1997) and

Galsworth (1994) discuss the cost of variety within the context of mass customization along with traditional costing approaches.

2.4 PPCEM and the Compromise Decision Support Problem

An important foundation of the proposed research is the *Product Platform Concept Exploration Method* (PPCEM) first presented by Simpson and his colleagues (1999). Application of the PPCEM involves solving a *Compromise Decision Support Problem* (C-DSP), which is a multiobjective optimization problem based on goal programming and math programming.

The input to the PPCEM is the overall design requirements, and the output is the product platform and resulting product family. The PPCEM consists of five steps that prescribe how to formulate the product family design problem and describe how to solve it; the actual implementation of each step is likely to vary from problem to problem. The five steps are shown in Figure 2-3 along with their associated tools/methods, and a brief overview of each step follows.

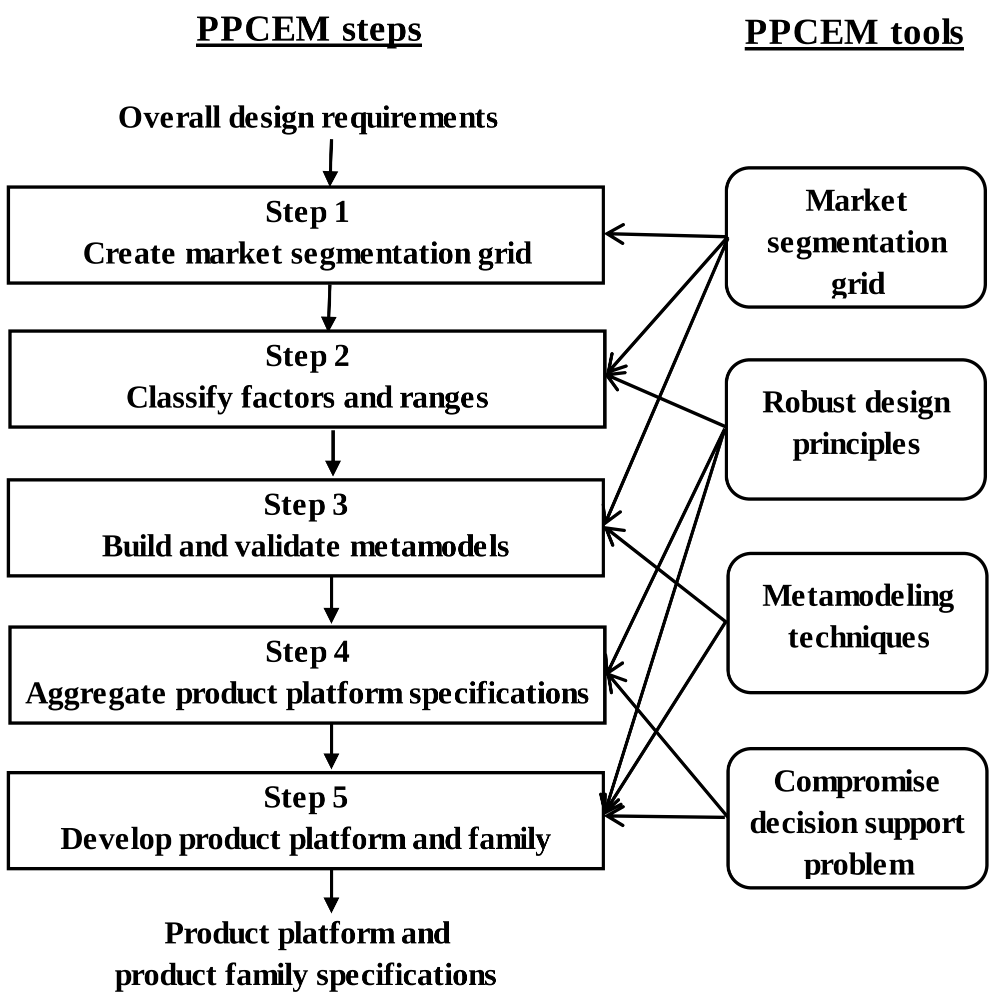


Figure 2-3: The Product Platform Concept Exploration Method

Step 1: Create the Market Segmentation Grid – This step involves mapping the overall design requirements into an appropriate market segmentation grid (Meyer 1997), as shown in Figure 2-4. The grid allows for identification of potential leveraging opportunities for the product platform to effectively satisfy a variety of market segments. As shown in Figure 2-4, horizontal, vertical, and beachhead approaches can enable effective platform leveraging both within and across different market segments.

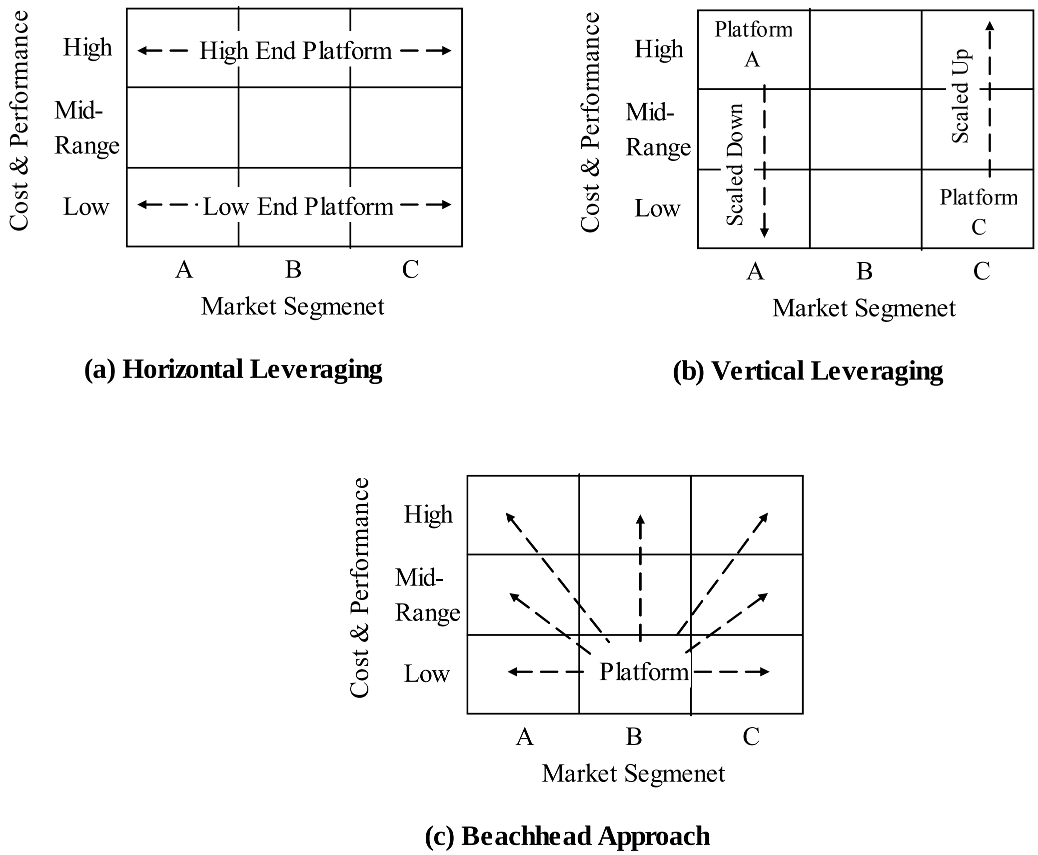


Figure 2-4: Market Segmentation Grid and Platform Leveraging Strategies (Meyer, 1997)

Step 2: Classify the Factors and Ranges – This step involves mapping the overall design requirements and market segmentation grid into appropriate factors and identifying corresponding ranges for each scaling variable. Scaling variables are the design variables that vary from product to product within a given product family and are used to "stretch" or "shrink" members of the product family to instantiate their individual performance. Scaling variables facilitate the platform leveraging strategies identified in Step 1.

Step 3: Build and Validate Metamodels – This step includes modeling computationally expensive computer simulation codes using computationally inexpensive metamodels (e.g., response surfaces, kriging (Simpson, et al. 1997b)).

Step 4: Aggregate Product Family and Product Platform Specifications – This step includes formulating the product platform and product family design problem based on the market segmentation grid, the factors and ranges, and the overall design requirements.

Step 5: Develop the Product Platform and Product Family – This step involves solving the product family design problem formulated in Step 4 to obtain the product platform and corresponding family of products, which best satisfy the overall design requirements. Farrell and Simpson (2003) formulate the optimization problem using an Excel spreadsheet that involves continuous non-linear functions, and the generalized reduced gradient (GRG) algorithm from (Belegundu and Chandrupatla 1999) is employed to solve it. Other algorithms could be used to perform the optimization of the non-linear problem; for instance, a simulated annealing algorithm was utilized by Farrell (1999) to optimize the bolted pressurized flange designs, which involves a similar non-linear optimization formulation.

In related work, researchers have replaced or modified the C-DSP formulation. Nayak, et al. (2000) employ a variation-based objective function where the design variables are formulated in terms of a mean and standard deviation and then the C-DSP is solved to find the best mean and deviation, and one result is the best design variables to use as platform variables. Physical Programming is incorporated into the PPCEM by Messac, et al. (2000) who claim better results than the PPCEM and also that the solution of the C-DSP does not guarantee a Pareto-optimal solution. Seepersad, et al. (2000) also consider Physical Programming and detailed product costs, and they also add utility theory to the PPCEM.

2.5 Product Platform Portfolio Optimization

In most research, the product platform portfolio and the design and platform variables are established prior to detailed design; however, there has been research involving optimization prior to detailed platform design (Seepersad, et al. 2002). Some research endeavors to distinguish between design variables, which change with each family member, and platform variables, which are constant within the family (D'Souza and Simpson 2002; Nayak, et al. 2000; Simpson, et al. 1997a). For instance, D'Souza and Simpson (2003) employ a non-dominated sorting genetic algorithm to optimize the balance between commonality and performance. Effectively, this optimizes the extent to which the design variables cover the targeted market segments. Because the genetic algorithm can be expensive, a “screening” experiment is employed to determine the significant design variables and hence reduce problem size.

In recent work by de Weck, et al. (2003), a method is presented to determine the optimal number of product platforms to maximize overall product family profit with simplifying assumptions. The methodology is demonstrated for a hypothetical automotive vehicle line that is required to fill seven market segments. Then, the portfolio can vary from one to seven platforms: the seven platform case corresponds to no leveraging, and the one platform case corresponds to maximum possible leveraging. The method simply examines the profit for each portfolio from the set of seven, and chooses the one that yields the highest profit as the optimal one; a three platform portfolio is determined to be optimal for their example.

Fujita and Yoshida (2001) advocate the simultaneous design of multiple products. Assuming module architecture, they propose a simultaneous optimization method for both module combination and module attributes of multiple products. The method models cost, profit, commonality, and similarity, and hybridizes a genetic algorithm, a mixed-integer programming method with a branch-and-bound technique, and a constrained nonlinear programming method. This is an extension of earlier work (Fujita 2002) where optimization of module combination and module attributes are treated separately.

In other research, product family selection is optimized based on a performance loss function (Fellini, et al. 2002), or optimization is based on combining business and engineering decisions (Georgiopoulos, et al. 2002). In a paper involving modular architecture artifacts, a GA-based method is used to optimize module sharing and creation of new modules (Gonzalez-Zugasti and Otto 2000). In work by Hernandez, et al. (2002), the goal is to minimize the impact of commonality on performance using the concept of space of customization. Farrell and Simpson (2006) employ an arbitrary un-constrained leveraging strategy to introduce commonality into an existing product line.

2.6 Collaborative Design Using the World Wide Web

Significant work exists regarding the utilization of the World Wide Web for distributed design and manufacturing involving collaboration among colleagues and partners (Balakrishnan, et al. 1999; Benami and Jin 2000; Coutinho, et al. 1998; Gerhard, et al. 2000; Gobinath, et al. 2006; Jayaram, et al. 2001; Parkinson, et al. 2004; Tumkor 2000; Wang, et al. 2006). For instance, Wright and his colleagues have pioneered a network manufacturing service called *CyberCut*™ for design and fabrication on the Internet (Ahn, et al. 2001; Wright 2001). Wallace and his co-authors are developing a Distributed Object-based Modeling Environment to link distributed and heterogeneous design "services" over the Internet to enable tradeoff analysis during production design (Abrahamson, et al. 1999; Senin, et al. 2003; Wallace, et al. 1999). Some work concentrates on Internet-based CAD/CAM services (Ahn, et al. 2001; Flores, et al. 2002; Han, et al. 1999; Satish, et al. 2006; Szykman and Sriram 1998).

There are many web-based expert systems that allow users to customize their products. Most are based on *assemble-to-order* customization (Duray, et al. 2000), and these are typically for high volume products for which the possible variety has been strategically targeted in advance to meet the needs of specific market segments. For example, assemble-to-order web-based customization is prevalent with the personal computer (Prince 2006), and automobile industries (Simison 2000). Alternatively, *engineer-to-order* systems are emerging (Chen, et al. 2001; Farrell, et al. 2007; Siddique and Shao 2001; Simpson, et al. 2003; Zhang, et al. 2007), where the end user is allowed direct involvement in the product design process.

2.7 Chapter Summary

This chapter presents a technology base from which a methodology for the redesign and implementation of a low volume, highly customized product line is built. The developed methodology is an extension of the PPCEM focused toward bottom-up platform development with special consideration for low volume custom products. The basic redesign methodology is presented next in Chapter 3 and builds upon the existing research regarding market segmentation grid leveraging, modularity, stretching and scaling, and Activity-Based Costing. This basic methodology requires supporting methodology for optimizing cost in a product platform portfolio, and Chapter 4 presents an optimization process that requires a zero-order optimizer such as provided by the Genetic Algorithm or the Simulated Annealing Algorithm. Overall, the proposed methodology advocates implementing the resulting product platform portfolio through a web-based interface to allow user interaction within the design process and to introduce custom design specifications early into the design process, and the existing research regarding collaboration using the World Wide Web provides inspiration. An algorithm is presented in Chapter 5 for implementing the portfolio using the web.

Chapter 3

Bottom-Up Product Platform Design Methodology

The Product Platform Concept Exploration Method (PPCEM) introduced in (Simpson, et al., 1999) was developed as a general top-down approach for product platform and product family design. This research focuses on employing the PPCEM as a bottom-up approach for the redesign of an existing product line with the goal of increasing cost effectiveness while meeting custom design specifications. A specific focus is toward the redesign of highly customized low volume products such as heavy industrial equipment used for material processing, manufacturing, or power production.

Rather than redesign an entire product line, a methodology is proposed for the redesign of specific components of an existing product line that have the highest potential for cost savings. Its implementation results in a product platform portfolio that is a hybrid between original product designs and redesigned targeted components. The methodology recognizes that the redesign effort must consider existing designs and existing design methodologies, and may require additional methodologies for adequately modeling cost.

After presenting the proposed methodology, it is applied to a detailed example involving the design of a set of valves for the highly regulated nuclear power industry.

3.1 Component Product Platform Development

Redesign of a highly customized low volume product line can be cost prohibitive, especially for a small firm. However, what may be justifiable is a strategic redesign of a limited set of component parts that have the highest potential for cost saving. A component part redesign effort can employ the product platform approach, and when applied across the product line, a *component-based* product platform portfolio results.

With the five steps of the PPCEM as a starting point, a design methodology is presented here for designing component platforms for low volume highly customized products. Although the 'top-down' approach may result in more efficient platforms in terms of cost and performance, the PPCEM assumes a clean slate, and small firms typically do not have the financial float and resources to implement such a radical approach. If even a rudimentary standard product line currently exists, the 'bottom-up' approach may be more feasible for them, and the proposed methodology focuses on this approach.

The proposed methodology is presented as an extension to the generalized PPCEM, and Table 3-1 outlines the generalized five-step top-down PPCEM methodology and alongside the corresponding and specific bottom-up methodology targeted toward redesigning component platforms for highly customized product from an existing product line. Implementing this bottom-up approach starts with gathering detailed design information about the existing product line and results in a component-based product platform portfolio.

Table 3-1: Component Platform Redesign Methodology for Existing Highly Customized Product

Step	General Top-Down PPCEM	Bottom-Up Component-Based Platform Redesign Methodology
1	Create the market segmentation grid.	Create the market segmentation grid based on past sales and sales projections, target portions of the existing product line with the highest sales potential.
2	Classify factors and ranges.	Target common components for redesign that often require modification. Classify critical design parameters from existing design data, and determine design inputs from an aggregate of known custom design specifications. Define a baseline standard product line from existing designs that span the target grid.
3	Develop metamodels as applicable.	Define component critical performance functions from existing and new design methodology as appropriate. Screening experiments may help reduce the number of required factors.
4	Aggregate Product Family and Product Platform specifications.	Develop a baseline standard redesign strategy around common component classes and corresponding standard optimization problems.
5	Develop the Product Platform and Product Family	Develop candidate component platforms by instantiating the component classes across the market segmentation grid, and then define a product platform portfolio by scaling/stretching a subset of the candidate component platforms.

It is further proposed to implement the methodology through a redesign team represented by every facet of the development process, and it is convenient to discuss the five-step methodology in terms of three basic phases of redesign team activity. Table 3-2 gives names for the phases (data collection, baseline standard development, and platform portfolio development) and associates methodology steps to the phases. In the first phase, the team collects design information about the existing product line, establishes a target market segmentation grid, and targets components for redesign. In the next phase, the team defines baseline standard product line members that span the established market segmentation grid. The baseline is where redesign begins, and the success of any redesign effort is judged against it. In the third phase, target component redesign strategies are developed around standard optimization problems resulting in target component class definitions, and instantiating the component classes into the baseline standard effectively yields a revised product line with improved design consistency among members. The resulting component designs form a set of candidate component platforms, and the resulting product platform portfolio is obtained by stretching and scaling a subset of the candidates.

Table 3-2: The Three Phases of Redesign Activity

Phase	Redesign Activity Phase	Table 3-1 Steps Involved
1	Data Collection	Steps 1, 2, 3 & 4
2	Baseline Standard Development	Steps 1, 2 & 3
3	Platform Portfolio Development	Steps 3, 4 & 5

The remainder of this section further describes the three phases. The final process of creating a component-based product platform portfolio is not addressed in detail here; however, a methodology for creating an optimal product platform portfolio from a set of candidate component platforms is discussed in Chapter 4.

3.1.1 Collection of Existing Knowledge, Databases, and Methodology

Critical first steps in starting any redesign project are (1) obtain a strong commitment of company resources from the highest level of upper management, (2) give the redesign team leadership authority to commit resources toward the project, and (3) include employees as redesign team members who represent every segment of the company such as sales, marketing, accounting, engineering, and manufacturing. A strong commitment is essential as the design team will likely have distracting concurrent production-related duties, and the danger of distraction is likely more probable with a small firm of limited resources.

Implementing the component-based platform methodology starts with collecting detailed knowledge of the targeted product line regarding sales history, sales projections, design methodologies, manufacturing techniques, and any known design and manufacturing challenges. Any data source can be useful, and all available sources should be considered. With a custom product line, the design process can be informal, and as such, information can be scattered among key employees, including those not part of the design team, who are holders of knowledge regarding past projects, and who are maintainers of 'grass-roots' databases that are used daily to efficiently carry out production. In addition, customer representatives may be willing to provide useful data if they sense potential for a better product and better service. Some of this information may be in paper form, and some may be digital, and a typical project will provide ample opportunity for data mining.

In the early stages of the redesign process (Steps 1 and 2), the design team consults the collected data and forms a consensus regarding the basic component-based product platform design strategy. Targeted portions of the company's product line are established through market segmentation grids, and specific components targeted for redesign are established. Since a highly customized low volume product is involved, information can be limited, as with sales projections for instance, and some subjective decisions may be required regarding the design strategy.

Existing design data is also required in the middle steps when critical design variables and critical design inputs are defined (Steps 3 and 4). Design variables come from the study of existing design details contained in design drawings for raw forms and machining details. The most likely source for critical design input is design specifications from past projects, and past engineering and manufacturing design evaluations such as design analysis reports and manufacturing specifications.

An existing product line is a constraint on the redesign process, which is fundamentally different from the top-down design approach that starts unconstrained. Although this constraint can add difficulty to the design team's decision process, any existing product line structure, or any existing design, marketing, and manufacturing strategies can make some decisions obvious and natural. In fact, it is important to work with natural product line constraints, which can define obvious natural market segmentations, such as basic product size, performance capacity, or industry focus. In addition, it may be important to continue to follow certain basic and existing design and marketing strategies to the extent that gross product line design changes do not occur.

Finally, uncertainty is inherent in any business, and if this uncertainty can be quantified in terms of probability statistics, it can be included in the methodology by applying robust design techniques.

3.1.2 The Baseline Standard Development

The second phase of the proposed methodology involves the establishment of a baseline standard product line, which consists of a set of existing product line artifacts that span the targeted market segment grid. In this work, an artifact is considered an established design that has been manufactured successfully in the past. There is a twofold purpose for the baseline standard: (1) it forms a baseline from which to start any redesign project, and (2) it provides a reference against which to compare any redesign effort, as any change deemed successful should result in a cost improvement over the baseline (Maupin and Stauffer 2000). The baseline standard is derived from source artifact design details such as bills of materials, design drawings, and manufacturing processes, and from existing design methodology and custom design specifications.

Since component redesign is the methodology's focus, it is important that the baseline standard focus on defining targeted components and their interface and interaction with the targeted product line. Design experience, obtained from interviews with design engineering staff members for instance, can help define candidate target components, i.e., those often requiring modification. Otherwise, use of a development tool such as a Design Structure Matrix (Baldwin and Clark 2000) can help define and isolate candidates.

Since the goal of the methodology is to reduce cost yet still meet custom design specifications, and since the methodology advocates a baseline standard redesign, baseline standard construction should consider known custom design specifications and include existing design methodology. Then, baseline standard development involves aggregating (1) design inputs from custom specifications, (2) design performance assessment methodology, and (3) a list of design parameters important in defining cost and performance. The list of parameters can become large, and it is important to focus only on those that affect the cost, performance, and interfacing of targeted components. It may be possible to reduce the required number of parameters through screening experiments (Meyers and Montgomery 2002; Montgomery 2001).

Because custom design requirements are involved, it can be challenging to determine design input that will envelop future performance requirements without resulting in over-designed components. Design input should be studied and aggregated to determine reasonable, perhaps average, design input. The resulting aggregate input specification should be defined as a function of market segmentation grid defining attributes; for instance, an input force may be a function of the artifact's 'size', where 'size', is a market segmentation attribute.

In order to overcome the potential for inappropriately proportioned components, a multi-tiered platform strategy may be necessary. The better multi-tiered strategies are those where a chosen component can be manufactured flexibly for each tier. In addition, recognizing that it is impossible to predict all future design requirements, the best redesign strategies will include an engineer-to-order methodology that is flexible and fits well within a multi-tiered strategy.

With highly customized products, existing design artifacts may have been created one-at-a-time, and a well-defined product line may not currently exist. This can challenge baseline standard development, requiring tradeoff between baseline standard members, the targeted market segmentation grid, components targeted for redesign, and redesign strategy. For instance, a scenario may require that the redesign team choose as a baseline member a single artifact that best meets the redesign strategy from multiple and varied artifacts.

3.1.3 Component Class and Platform Development

The proposed methodology centers on devising a component redesign strategy that introduces commonality into the targeted product line, and this is accomplished through the definition of component classes. Then, existing targeted components from the baseline standard are replaced by instantiations of a component class, and required component performance is achieved by assigning appropriate values to design variables for each instantiation.

A component class is similar in concept to a class construct in object-oriented programming languages such as C++ for instance, where multiple objects can be created from a single class (Eckel 2000). For example, multiple text box objects can be created, or instantiated, from the text box class for use in a user input form, and each text box object can be assigned unique attributes such as border outline thickness, and each can be used to collect different user input. In the same way, a component class can be instantiated to create multiple components to span the targeted product line.

In this work, a component class is defined by a standard optimization problem consisting of a collection of design variables, objective functions, constraint equations, and the aggregate performance specification. For each instantiation, the objective functions and constraint equations remain the same, but performance input changes, and problem solution results in optimal design variable values that become component defining attributes. The common objective functions and constraint equations are determined from aggregating the performance assessment methodology of the baseline standard, and performance input depends on the artifact's place within the market segmentation grid.

The methodology proposes that the resulting component class instantiations define a set of candidate component platforms, a subset of which is used to create a product platform portfolio that spans the targeted market segmentation grid. The portfolio is created by replacing baseline standard components with strategically selected component platforms. A single component platform may replace multiple baseline standard components, and this is accomplished through stretching and/or scaling key component platform parameters. Chapter 4 discusses a process for strategically selecting component platforms from the candidates using optimization techniques. Inherent in the process is an assessment of any proposed product platform portfolio regarding its total implementation cost relative to the baseline standard.

The component class objective functions must adequately address aggregate performance and cost. Although a methodology probably already exists that adequately addresses performance, manufacturers typically use traditional costing based on the material, labor, and overhead model. As discussed in Chapter 2, this traditional costing approach does not adequately addresses the relationship between design parameters and cost. Alternatively, it is proposed to apply Activity Based Costing (ABC), which is based on production process steps more readily associated with design parameters. Section

4.3.1 presents a cost model based on ABC that is customized to the example used throughout this thesis, which is formally introduced next.

3.2 Valve Yoke Component Design Example

Implementation of the bottom-up component platform design methodology is demonstrated using an example involving the redesign of yokes from a targeted market segmentation grid consisting of nuclear-grade valves. The subject valve product line is an excellent representative of the type that is the focus of the research, i.e., low volume highly customized products. Although the example addresses a real product line, a formal redesign team has not been assembled as advocated by the methodology, and thus the example redesign team decisions are strictly based on the opinion of the author. In the example then, the word ‘redesigner’ is used as a surrogate for ‘redesign team’. However, although the redesign team is lacking, the presentation does adequately demonstrate implementation of the proposed methodology, and it potentially provides a valuable starting point for a proper redesign team.

Before demonstrating implementation of the bottom-up product platform design methodology, the fundamentals of valve operation and valve design are discussed.

3.2.1 Valve Fundamentals

Valves are common components in nuclear plant piping systems, and many of them are custom built to respond to specific design and accident scenarios. The example considers a product line consisting of automatically actuated gate valves such as those shown in Figure 3-1. This product line is chosen by the redesigner because it is a principal product line for the company and could benefit from redesign using component platforms. Gate valves are used to isolate flow, and they can accomplish this better than most other valve types because (1) they are reliable due to their simple design, (2) they require less actuator force while closing against flow, (3) they introduce minimal flow resistance while open, and (4) differential pressure across the gate aids in sealing off flow.

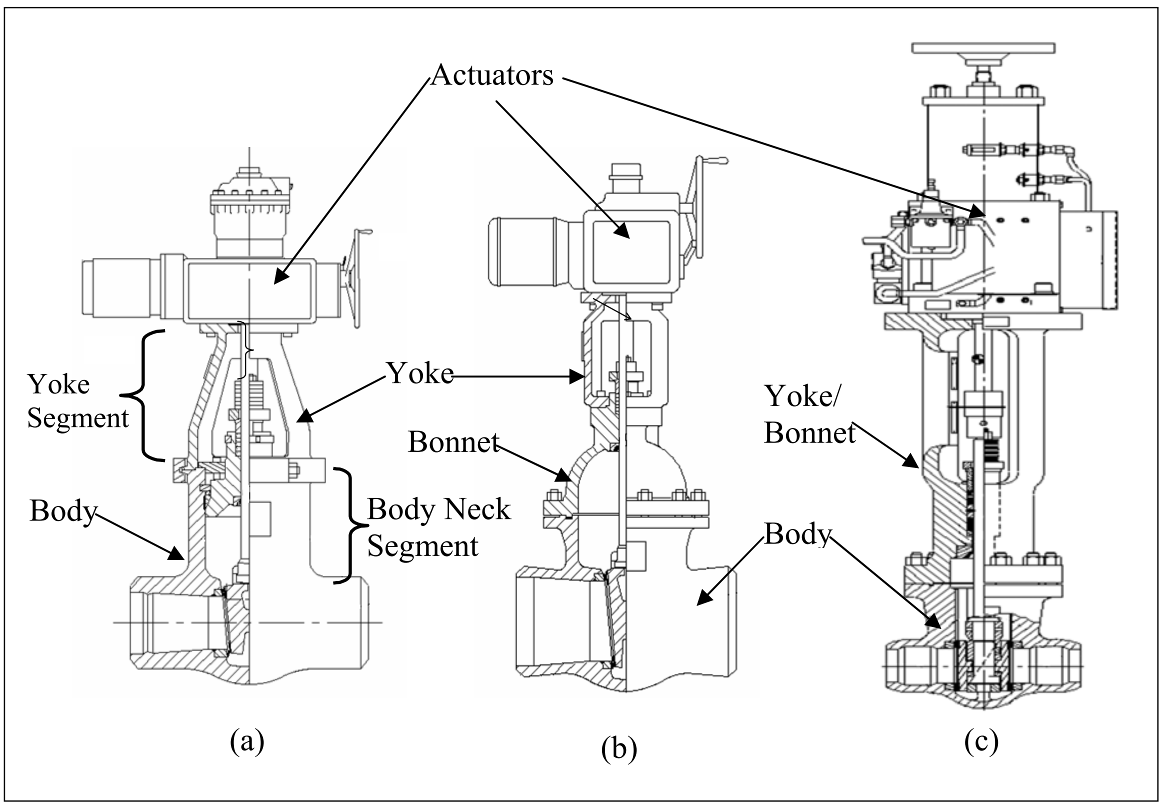


Figure 3-1: Typical Gate Valves (Courtesy of Flowserve Corporation): (a) Size 6, Class 900 Flex Wedge, (b) Size 8, Class 150 Flex Wedge, (c) Size 4, Class 150 Double Disc

As an example, Figure 3-2 shows a flex wedge gate in the closed position. Flow isolation and sealing are achieved through bearing contact between the gate and the seat ring that is welded into the valve body. The actuator, which can be manually, electrically, pneumatically, or hydraulically energized, provides thrust to the gate and must provide enough force to overcome frictional and flow induced drag and to wedge the gate into the seat. Once closed, differential pressure can develop that forces the gate against the seat on the downstream side of the valve. Then, both differential pressure and wedging forces are available to affect a seal between the gate and seat. Often, differential pressure alone provides adequate bearing stress to seal. Due to design symmetry, a flex wedge gate valve is bi-directional in that it can isolate flow moving in either direction.

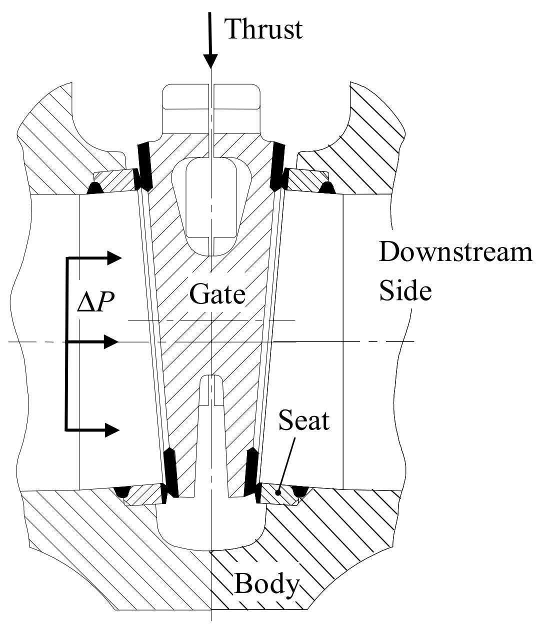


Figure 3-2: Flex Wedge Gate Valve Sealing

Two gate valve types are prevalent within the product line: the flex wedge gate valve, which is denoted by ‘FW’, and the double disc gate valve, which is denoted by ‘DD’. Whereas the flex wedge achieves flow isolation with a simple wedge, the double disc design consists of a four-piece wedging mechanism as shown in Figure 3-3, where two discs provide sealing against the process fluid, and an upper-lower wedge pair provides wedging force. The double disc is more complex, and hence more expensive, but it provides better performance for cases when differential pressure is low or significant thermal transients are expected. Compared to a flex wedge gate valve, a double disc gate valve’s independent discs seal better under low differential pressure, and the two-piece wedge has a larger wedge angle that prevents the assembly from becoming stuck from thermally induced strain.

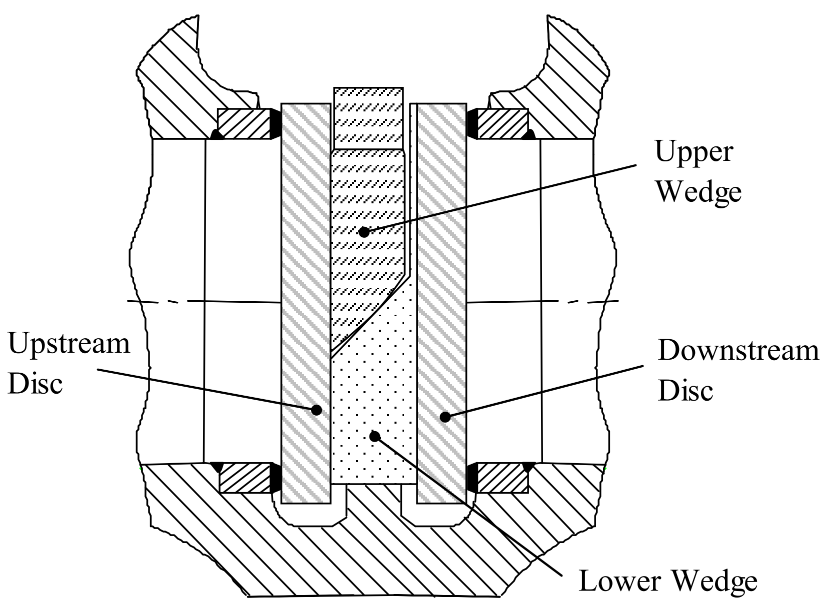


Figure 3-3: Four-Piece Double Disc Gate Wedging Mechanism

3.2.2 The Targeted Market Segmentation Grid

The market segmentation grid for the targeted portion of the product line (i.e., flex wedge (FW) and double disc (DD) gate valves) is constructed based on available information from past design analyses performed to support past projects, although one must realize that with a formal project, a redesign team must consider all available information sources. The gate valve product line is naturally segmented in terms of valve type (FW or DD), valve pressure class, and connecting piping nominal size. Both pressure class and pipe size are unit-less quantities that manufactures use to identify valves. Although unit-less, pressure class, which denotes a valve's internal pressure containing capacity, is roughly in psig, and nominal pipe size is roughly in inches. Figure 3-4 is a chart of valve quantity per segment from the available data, and this is an example of data collection task that a redesign team might perform. Appendix B includes the source data for the charts.

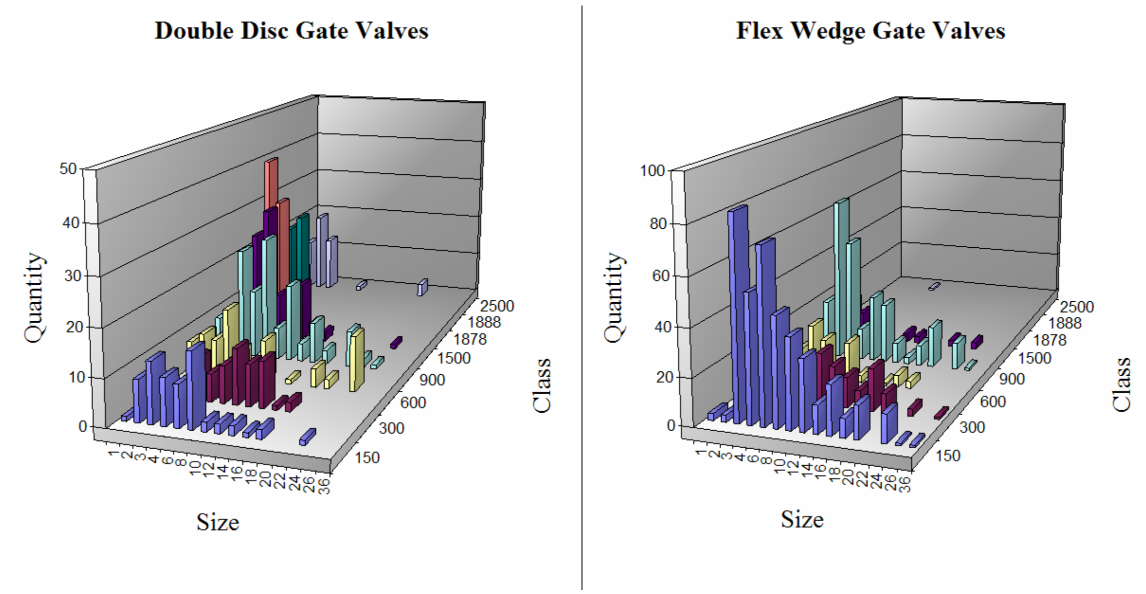


Figure 3-4: Valve Quantities by Type, Size, and Class

Of the valve sizes included in the Figure 3-4, valves smaller than size 3 were designed as a group with common design features, and it is decided to exclude these from the project because reinvestigating this commonality it is not cost effective. Then, based on the given quantities for the remaining FW and DD valves, the target market segmentation grid depicted in Table 3-3 is created. Each member of the grid is given a sequential artifact ordinal number that will be helpful during future process steps, and the grid consists of 60 valve artifacts as can be seen. Then, given the defined targeted market segmentation grid, implementation of Step 1 of the proposed methodology per Table 3-1 is demonstrated.

Table 3-3: Market Segmentation Grid Artifact Ordinals

		Size					
		3	4	6	8	10	12
Type	Class	Ordinal	Ordinal	Ordinal	Ordinal	Ordinal	Ordinal
DD	150	1	2	3	4	5	6
	300	7	8	9	10	11	12
	600	13	14	15	16	17	18
	900	19	20	21	22	23	24
	1500	25	26	27	28	29	30
	Total						
FW	150	31	32	33	34	35	36
	300	37	38	39	40	41	42
	600	43	44	45	46	47	48
	900	49	50	51	52	53	54
	1500	55	56	57	58	59	60

3.2.3 The Yoke Leg Targeted Component

Step 2 of the methodology involves targeting components for redesign that are common to all member artifacts of the targeted market segmentation grid. Based on previous redesign experience, the yoke is the major valve component that often requires modification to respond to specific customer requirements such as loading associated with an anticipated seismic event, the installation of sensors or controls, and mounting and support for the specific actuator size and type. As shown in Figure 3-5, the yoke consists of top and bottom mounting flanges joined by two legs. This example has a transition neck between the legs and the actuator mounting flange.

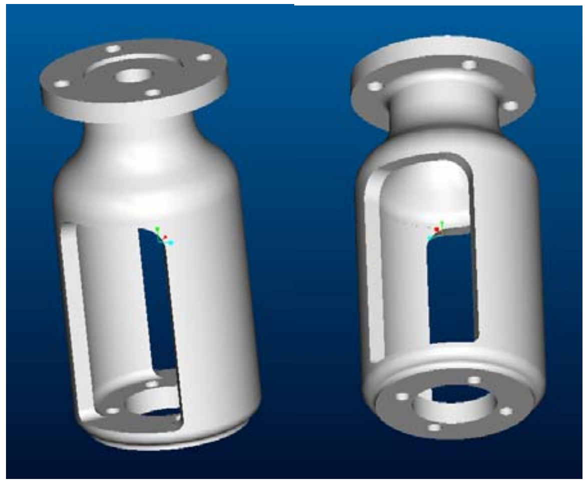


Figure 3-5: Solid Model Views of a Typical Yoke

Step 2 also involves classifying critical design variables and design inputs, which requires knowledge of the interface of the targeted component with the artifact. A Design Structure Matrix (DSM) can help define the interface, and Table 3-4 provides a DSM for a typical gate valve with sufficient detail for defining interfaces. Cells marked with ‘x’ indicate a structural relationship between the corresponding row and column parameter entities. The matrix divides the valve into external components, including the yoke, and internal components. The square boxes identify existing modules, including the yoke, and the overlapping of the yoke box/module with other boxes/modules help define important design parameters involved. For instance, the actuator and yoke have a common flange interface. In addition, x-cells show that the stem and packing assembly internal components interface with the yoke.

Table 3-4: Gate Valve Design Structure Matrix

	Parameter	Parameter	Actuator	Actuator-Yoke Bolting	Actuator-Yoke B.C.	Yoke Top Flange	Yoke Cross-Sectopm	Yoke Window	Yoke Length	Yoke Bottom Flange	Yoke-Bonnet B.C.	Yoke-Bonnet Bolting	Bonnet Top Flange	Bonnet Neck/Shell	Bonnet Bottom Flange	Bonnet Gasket	Body-Bonnet B.C.	Body-Bonnet Bolting	Body Flange	Body Neck	Packing Assembly	Stem Nut	Stem Threads	Stem Length (stroke)	Stem-Disc Interface	Stem Basic Diameter
			External Structure																		Internal Structure					
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
External Structure	Actuator	1	o	x	x																	x				
	Actuator-Yoke Bolting	2	x	o	x	x	x	x																		
	Actuator-Yoke B.C.	3	x	x	o	x	x	x																		
	Yoke Top Flange	4		x	x	o	x	x																		x
	Yoke Cross-Section	5		x	x	x	o	x		x	x	x												x		
	Yoke Window	6		x	x	x	x	o		x	x	x									x					x
	Yoke Length	7							o												x			x		
	Yoke Bottom Flange	8					x	x		o	x	x									x					x
	Yoke-Bonnet B.C.	9					x	x		x	o	x	x													
	Yoke-Bonnet Bolting	10					x	x		x	x	o	x								x					
	Bonnet Top Flange	11									x	x	o	x							x					
	Bonnet Neck/Shell	12											x	o	x						x			x		
	Bonnet Bottom Flange	13												x	o	x	x	x	x							
	Bonnet Gasket	14													x	o	x	x	x							
	Body-Bonnet B.C.	15													x	x	o	x	x							
	Body-Bonnet Bolting	16													x	x	x	o	x							
	Body Flange	17													x	x	x	x	o	x						
	Body Neck	18																	x	o				x		
Internal Structure	Packing Assembly	19						x	x	x		x	x	x							o			x		x
	Stem Nut	20	x																			o	x			x
	Stem Threads	21																				x	o			x
	Stem Length (stroke)	22					x		x					x						x	x			o	x	
	Stem-Disc Interface	23																						x	o	
	Stem Basic Diameter	24				x		x		x											x	x	x			o

3.2.4 The Baseline Standard

Given the yoke as the single target component, Step 2 continues with the classification of design variables and the determination of an aggregate design input specification. For the example, study of the existing design analysis reports, the underlining analysis methodology, and known specific customer design specifications, results in a collection of critical design parameters. With respect to yoke design, specifications generally are concerned with the ability of the valve, and hence the yoke, to survive plant vibration and accident scenarios, and the most severe loading is associated with a seismic event. Typically, valves must be designed rigid with respect to attached piping, and this imposes a natural frequency requirement. In addition, many valves are classified as ‘active’ in that the actuator must be capable of operating the valve during a seismic event, and thus actuator induced loading is considered. Therefore, the project focus is with yoke strength (i.e., stress) under combined seismic and actuator induced loading and natural frequency. Another focus is toward motor actuated valves, as they have been specified in a majority of past projects.

The current design analysis methodology employs Microsoft Excel™ spreadsheets and Microsoft’s Visual Basic for Applications macros, and Table 3-5 shows a portion of one such spreadsheet. Critical input associated with the yoke component design are noted, and these include (1) input associated with the actuator including weight and center of gravity, (2) input associated with yoke geometry including yoke leg cross-section geometry and leg length, (3) input associated with the valve pressure class, which is a market segmentation grid distinction, including pressure and differential pressure, and (4) input associated with the aggregate of custom design specification requirements including seismic loading, natural frequency limit, temperature, and yoke material.

Table 3-5: Portion of a Sample Analysis Input Form for Artifact 2:
Size 4, Class 150 Double Disc Gate

LOAD CASE					
pressure class	150 (3)				
calc pressure [psi]	290 (3)				
default temp. [^{O}F]	100 (4)				
Actuator Torque [in-lb]	1000 (1)				
Actuator Thrust [lb]	8000 (1)				
Seismic Load [g's]	11. (4)				
frequency limit [Hz]	33 (4)				
	Actuator	Yoke Legs	Bonnet Neck	Body Neck	
MODEL ELEMENTS		Flange, Stem	Packing Assy.	Flange, Disc Pack	
W [lb]	149 (1)	20	25	35	
W' [lb]		30	5	45	
L [in]	7 (1)	7.5 (2)	4.5	9	
E [msi]					
X [in]	4.6 (1)				
CROSS-SECTIONS	1	2	3		
Code	1 (2)	12	14		
A [in]	2.625 (2)	1.5	3.469		
B [in]	3.5 (2)	0.75	2.25		
C [in]	0.611 (2)	2.375	2.938		
D [in]		1.125	1.719		
COMPONENT CASE					
section or node			1		
component code	5	9	23	51	45
Analysis Code	R	R	R	RZ	R
1: Description			Yoke	Stem	DD
Drawing					
Mat'l Funct.			8 (4)	21	
A				1	4.4
B				4	1
C				2	0.35
D					320
E					
F					290 (3)
G				2	290 (3)

It is well known by experience that the noted parameters significantly affect required yoke leg size, and although the parameters are segregated into categories, all requirements have their origin from design specifications in practice. The segregation is convenient for defining the source of the parameters with respect to the process of classifying input. For instance, the actuator must be properly sized to operate the valve, and the redesign effort employs existing sizing methodology to determine aggregate actuator parameters, including the basic actuator size; this process is automated for the project, and the given sample input form includes resulting actuator parameters of weight, center of gravity, and thrust and torque. In addition, the sample spreadsheet includes the four chosen aggregated custom specification inputs, which are judged to reasonably meet past project requirements yet not result in ill proportioned yokes.

Appendix A provides a sample design analysis that describes the underlying methodology and presents calculation details. This sample uses the parameters of Table 3-5 as input, and further describes aggregated custom specification input, actuator sizing methodology, stress and natural frequency determination, and generally describes input and results parameters. In addition, aggregate custom specification acceptance criteria are described that includes allowable stress criteria and minimum natural frequency limit.

The baseline standard is developed by preparing a spreadsheet similar to the given example for each artifact of the targeted market segmentation grid per Table 3-3. Although the artifacts are chosen based on those judged to best meet the developed aggregate performance requirements, this is not a strict requirement. In fact, it is important to permit artifacts that are infeasible (i.e., that do not meet the aggregate specification) because there is no guarantee that a feasible artifact exists in every case. Note that in the sample spreadsheet, parameters without an attached note are static as they are associated with valve components other than the yoke. However, they can affect the yoke design; for instance, the weight and length of other components can affect overall valve natural frequency which is a consideration when designing a yoke.

Spreadsheet data is condensed with respect to what might normally be addressed with a production valve. Input associated with component analysis unrelated to the core objective of yoke redesign is removed. For instance, the input associated with the analysis of flanges, the stem, and the wedge is removed. However, it is important to address actuator and yoke mounting interfaces in the baseline standard redesign strategy.

3.2.5 New Performance Functions

Step 3 of the proposed methodology involves defining critical performance functions from existing and new design processes as appropriate. In this example, most critical performance functions were defined previously during the baseline standard development. However, the existing design process lacks an adequate costing procedure, which is important for any redesign strategy since the goal is to improve cost. Then, as proposed by the component-based platform redesign methodology, a new Activity-Based Costing model is developed.

For this example, the cost model is needed during the final step of the methodology (Step 5) when the product platform portfolio is created by stretching and scaling a subset of candidate component product platforms. The methodology is presented in the next chapter for product platform portfolio optimization, and creation of a portfolio for the example problem is saved until then. Therefore, presentation of the cost model is also reserved until the next chapter.

Although creation of the product platform portfolio is the last part of Step 5, strategy for redesigning the baseline standard, which is the beginning part of Step 4, must look forward to portfolio creation and the corresponding strategy for stretching and scaling component platforms.

3.2.6 Baseline Standard Redesign Strategy

The redesign strategy consists of two parts as described below. The first part is a strategy for stretching and scaling a component platform so that it can be used on multiple artifacts, which is required for the final part of Step 5. The second part is a strategy for creating a yoke component class, which is part of Step 4.

3.2.6.1 Component Platform Stretching and Scaling Strategy

A candidate yoke component platform must be capable of interfacing with multiple artifacts, i.e., stretched and/or scaled, and the part of the component platform redesign strategy that addresses this is a yoke casting pattern modular architecture. Two potential architectures are proposed as shown in Figure 3-6, and these are similar except for the yoke mounting flange interface. With the *module* model, it is proposed to employ multiple casting pattern change pieces, which is a common casting pattern modification technique, and with the *stretched* model, the flanges are machined out of common stock.

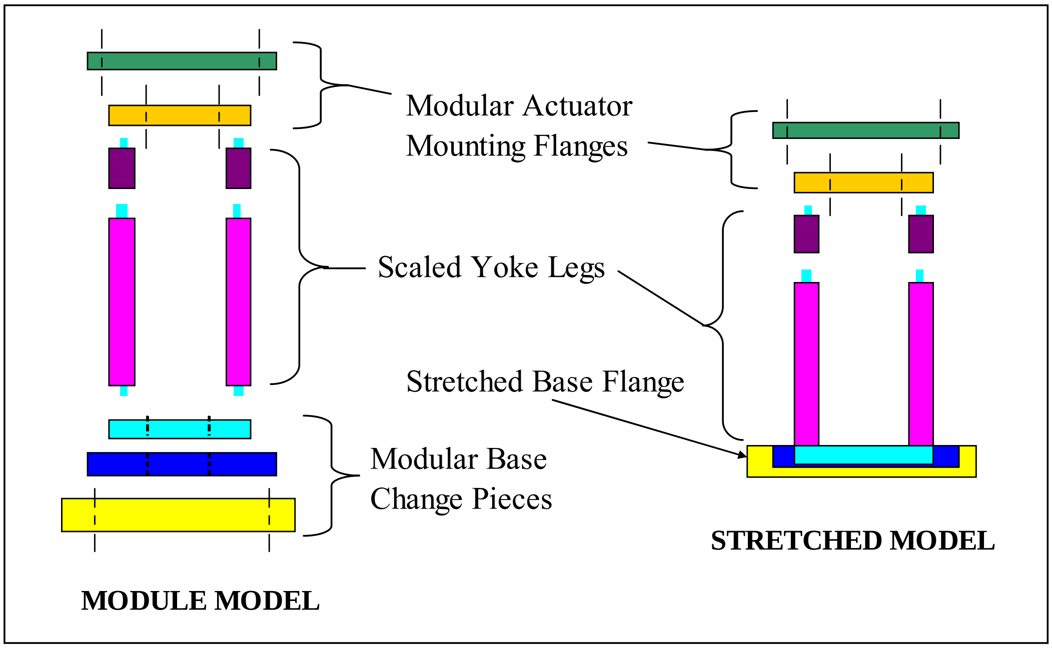


Figure 3-6: Module and Stretched Yoke Component Platform Models

Both models assume the yoke leg length is stretched to accommodate the practical need of the valve artifact using casting pattern change pieces, and both assume the pre-existence of actuator mounting flange yoke casting pattern change piece modules. Although it is appropriate to study the cost of implementing different actuator mounting schemes, the example is kept simple and does not address this. Notice that when only one artifact is involved, both models reduce to the same scheme. Which model is best will be decided by cost analysis, and as stated earlier, this is addressed in the next chapter using ABC.

3.2.6.2 Component Class Design Strategy

The baseline standard artifacts contain yoke legs with variously shaped cross-sections, and it is desired to design the legs around the common shape shown in Figure 3-7. The figure shows the design variables, *a*, *b*, *c*, that effect critical performance, including valve fundamental natural frequency of vibration and yoke leg stress.

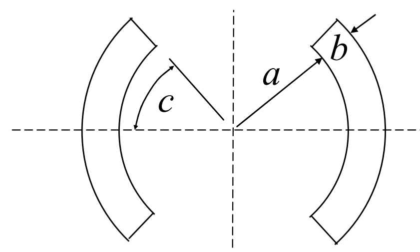


Figure 3-7: Generalized Yoke Legs Cross-Section

Then, a yoke component class consists of yoke legs shaped as shown in Figure 3-7 and a yoke casting pattern modular architecture that can be stretched and scaled to interface with multiple artifacts. The three parameters *a*, *b*, *c* given in Figure 3-7 are the design variables for a standard optimization problem, which is solved for each baseline standard artifact resulting in component class instantiations.

3.2.7 Yoke Leg Cross-Section Optimization

For this example, the goal is to minimize yoke leg cross-section area yet satisfy aggregate performance constraints consisting of allowable stress limits and minimum allowed natural frequency, and the corresponding optimization problem is given by Eq. 3.1.

Minimize: (3.1)

$$F = A(X) + (f_1(X) + f_2(X)) - (\sigma_1(X) + \sigma_2(X))$$

Subject to:

$$P_1 = (1 - f_1(X) / f_{MIN}) \leq 0$$
$$P_2 = (1 - f_2(X) / f_{MIN}) \leq 0$$
$$P_3 = (\sigma_1(X) / S_A - 1) \leq 0$$
$$P_4 = (\sigma_2(X) / S_A - 1) \leq 0$$
$$B_1 = a_{MIN} - a \leq 0$$
$$B_2 = a - a_{MAX} \leq 0$$
$$B_3 = a+b - r_{MAX} \leq 0$$
$$X > 0$$

Where:

F = Objective Function

X = Design Variables (a, b, c) per Figure 3-7

A = Yoke Leg Cross-Section Area

f_1, f_2, = Beam/Frame Mode Natural Frequencies

σ_1, σ_2 = Beam/Frame Mode Principal Stress

f_{MIN} = Natural Frequency Limit (33 Hz)

S_A = Allowable Stress Limit (26.25 ksi)

P = Performance Constraint

B = Bounds Constraint

a = Yoke Leg Inside Radius (see Figure 3-7)

b = Yoke Leg Thickness (see Figure 3-7)

r_{MAX} = Maximum Allowed Yoke Leg Outside Radius

All parameters except f_{MIN} and S_A, which are common aggregate performance constraint parameters, are different for each artifact, and are therefore all functions of the artifact ordinal as defined in Table 3-3. For each artifact, the natural frequency constraint, f_{MIN}, is 33 Hz, and the maximum allowable stress limit, S_A, is 26.25 ksi. The presence of the performance parameters f and σ in the objective function force the solution to satisfy the aggregate performance constraints as close as possible to their limits. When cross-section area is expressed in square inches, natural frequencies are expressed in Hertz, and yoke leg stresses are in ksi, each term in the objective function are approximately equal in magnitude, which implies that area, natural frequency, and stress have equal importance with respect to objective function value. Meanwhile, the bounds constraints on the design variables, B, ensure proper fit of the yoke on the corresponding artifact and vary as summarized in Appendix B.1. Fit is governed by the size and type of the connection such as a flanged or clamped connection, and the optimized yoke must conform to the artifact's existing connection design.

The optimization problem is solved for each artifact of the targeted market segmentation grid, and what results is a collection of candidate component platforms, and the design variables (a, b, and c), which define the candidate component platforms, are given in Appendix B.2. Details regarding the solution phase follow, and this completes the first part of Step 5. The final part of Step 5 is the creation of a product platform portfolio consisting of a subset of the candidate component platforms; however, this is not presented here as Chapter 4 presents the methodology for this. At this point, though, it is helpful to realize that any developed candidate component-based platform can be used potentially as a platform for any market segmentation grid artifact.

Each artifact's yoke leg cross-section size is optimized using the Solver Add-in from Microsoft Excel™. It is desired that the resulting cross-section dimensions have a specified precision, i.e., lengths in eighth-inch increments and angles in five-degree increments, and the integer programming capabilities of the Excel Solver add-in make this possible. In addition, Microsoft Excel™ is used to perform calculations and store platform design parameters, and a Microsoft Access™ database is used to track optimization statistics. A single workbook contains a collection of spreadsheets, with each similar to the Table 3-5 example presented previously, and other workbooks contain macros used to access performance and to conduct the optimizations.

Although the source of the data that defines the baseline standard is primarily from spreadsheets similar to the example in Table 3-5, a significant amount of data manipulation is required to build the collection of baseline standard spreadsheets and to setup the Excel Solver optimization problems. Some manual manipulation is involved, but a significant portion was performed using a Microsoft Access™ database under the control of Microsoft Visual Basic for Applications™ macros, which can access both databases and spreadsheets through object-oriented programming. Although the data manipulation and programming effort is somewhat laborious, the details do not contribute significant insight into the example problem. However, it is worth noting that the manipulation was performed using readily available tools and standard programming techniques.

The Excel Solver optimization is performed through a combination of user defined spreadsheet functions and automatic setup of Solver's parameters. Table 3-6 and Table 3-7 demonstrate how setup data appears in sheet cells, and also how the corresponding user functions are applied for the objective function, design variables, and constraints. For consistency, the presented data is based on the same artifact that is addressed in Table 3-5 (i.e. Artifact 2: Size 4, Class 150 Double Disc Gate Valve). Note that range names are employed, and column headings give column range names in parentheses.

Table 3-6: Example Spreadsheet Portion Showing Design Variables and Objective Function

Design Variable and Objective Function

Objective Function (F)	Design Variables (X)	DV Integer Conversion (XI)	Lower Bound on XI (XL)	Upper Bound on XI (XU)
76.84895527	2.375	19	10.5	21
	0.625	5	5	20
	0.523596	6	5.993170436	17.99097052

Design Variable/Objective Underlying Formulae

Objective Function (F)	Design Variables (X)	DV Integer Conversion (XI)	Lower Bound on XI (XL)	Upper Bound on XI (XU)
=engine1.xls!Fsolver(X)	=INDEX(X,1)*0.125	19	10.5	21
	=INDEX(X,2)*0.125	5	5	20
	=INDEX(X,3)*0.087266	6	5.9932	17.991

Table 3-7: Example Spreadsheet Portion Showing Constraints

Constraints

Constraints (G)		Limits on G (Z)	Description of G
-0.331809524	<=	0	beam stress
-0.108571429	<=	0	frame stress
-0.716666667	<=	0	beam frequency
-0.799393939	<=	0	frame frequency
-0.05681363	<=	0	minimum window width
0	<=	0	max. inside rad.
-1.0625	<=	0	min. inside rad.
-0.4375	<=	0	max. inside rad.
0	<=	0	max. outside rad.

Constraints Underlying Formulae

Constraints (G)		Limits on G (Z)	Description of G
=engine1.xls!Gsolver(1,X)	<=	0	beam stress
=engine1.xls!Gsolver(2,X)	<=	0	frame stress
=engine1.xls!Gsolver(3,X)	<=	0	beam frequency
=engine1.xls!Gsolver(4,X)	<=	0	frame frequency
=-INDEX(X,1) * COS(INDEX(X,3)) + 2	<=	0	minimum window width
=0	<=	0	max. inside rad.
=-INDEX(X,1)+1.3125	<=	0	min. inside rad.
=+INDEX(X,1)-2.8125	<=	0	max. inside rad.
=0	<=	0	max. outside rad.

The Solver Add-In can be accessed through object-oriented programming, and Figure 3-8 is a subroutine listing that is employed to perform the setup. In this routine, ‘Xrange’, ‘Grange’, and ‘Frange’ correspond to the ‘X’, ‘G’, and ‘F’ range names defined above, ‘Optx’ is an implementation of a class construct that manages the database for a market segmentation grid artifact. The optimization is conducted as follows: for each artifact, an Optx object is created, the optimization is performed by calling the listed routine, results are saved to the management database through the Optx object, and then the Optx object is destroyed in preparation for the next artifact.

```
Sub Do_Solver(Xrange As Range, Grange As Range, Frange As Range, Optx As Object, MSG As String)
    SOLVER.SolvReset
    'setup basics(F And X)
      SolverOk SetCell:=Frange.Cells(1, 1).Address, MaxMinVal:=2, ByChange:=Xrange.Address
    'setup natural constraints
    For i = 1 To Optx.nG
      SolverAdd CellRef:=Grange.Cells(i, 1).Address, Relation:=1, FormulaText:=Grange.Cells(i, 3).Address
    Next
    'setup DV bounds
    For i = 1 To Optx.nX
      SolverAdd CellRef:=Xrange.Cells(i, 1).Address, Relation:=1, FormulaText:=Xrange.Cells(i, 3).Address
      SolverAdd CellRef:=Xrange.Cells(i, 1).Address, Relation:=3, FormulaText:=Xrange.Cells(i, 2).Address
    Next
    'setup precision conversion (integer constraints)
    For i = 1 To optx.nX
      If Optx.precision(i) Then SolverAdd CellRef:=Xrange.Cells(i, 1).Address, Relation:=4
    Next
    'solve it!
    SolverSolve True
    MSG = "SOLVER OK"
End Sub
```

Figure 3-8: Excel Solver Automatic Setup Subroutine

The optimization of all baseline standard artifacts yields a set of candidate component platforms, and each candidate is defined by the resulting optimal cross-section design variables and the baseline standard redesign strategy discussed previously. As the last part of the final step (Step 5), a product platform portfolio is created from a subset of the candidates. As mentioned previously, however, the next chapter provides additional methodology for determining an optimal subset of component platforms, and thus, detailed discussion of product platform portfolio creation is delayed until then along with further detail regarding creation of the example candidate component platforms.

3.3 Chapter Summary

This chapter presents a methodology for redesigning an existing line of low volume highly customized product using a bottom-up product platform development approach that is based on the PPCEM. Rather than redesign an entire product line, the focus is toward the redesign of a limited set of components with the highest potential for cost savings, and when applied across the product line, a *component-based* product platform portfolio results.

A five-step method is presented in Table 3-1 where the generalized Top-Down PPCEM is presented along side the Bottom-Up methodology specific to component-based product platform portfolio redesign. The five-step methodology is presented on its own in Table 3-8, and it is best described by three phases of redesign team activity: (1) the data collection phase, (2) the baseline standard development phase, and (3) the platform portfolio development phase. In Phase 1, design knowledge and history is collected about every aspect of the existing product line, and this information is needed to carry out all five steps of the methodology. Phase 2 is the development of a baseline standard product line that provides a reference to compare with any redesign effort, and this involves defining a targeted market segmentation grid, which is Step 1, and defining targeted components for redesign, aggregating design inputs, and defining the baseline standard, which is Step 2. Phase 3 is the development of targeted component classes that are then instantiated to yield candidate component platforms, which is part of Step 5, and as precursors, Step 3 involves the definition of critical component performance functions, and Step 4 involves developing a baseline standard redesign strategy around common component classes.

Table 3-8: Bottom-Up Component-Based Platform Redesign Methodology

Phases	Step	Step Description
1 & 2	1	Create the market segmentation grid based on past sales and sales projections, target portions of the existing product line with the highest sales potential.
1 & 2	2	Target common components for redesign that often require modification. Classify critical design parameters from existing design data, and determine design inputs from an aggregate of known custom design specifications. Define a baseline standard product line from existing designs that span the target grid.
1, 2 & 3	3	Define component critical performance functions from existing and new design methodology as appropriate. Screening experiments may help reduce the number of required factors.
1 & 3	4	Develop a baseline standard redesign strategy around common component classes and corresponding standard optimization problems.
3	5	Develop candidate component platforms by instantiating the component classes across the market segmentation grid, and then define a product platform portfolio by scaling/stretching a subset of the candidate component platforms.

Given a set of candidate component platforms, a product platform portfolio is created by replacing baseline standard components with a select subset of candidate platforms by stretching and/or scaling key platform parameters. Although no strategy is given in this chapter for determining the subset of candidate platforms, Chapter 4 provides a methodology for creating a product platform portfolio from a subset of component platforms that optimizes the cost effectiveness of the portfolio.

The methodology is illustrated with an example involving the redesign of yokes on a product line of nuclear-grade valves. The valve product line is introduced and component platform redesign methodology is applied step-by-step. A targeted market segmentation grid is defined, a baseline standard product line is defined from existing artifacts and from existing product knowledge, a redesign strategy is presented involving a yoke component class and two alternative yoke mounting interface models, and finally, the yoke component class is instantiated for each member of the targeted market segmentation grid to yield a set of candidate component platforms. The example is continued in Chapter 4 where a valve product platform portfolio is created based on a subset the candidate platforms, and further detail is given regarding creation of the candidate platforms.

Chapter 4

Component-Based Product Platform Portfolio Optimization

Application of the component platform design methodology presented in Chapter 3 results in a set of candidate component platforms, and the final step is to define a component-based product platform portfolio by scaling/stretching a subset of the candidate designs, but no methodology is presented there for choosing the subset. In this chapter, this final step is addressed with a proposed product platform portfolio optimization procedure for determining a component platform subset that spans the targeted market segmentation grid most cost effectively.

The goal of the component-based product platform portfolio optimization procedure is to minimize manufacturing cost without sacrificing product performance or customer perceived variety. The proposed methodology is a four-step process that is described in detail in the next section. Then, the yoke leg component platform redesign example from Section 3.2 is continued, and several component-based product platform portfolios are created. An example is given in Section 4.2 that is kept simple in order to demonstrate the four-step process in clear detail, and a portfolio is created that minimizes the number of component platforms required to span the market segmentation grid, thus maximizing commonality. This example is considered simple because no component stretching or scaling is required, and no cost model is required. In Section 4.3, a cost model is developed prior to portfolio creation based on the ABC methodology presented in Section 4.3.1, which is customized to the example, and then two portfolios are created with the realistic objective of minimizing manufacturing cost. The two developed portfolios address the two stretching/scaling strategies proposed in Section 3.2.6, and the winning strategy is revealed as the one that is most cost efficient. Finally, Section 4.4 presents a chapter summary.

The methodology does not rely on the traditional vertical, horizontal, or beachhead market segmentation grid leveraging strategies illustrated in Figure 2-4. Rather, it employs an unconstrained leveraging strategy, which is especially beneficial when applied to an existing product line that was develop one-at-a-time time such that artifact designs are inconsistent from one to another. For example, a simple twelve-artifact valve yoke component platform is illustrated in Figure 4-1, which demonstrates how a single component platform from sample artifact 5 is leveraged three times. The three variants can be placed anywhere in the market segmentation grid by stretching/scaling the component platform, and it is the task of the four-step optimization process to determine both the number of component platforms to use and their placement within the grid that is most cost effective.

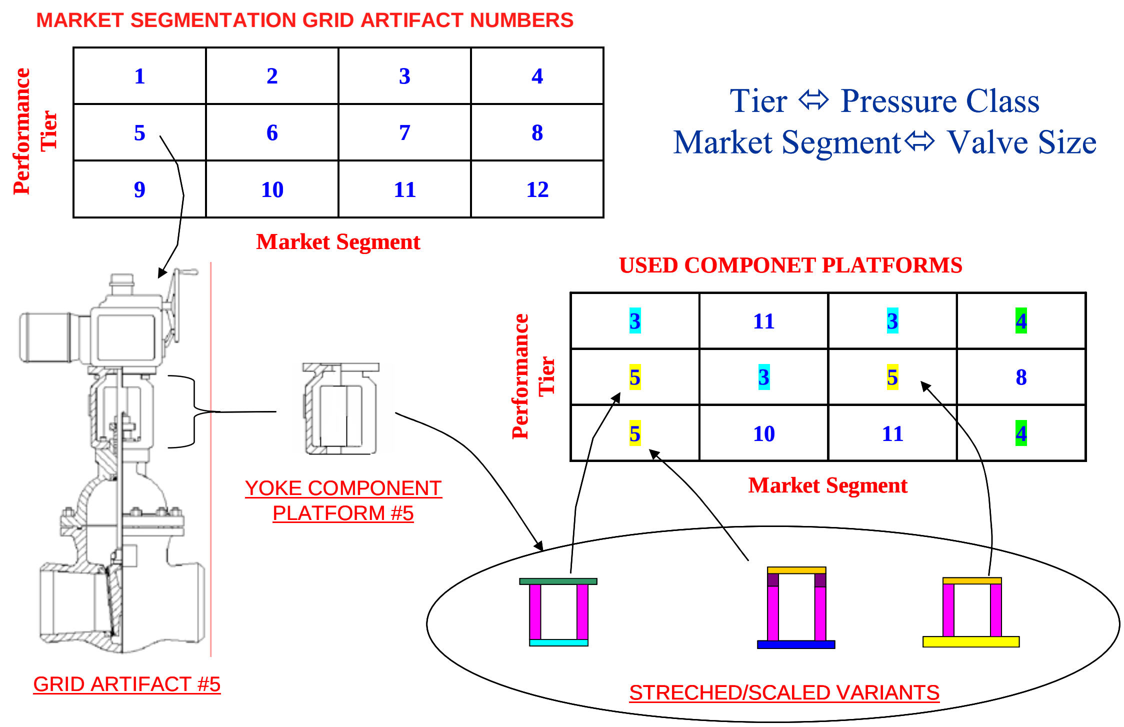


Figure 4-1: The Unconstrained Leveraging Strategy

4.1 The Four-Step Process

As a precursor, we assign an ordinal (*i*) to each artifact in the market segmentation grid. Then, the grid is symbolized by an array (S) with *n* members, and the elements of S contain sequential numbers from 1 to *i* to *n*. At a minimum, a design strategy must exist that can be implemented on artifact *i* to determine optimal critical component design parameters (X_i^*) that yield an optimal objective function (F_i^*).

Although the four-step process is used as a product platform portfolio solver for the component-based platform redesign methodology, it is presented generically as a stand-alone procedure. Then, any procedure assumptions are inherently met by the component-based platform redesign methodology. For instance, component-based platform redesign also requires the definition of market segmentation grid artifacts and a component redesign strategy.

Description of the four steps of the proposed optimization procedure follows.

4.1.1 Step1: Determine Optimal Component Solutions

The first step is to determine an optimal component solution for each member (*i*) of the market segment grid. Each solution is a candidate component platform and consists of an optimal objective function (F_i^*), an array of optimal design variables (X_i^*), an array of design value constraints associated with performance (P_i), and an array of constraints (B_i) associated with the upper and lower bounds on X_i. The X_i^* array, and the means to reformulate the constraint equations B_i and P_i are saved for subsequent steps. The method assumes that the optimal product platform portfolio consists of a subset of the resulting optimal designs. This step mimics the two-step approach first advocated by Nelson, et al. (2001) and then refined by Fellini, et al. (2005a; 2005b) who first optimize the individual products – to determine what the best possible performance is for each product when there is no commonality – before optimizing the family of products (i.e., their commonality), which is performed in Steps 3 and 4 of this methodology.

It is not necessary that the resulting designs are globally optimal, as this can be difficult to achieve and prove in general practice because of problem complexity such as ill-behaved functionality or quickly changing market needs. Rather, what are required are feasible designs along with a methodology for assessing feasibility of design variable constraints and performance constraints. For instance, it is acceptable to start with existing artifact component designs as long as the methodology exists, or is developed, and the existing designs are feasible. Generally, the goal of any engineering design problem is to obtain and employ the best available solution, and in this paper, the term 'optimal design' is considered synonymous with 'the best available solution'.

Application of the component platform redesign methodology from Chapter 3 yields a set of candidate component platforms that meet the requirements of Step 1. Specifically, component class development described in Section 3.1.3 includes a standard optimization problem with design variables, an objective function, and performance and bounds constraints that meet the criteria described above. The resulting candidate component platforms have a potential advantage over other candidate designs, such as components from a baseline standard product line, because they were created from a common component class that includes a stretching/scaling strategy for instantiating the component on multiple artifacts, which greatly enhances the potential for leveraging opportunities.

4.1.2 Step 2: Feasibility Testing

For each optimal component, Step 2 is to test the feasibility of using it as a platform on each market segment member. Assuming the bounds and performance constraints are in standard form, i.e., the value of the constraint function is less than or equal to zero when the constraint is satisfied, an optimal component (component j) is a candidate component product platform for a market segment member (member *i*) when Eq. 4.1 is satisfied.

$$X_j^* \in \{ X_i \mid B_i(X_i) \leq 0 \text{ and } P_i(X_i) \leq 0 \} \qquad 4.1$$

Given the n market segment members and the corresponding n optimal components, $(n^2 - n)$ tests are required, where n-1 component feasibility tests are associated with each of the n market segment members. Notice that testing a component against its own source member is not required as its feasibility is assured in advance. Then, any one test involves inserting each component's optimal solution design variables X_j^* into each market segment member *i's* constraint equations B_i and P_i, and assessing whether the constraints are satisfied. That is, Step 2 involves testing whether X_j^* is a feasible solution to member *i*'s optimization problem for all *j* not equal to *i*.

The best approach that results in efficient feasibility testing is to examine each artifact (*i*) in turn so that each optimization problem from Step 1 is reformulated just once. In order to further save computing effort, each component (*j*) is tested in two phases. In Phase 1, test only the bounds constraints (B_i), and in Phase 2, test the remaining constraints (P_i). The two-phase testing procedure can save effort because bounds constraint equations are typically simpler than performance constraint equations, which may involve complex analyses. For instance, performance constraint evaluation may require solving a complex finite element model to determine some physical parameter such as a stress level, a flow rate, or a frequency response to name just a few. It is likely that the required number of more expensive tests (Phase 2) is only a fraction of the required number of Phase 1 tests, which is n-1. Then, despite the $(n^2 - n)$ required tests, the methodology has potential for successful application on problems with a large number of artifacts. Similar two-phase approaches are used in other disciplines when the computational expense of some analyses is high. In the aerospace community, for instance, lower fidelity models that are inexpensive to compute are first used to reduce the design space or identify a "reasonable" design space before invoking higher fidelity models that are much more expensive to compute to perform analyses in that reduced region (Balabanov, et al. 1999; Knill, et al. 1999).

4.1.2.1 Step 2, Phase 1: Bounds Feasibility Test

In Phase 1, the bounds constraints are tested for feasibility without regard for performance feasibility, and this postpones reformulation of the complete optimization problem until needed during the Phase 2. For each artifact, n-1 bounds tests are required, and what results is a collection of bounds-feasible candidate component platforms. Let the resulting number of bounds-feasible candidates equal n_B, then this number can range from one (i.e. only the artifact's own platform is feasible) to n (i.e all candidate platforms are bounds-feasible), but it is probable that the resulting number is significantly less than n.

4.1.2.2 Step 2, Phase 2: Performance Feasibility Test

In Phase 2, only the bounds-feasible candidate component platforms from Step 1 are tested for performance constraint feasibility. Although evaluation of performance constraints may involve costly computations, the effort is reduced since Phase 1 testing has eliminated bounds-infeasible candidates. Performance constraint equations need to be formulated only once for each artifact, and each bounds-feasible candidate test is a load case that is solved for performance feasibility. What results is a further reduced set of candidates, let the set quantity equal n_P, that are both bounds-feasible and performance-feasible, and n_P can range from one (i.e., only the artifact's own platform is feasible) to n_B (i.e., all bounds-feasible platforms are also performance-feasible). Notice that if n_P equals one, any product platform portfolio must include this artifact's component platform.

4.1.3 Step 3: Optimization Problem Formulation

For Step 3, an optimization problem is formulated, and its solution is a component-based product platform portfolio. From the previous step's results, we construct arrays of candidate platforms (C_j) for each optimal component (j), and then each C_j contains the grid member ordinals (i) for which the component (j) satisfies constraints. Then, the component portfolio platform design variables (X^P) consist of n elements, one for each component (j). The value of a portfolio platform design variable ($X^P{}_j$) equals the index into the component's C_j array. Each element of X^P is bounded from one to the size of C_j. The design variables define which component is used as a platform for each grid member such that the n used platforms are given by $C(X^P)$.

The goal in the optimization process is to minimize the cost of implementing the resulting component product platform portfolio without jeopardizing its ability to meet performance objectives. In general then, achieving this goal involves a tradeoff between cost and performance, and the methodology assumes that a single tradeoff metric (*T*) can be formulated that adequately measures this objective. Given the assumption from Step 1 that the component product platform portfolio consists of a subset of the optimal artifact component designs, *T* can be expressed as a function of the used component platforms given by $C(X^P)$. The generalized optimization problem is thus stated in Eq. 4.2.

$$\text{Minimize } T(X^P)$$
$$\text{Subject to the upper and lower bounds on } X^P. \qquad 4.2$$

The majority of product platform design methodology assumes that maximizing commonality is a surrogate for minimizing cost (Simpson 2005). If this assumption is employed, then any of the commonality indices available in the literature (see Thevenot and Simpson (2006) for a recent review) can be used for the tradeoff metric (*T*) when a more sophisticated metric or cost model is not available. In fact, Khajavirad and Michalek (2007) recently argued that the commonality index (CI) introduced by Martin and Ishii (1997) captures the tooling cost savings of component commonality better than other commonality metric. If we use this index as our starting point, then an effective tradeoff metric (*T*) for our problem is *N* – where *N* is the number of unique ordinals in $C(X^P)$ – since we are dealing with a component platform (i.e., a single component that is standardized across as many market segments as possible. For instance, if $C(X^P)$ equals {1, 2, 1, 3, 2}, then N equals 3.

4.1.4 Step 4: Optimization Problem Solution

In Step 4, the optimization problem is solved. Finding a solution requires a zero-order algorithm such as the Simulated Annealing (SA) Algorithm or the Genetic Algorithm (GA), which is capable of addressing integer design variables. Given the optimal solution (T^*), the components to use as platforms are given by the unique ordinals in $C(X^{P*})$, and the platforms to use for each grid member is given by $C(X^{P*})$.

The solution to Eq. 4.2, which is denoted as T*, can have two extremes depending on the tradeoff metric employed. If T is taken as a commonality index as discussed in the previous step, then the solution, N*, denotes the number of component platforms needed to span the market segmentation grid. The other extreme occurs when T is so biased toward performance constraints that no commonality is achievable. In this case, the resulting component platform portfolio is defined by $C(X^P*)=i$ for every artifact i, which is referred to as the *null platform* (Nelson, et al. 2001) in that there is no suitable level of commonality within the product family for the market.

4.2 Maximum Commonality Component Product Platform Portfolio Example

Implementation of the four-step process is demonstrated using the yoke component platform redesign example from Section 3.2. The example is kept simple in order to demonstrate the four-step process in clear detail in that no component stretching or scaling is included, and as such, no cost model is required. What results is a component-based product platform portfolio that minimizes the number of component platforms required to span the market segmentation grid, thus maximizing commonality in the portfolio.

The market segmentation grid ordinals from Table 3-3 define artifact ordinal numbers from 1 to 60, and the optimization problem defined in Section 3.2.7 is a design strategy for determining critical yoke leg design variables for the yoke redesign strategy, and these provide the required precursors for the four-step process.

4.2.1 Step 1: Determine Optimal Yoke Leg Cross-Sections

As described in Section 3.2.7, each artifact's yoke leg cross-section size (defined by the variables *a, b,* and *c*) was optimized using Excel's Solver Add-in, which results in the collection of candidate component platforms given in Appendix B.2. Then, resulting optimal designs are instantiated on each artifact of the baseline standard. What results is a collection of 60 spreadsheets similar to the example given in Table 3-5 except yoke leg input, which is noted by '(2)' in the table, is replaced with the optimal solution.

Table 4-1 shows the portion of the Table 3-5 example baseline standard spreadsheet that is instantiated with the resulting optimal cross-section data, and Table 4-2 gives corresponding results needed to determine the value of the objective function F_2*. Notice that design variables *a*, *b*, and *c* are as denoted in Figure 3-7, whereas parameters *A*, *B*, and *C* in Table 4-1 are as denoted in Figure A-2 according to the Appendix 2 cross-section property calculation methodology. In addition, notice that design variable *b* equals yoke leg thickness, whereas parameter *B* equals the yoke leg outside radius (i.e., $B = a + b$), and using thickness as the design variable assures positive yoke leg area solutions. Finally, notice that the results needed to determine the objective function for the baseline standard artifact 2 are contained in Appendix A. For comparison, the objective function value for the baseline standard equals 110.0 and for the candidate component platform, the value is 81.8.

Table 4-1: Instantiated portion of the Sample Input Form
(Artifact 2: Size 4, Class 150 Double Disc Gate)

CROSS-SECTIONS	1
Code	1
A [in]	2.625
B [in]	3.375
C [rad]	0.5236

Table 4-2: Instantiated portion of the Sample Input Form
(Artifact 2: Size 4, Class 150 Double Disc Gate)

Analysis	*Criteria*	Calculated	Limit	Units
Beam Mode Natural Frequency	$F_N > 33.$	57.56	60.	Hz
Frame Mode Natural Frequency	$F_N > 33.$	63.91	60.	Hz
Beam Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	17.03	26.25	ksi
Frame Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	24.97	26.25	ksi
Yoke Cross-Section Area	n/a	2.356	n/a	in^2

4.2.2 Step 2, Feasibility Testing

For any given artifact, only the candidate yoke component platforms that satisfy performance and bounds constraints for that artifact are feasible platforms for instantiation on that artifact. In Step 2, each of the 60 candidate yoke component platforms are tested for potential (i.e., feasible) instantiation on each of the 60 artifacts. As proposed by the methodology, the testing is conducted in two steps.

4.2.2.1 Step 2, Phase 1: Bounds Feasibility Test

During the optimization process in Step 1, optimal yoke leg parameters (*a*, *b*, and *c*) are instantiated in the 60 spreadsheets, and bounds constraints (B_1, B_2, and B_3) for the 60 valves are stored in a database table for use in this step. For the first test phase, each member is tested in turn for bounds constraint feasibility with cross-section parameter input equal to the optimal parameters from all other members. Each member requires 59 tests (the member's own optimal parameters are feasible by definition), and so a total of 3540 tests are required (= 60^2 - 60). If the bounds constraints are satisfied, then that cross-section represents a candidate platform, and a one "1" is assigned to a test result variable; otherwise, zero "0" is assigned. A star "*" is assigned to the test variable for a member's self-parameter test. For each member, test results are stored in a character string of length 60, and the sequential row upon row combined results for the 60 valve members yields a square matrix of dimension 60, with ones or zeros off diagonal, and stars along the diagonal. Although many tests are required (3540), this sub-step takes little time because reformulation of the optimization problem is not required.

4.2.2.2 Step 2, Phase 2: Performance Feasibility Test

In Phase 2, each candidate (i.e., those corresponding to a "1" from the matrix) is tested to determine if the performance constraints (P_1 through P_4 in Eq. 3.1) are satisfied. Because performance constraints are involved, reformulation of the optimization problem is required, but only once for each artifact. Although the reformulation can be time consuming, the test needs to be conducted over only these candidates – not every entry in the matrix. If the candidate meets the constraints, then the test matrix entry is marked with "2". Once complete, the final candidates are those marked with "2" or "*".

For this example, the resulting matrix is shown in Appendix D.1. Note that of the 3540 required Phase 1 feasibility tests, only 1250 tests are required during Phase 2; thus, only 35% of the candidates need to be evaluated with the more expensive analyses in Phase 2. Phase 2 testing yields 734 feasible candidates (those marked with either "2" or *").

Table 4-3 shows five examples of Step 2 feasibility tests for artifact 15, which corresponds to the size 6 class 600 double disc gate valve according to the numbering scheme from Table 3-3. These sample tests correspond to the boxed and shaded region shown in Appendix C. The table includes data to verify the given bounds constraints, but notice that constraint B_2 is not applicable for this artifact (i.e., design variable a is unconstrained in the upper limit). As can be seen, candidate component platforms 2 and 5 fail to meet the bounds constraints, and thus these two candidates are no longer considered. Evaluation of the performance constraints for the remaining candidates 1, 3, and 4 involve determining valve extended structure natural frequencies and yoke leg stress levels using the analysis procedures demonstrated in Appendix A. Although the stress and natural frequency calculation details for the three remaining candidates are not given, the table shows resulting performance constraint values, which adequately demonstrates the methodology. The table shows that only component platform 3 meets all four performance requirements and earns a "2" in the matrix as the final test result. As can be seen, the testing process is straightforward, and further details are not really needed to illustrate the novel aspects of the proposed four-step procedure.

Table 4-3: Five Examples of Step 2 Testing For Artifact 15†

Component Ordinal, j			1	2	3	4	5
Component Design Variables, X_j		a [in]	5.5	2.625	3.5	4.75	3.125
		b [in]	0.625	0.75	1.125	0.625	1
		c [in]	0.5236	0.5236	0.5236	0.5236	0.6109
Artifact Constraints, B_i, P_i	Step 2a	B_1	-2.058	0.817	-0.058	-1.308	0.317
		B_2	not applicable				
		B_3	-1.183	-3.933	-2.683	-1.933	-3.183
	Step 2b	P_1	-0.371	not required	-0.2697	-0.1798	not required
		P_2	0.0507		-0.2354	0.3177	
		P_3	-0.7236		-0.5194	-0.5452	
		P_4	-0.8667		-1.012	-0.7415	
Test Result			1	0	2	1	0

†Note: for artifact 15, a_{MIN} = 3.442 in, a_{MAX} is not applicable, and r_{MAX} = 7.308 in as noted in Appendix B.1.

4.2.3 Step 3: Optimization Problem Formulation

The most innovative part of the proposed four-step process involves optimization problem formulation. The optimization requires building candidate platform arrays from the matrix in Appendix D.1. Using the first row as an example, fourteen cross-sections satisfy all valve ordinal 1 constraints; therefore, 14 is the size of the C_1 array as well as the upper bound on $X^P{}_1$. As another example, the last row in the matrix (60) has four feasible cross-sections such that the upper bound for $X^P{}_{60}$ is 4, and the candidate array (C_{60}) is {29, 30, 59, 60}; notice that the valve's own cross-section is included (60 in this case), which should always be a condition.

The first three columns of the table in Appendix D.2 give candidate arrays and the maximum allowed X^P values for each artifact, which is the complete input required to set up the component-based platform portfolio optimization problem. As discussed previously, minimizing N is the objective (to maximize commonality), where N is computed as the number of unique members of $C(X^P)$, where $C(X^P)$ defines the component platform ordinals used to span the market segments. The next step is to solve the optimization problem.

4.2.4 Step 4: Solving the Optimization Problem

The optimization is solved using a Simulated Annealing (SA) algorithm that is presented in Belegundu and Chandrupatla (1999). The starting temperature was 10000, the temperature reduction factor was 0.7, the number of temperature reductions was 5, the number of search cycles per temperature reduction was 120, and the convergence criterion was set to 0.0001. The SA algorithm consistently converges to a feasible solution, but the resulting optimal number of component platforms (N^*) can vary from 7 to 12. Because of this result inconsistency, more than 50 runs were performed before declaring $N^{*}=7$ the maximum achievable commonality. The nature of this inconsistency requires additional investigation; however, it does not diminish the utility of the proposed four-step methodology since all of the solutions offer improved commonality over the existing product line.

In addition to the inconsistency, use of the SA algorithm is computationally expensive, but the expense is offset by the simplicity of the example portfolio objective function. One run for this example takes about six minutes on a 1.8 GHz PC running Windows XP Professional™ and requires about 1,500,000 function calls, which could be reduced by using less conservative parameter settings in the SA. For comparison, the number of function calls required by an exhaustive search equals the product of all the upper bounds of the X^P array, which, for this example, is greater than 2.7E+58 evaluations based on the maximum X^P column in Appendix D.2. Additional work is needed to reduce the number of function calls by the SA algorithm, in particular, and for solving this optimization problem, in general. Parallel computing techniques could also be employed as the problem is easily parallelizable for different market segments.

The last two columns from the table in Appendix D.2 give two $N^{*}=7$ optimal solutions, where the optimal X^P array and the corresponding used platforms $C(X^P)$ are given. In addition, Table 4-4 and Table 4-5 contain pivot tables on the left that graphically define the solutions, and the numbers in the tables correspond to the unique source component platform ordinals and descriptions listed on the right. The tables help reveal patterns: for instance, both solutions employ platforms 30, 37, and 47, which are shown shaded, and platform 30 can be used in at least 10 different artifacts, which represents a significant gain in commonality.

Table 4-4: Platform Portfolio Solution 1

		Size					
Type	Class	3	4	6	8	10	12
DD	150	23	37	48	29	48	30
	300	29	29	29	23	47	23
	600	37	48	29	47	30	30
	900	23	37	29	23	23	30
	1500	37	23	30	30	29	30
FW	150	37	37	48	48	47	29
	300	37	37	29	48	48	47
	600	37	44	48	47	47	48
	900	44	44	48	47	30	30
	1500	48	47	29	48	29	30

Ordinal	Cross-Section Source	Qty
23	10-900-DD	7
29	10-1500-DD	11
30	12-1500-DD	10
37	3-300-FW	9
44	4-600-FW	3
47	10-600-FW	8
48	12-600-FW	12

Table 4-5: Platform Portfolio Solution 2

		Size					
Type	Class	3	4	6	8	10	12
DD	150	47	20	51	26	51	47
	300	26	26	26	26	47	47
	600	37	26	26	30	30	30
	900	47	20	26	47	30	30
	1500	37	26	30	30	30	30
FW	150	20	20	45	45	26	47
	300	37	20	45	26	26	47
	600	37	51	45	47	47	51
	900	37	51	51	47	30	30
	1500	51	47	47	51	30	30

Ordinal	Cross-Section Source	Qty
20	4-900-DD	5
26	4-1500-DD	12
30	12-1500-DD	13
37	3-300-FW	5
45	6-600-FW	4
47	10-600-FW	13
51	6-900-FW	8

In addition to the multiple solutions noted earlier, the corresponding platform ordinals can vary widely between solutions; however, all of the results are feasible. A good reason for the varied results is this: given that a certain platform is suitable for a given valve, that valve's cross-section may be suitable for the platform's valve and also for many of the valves that use the platform. In other words, the platforms can have a 'reflexive' property in that it may be possible to switch a used platform for the platform of one of its users. Table 4-6 gives the two example solutions side-by-side and demonstrates this reflexive property in that component platform 20 is interchangeable with platform 37 in the exact same set of market segments.

Table 4-6: Demonstration of the Component Platform Use 'Reflexive' Property

	Size					
Class	3	4	6	8	10	12
150	23	37	48	29	48	30
300	29	29	29	23	47	23
600	37	48	29	47	30	30
900	23	37	29	23	23	30
1500	37	23	30	30	29	30
150	37	37	48	48	47	29
300	37	37	29	48	48	47
600	37	44	48	47	47	48
900	44	44	48	47	30	30
1500	48	47	29	48	29	30

	Size					
Class	3	4	6	8	10	12
150	47	20	51	26	51	47
300	26	26	26	26	47	47
600	37	26	26	30	30	30
900	47	20	26	47	30	30
1500	37	26	30	30	30	30
150	20	20	45	45	26	47
300	37	20	45	26	26	47
600	37	51	45	47	47	51
900	37	51	51	47	30	30
1500	51	47	47	51	30	30

At first glance, some of the leveraging apparent in the solutions does not seem viable. For instance, use of platform 48 (from the size 12, class 600 flex wedge gate valve) on valve 55 (the size 3, class 1500, flex wedge gate valve) seems discrepant; however, this is a verified feasible fit. A reason for the discrepancy is that the underlying valve artifacts are currently lacking in commonality, as no smooth transition in yoke mounting parameters exists among valve sizes, pressure classes, or types. In fact, this demonstrates the advantage of employing the arbitrary leveraging strategy that does not rely on the traditional horizontal, vertical, or beachhead market segmentation grid leveraging strategies.

4.3 Minimum Cost Component Product Platform Portfolio Example

Any realistic component-based product platform portfolio solution must contain properly stretched/scaled yoke component platforms, and the associated manufacturing cost must be captured. The yoke component platform redesign strategy proposes two potential architectures as shown in Figure 3-6, and implementation of this strategy requires a corresponding model for capturing associated manufacturing cost. Section 4.3.1 presents a general model based on ABC methodology and describes details on how the general model is customized to the example. The customized cost model includes automatic yoke mounting flange design methodology for specifying the interface between the yoke and the rest of the valve extended structure, and this is presented in Section 4.3.2. The flange interface methodology determines required interface flange volume which is an ingredient of the ABC model.

In Section 4.3.3, two component product platform portfolios are developed that model the two stretching/scaling strategies: the module and stretch strategies as described in Section 3.2.6.1. The winning strategy is revealed as the one that is most cost efficient.

4.3.1 ABC for Low Volume Highly Customized Product

Use of Activity Based Costing (ABC) methodology is advocated that provides a realistic model of manufacturing cost including cost due to new tooling and other capital, raw material, machining time, setup, plant operation, and labor. The ABC model should consider fixed cost that is independent of the quantity of artifacts manufactured, and variable cost that is a function of production volume. Important fixed costs include new tooling and other capital costs, plant operation, and indirect labor cost due to such activities as engineering design and research, whereas important variable costs include raw material, machining time and labor, tool wear, machine maintenance, and other direct labor costs for activities such as material handling.

An ABC model must sufficiently capture every important cost driver related to a specific problem, which can result in book keeping details that can seem overwhelming. In order to enhance clarity, methodology details are presented in two parts: first, general considerations are discussed for application to any redesign project in Section 4.3.1.1, and second, example-specific details are presented in Section 4.3.1.2 that addresses both the module and stretched yoke mounting flange options.

4.3.1.1 General Considerations

How costs are divided between fixed and variable can depend on the scenario, and the choice can be subjective. The goal is to realistically model the cost of doing business so that any change in manufacturing techniques or product volume is accurately reflected in the cost model. For instance, the division of cost can be different depending on production volume. In a high volume operation, it is probably appropriate to consider all setup cost as fixed, but in a very low volume situation, where components are typically produced one-at-a-time, some setup cost should be considered variable.

With respect to component product platform design, the cost model should be capable of capturing the cost benefit of implementing the platform. It should include sales volume projections as input so that payback time may be assessed. The component-based product platform portfolio optimization methodology assumes that cost improvement is achievable through part commonality resulting from leveraging component platforms across portions of the market segmentation grid, and the cost model must be capable of accurately capturing the savings. Because cost savings due to the leveraging typically requires significant sales volume, such cost savings may be difficult to achieve for low volume products, which is the focus of this thesis.

Eq. 4.3 defines a generalized ABC model for an artifact, where A_T is the artifact total manufacturing cost, A_F is its fixed cost, and A_V is its variable cost. The fixed cost consists of tooling cost (F_T), and fixed overhead (F_{OH}), while the variable cost consists of raw material cost (V_{RAW}), machining cost (V_{MACH}), and variable overhead (V_{OH}).

$$\begin{aligned} A_T &= A_F + A_V \\ A_F &= F_{TOOL} + F_{OH} \\ A_V &= V_{RAW} + V_{MACH} + V_{OH} \end{aligned} \qquad 4.3$$

This artifact cost model is used in the formulation of the platform tradeoff metric (T), which is given by Eq. 4.4, and which captures the potential cost savings from implementing a component-based product platform portfolio. It equals the difference in cost between the product platform portfolio and baseline standard manufacture of all member artifacts of the targeted market segmentation grid. The subscripts F and V are as used in Eq. 4.3, and the subscripts P and B refer to the platform and baseline implementation of the market segmentation, respectively. The *turns* parameter (t) is the assumed number of times the members of the market segmentation grid are produced and gives a means for capturing market volume. In general t can be different for individual members of the market segmentation grid, and thus, t is inside the summations. The first two terms apply to the portfolio implementation, where N denotes the number of component platforms required to span the market segmentation grid, and q denotes the number of times a given platform is used in the grid. The last terms apply to the baseline implementation, where n is the number of members in the market segmentation grid.

$$T = \sum_N \left(A_{FP} + \sum_q t A_{VP} \right) - \sum_n \left(A_{FB} + t A_{VB} \right) \qquad 4.4$$

4.3.1.2 Example-Specific Details

In order to decide on the better solution between the module and stretched models, the cost model must capture the cost differences between the approaches. On the one hand, both require flange machining, but the module approach requires less. On the other hand, the module approach requires change pieces while the stretched model does not. The better solution will be determined by studying the manufacturing activity required to produce a result, and this is precisely the focus of the ABC approach.

Eq. 4.5 gives the employed cost model based on the generalized model presented previously in Section 4.3.1.1; however, the tradeoff metric is simplified in that it is assumed that each artifact has equal probability of production. Then, the turns parameter (*t*) does not depend on the artifact as with the generalized model.

$$T = \sum_{N} \left(A_{FP} + tqA_{VP} \right) - \sum_{n} \left(A_{FB} + tA_{VB} \right) \qquad 4.5$$

The notation of Eq. 4.5 is the same as per the general model: A_{FP} is a platform artifact fixed cost, A_{VP} is a platform artifact variable cost, A_{FB} is a baseline artifact fixed cost, A_{VB} is a baseline standard artifact variable cost, N is the required number of component platforms, n is the total number of artifacts, and q is number of times a given component platform is used.

For a single turn (i.e., t equal to one), Eq. 4.5 yields the difference in manufacturing cost between a completely instantiated portfolio and a complete set of baseline standard artifacts. It is implied that all platform artifacts and all baseline standard artifacts must satisfy the aggregate performance requirements presented in Section 3.2.4. In addition, as discussed in Section 3.2.4, it is possible that a baseline standard artifact is infeasible, and the model includes the cost of making it feasible, which is just as the modification would be required in practice if a custom specification equaled the aggregate specification. Therefore, in the discussion that follows, there is a distinction between an infeasible and a feasible baseline standard artifact.

A significant portion of total yoke manufacturing cost is associated with raw material, which is directly related to material volume. Then, yoke metal volume is required for both yoke platform instantiations and for baseline standard yokes. An important volume component is for a yoke mounting flange, and Section 4.3.2 gives mounting flange design methodology, including equations for determining its volume.

Yoke volumes for needed options are given by Eq. 4.6, and each equals the sum of yoke leg and yoke mounting flange volumes. The actuator mounting flange is not considered as no distinction exists between platform and baseline actuator mounting flanges. However, a distinction is made between the volume of a feasible (V_{BF}), and infeasible (V_{BI}) baseline standard yoke leg. In addition, there is a distinction between volumes for a modular platform yoke (V_{PM}) and stretched platform yoke (V_{PS}) according to the yoke casting pattern schemes presented previously.

$$\begin{aligned} V_{BF} &= V_{STD} + V_{MTG} \\ V_{BI} &= V_{OPT} + V_{MTG} \\ V_{PS} &= V_{OPT,P} + V_{MTG,MAX} \\ V_{PM} &= V_{OPT,P} + V_{MTG} \end{aligned} \qquad 4.6$$

In Eq. 4.6, $V_{OPT,P}$, V_{OPT}, and V_{STD} are associated with yoke leg volume and are different between a component platform yoke and a baseline standard yoke. For a given artifact, yoke leg length must be the same for both the baseline and platform, and therefore volume differences are due to area differences. The term $V_{OPT,P}$ is the yoke leg area for an instantiated platform and equals the platform's yoke leg area times the artifact yoke leg length. If the baseline standard yoke leg meets the established performance criteria, the baseline yoke leg volume (V_{STD}) equals the baseline yoke volume. However, if the baseline yoke is infeasible, a yoke leg modification is required and it is assumed that its candidate platform yoke leg cross-section is used (see Section 3.2.6.2 for the definition of a candidate platform), which is denoted as V_{OPT}. In addition, as described later, an extra setup cost is assigned when a baseline is infeasible that accounts for required yoke casting pattern modifications.

Table 4-7 defines the elements of the simple cost model used in the example, and Table 4-8 gives numerical values for costing rates involved. Although costs are given in dollars ($), true cost magnitudes are masked somewhat to protect confidential sources; however, the data does meet the important objective of capturing the relative cost among the various activities. An interesting aspect is that some setup costs, including jig reuse and jig setup costs, which are traditionally considered as fixed costs, are considered here as variable costs. These are variable because a low volume custom product is the focus where the yokes would be typically manufactured one-at-a-time. In addition, the jig reuse cost for a platform is less then for a baseline, and this reflects cost savings from improved yoke casting pattern design in accordance with the scheme discussed in Section 3.2.6.1. Then, this distinction helps reduce the cost of implementing a platform and increases the potential of successful implementation. Another interesting aspect of the model is that the platform fixed costs for yoke casting pattern creation (C_F, C_P, and C_J) are high relative to the baseline standard casting pattern modification cost (C_B), and therefore sufficient commonality must be introduced by the platform portfolio in order to overcome the casting pattern creation cost.

Table 4-7: Example Simple Cost Models

Artifact Type	**Relative Fixed Cost**		**Variable Cost**	
	Description	**Equation**	**Description**	**Equation**
Infeasible Baseline	Design Overhead, Modify Pattern	$A_{FB} = C_O + C_B$	Jig Setup and Raw Material	$A_{VB} = C_{JB} + V_{BI} C_R$
Feasible Baseline	Design Overhead	$A_{FB} = C_O$	Jig Setup Raw Material	$A_{VB} = C_{JB} + V_{BF} C_R$
Modular Platform	Design Overhead, New Pattern, Jig Fixture, and Flange Modules	$A_{FP} = C_O + C_P + C_J + (q-1) C_F$	Jig Reuse and Raw Material	$A_{VP} = C_{JP} + V_{PM} C_R$
Stretched Platform	Design Overhead, New Pattern and Jig Fixture	$A_{FP} = C_O + C_P + C_J$	Jig Reuse, Raw Material, and Machining	$A_{VP} = C_{JP} + V_{PS} C_R + (V_{MTG,MAX} - V_{MTG}) C_M$

Table 4-8: Example Costing Rates

Symbol	Variable or Fixed Cost	Module	Stretch	Description
C_O	Fixed	100	100	Design Database Overhead Cost [$/design]
C_F	Fixed	200	n/a	Flange Module Pattern Creation Cost [$/flange]
C_P	Fixed	1000	1000	Platform Pattern Creation Cost [$/pattern]
C_B	Fixed	500	500	Pattern Modification Cost for an Infeasible Baseline Standard Yoke [$/pattern]
C_J	Fixed	300	300	Jig Fixture Creation Cost for a Platform Yoke [$/jig]
C_{JP}	Variable	200	200	Jig Fixture Reuse Cost for a Platform Yoke [$/reuse]
C_{JB}	Variable	500	500	Jig Fixture Reuse Cost for a Baseline Standard Yoke [$/reuse]
C_R	Variable	2	2	Raw Material Cost per Unit Volume [$/in^3]
C_M	Variable	n/a	1	Machining Cost per Unit Volume of Removed Material [$/in^3]

4.3.2 Flange Interface Design

A plan view for the assumed yoke mounting interface flange geometry is given in Figure 4-2, and the parameter w is determined from Eq. 4.7, and r_O and r_I are defined in Table 4-9. Eq. 4.7 is based on the standard stress analysis methodology employed by the manufacturer, with conservatism; however, whereas bending stress is normally determined, the equation is posed in terms of thickness required to reach a target stress level equal to a conservative allowable. Flange stress is largely a function of a moment arm (x) and external *Moment* and *Thrust* from the aggregate specification. Table 4-9 gives flange section views for three possible interface models and corresponding equations that determine required final machined yoke mounting flange volume V_{MTG}. Two models addresses possible clamped flange configurations, and one address a bolted configuration. The procedure in Table 4-9 is applied to the module platform mountings and to the baseline mountings. It is conservative to apply this model to the baseline standard because no penalty results if the existing baseline flange is too thick (i.e., more raw material cost), or it does not satisfy target stress criteria requiring design modification. For a stretch platform yoke, which by definition may be instantiated on multiple artifacts, raw material volume equals the maximum resulting volume among the associated instantiations, and this is denoted as $V_{MTG,MAX}$ in Eq. 4.6**.**

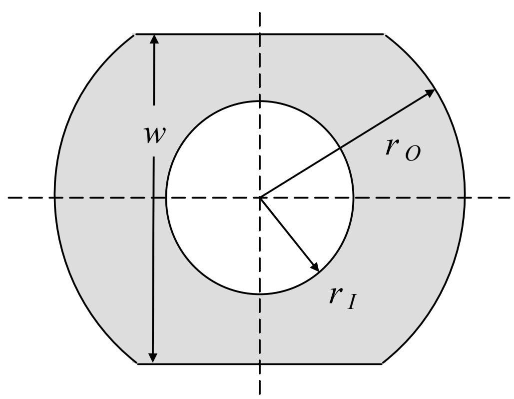


Figure 4-2: Yoke Flange Interface Model

$$F = Thrust + \frac{Moment}{r} \qquad (4.7)$$

$$\sigma = S = \frac{6xF}{wt^2}$$

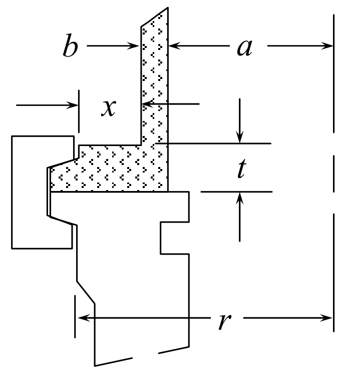
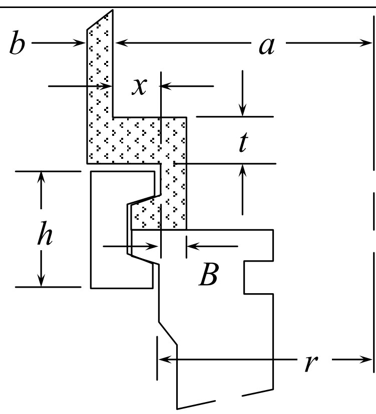
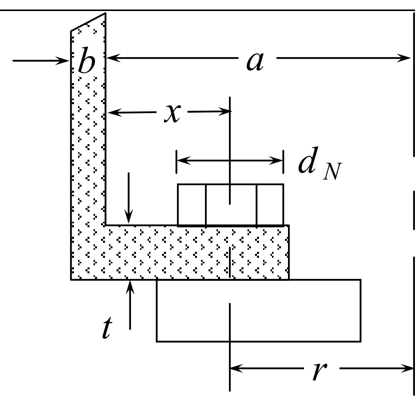
$$w = 2(A+B)\sin(C)$$

$$\therefore t = \sqrt{\frac{6xF}{Sw}}$$

where:

Thrust = External Thrust
Moment = External Moment
x = Bending Moment Arm
r = Moment Equivalent Contact Force Location
S = Allowable Bending Stress
w = flange width

Table 4-9**:** Determination of the Yoke Mounting Flange Volume (V_{MTG})

	Yoke Mounting Sketch	Flange Volume Equation
Clamped Joint, Inside Flange		$r_O = r$ $r_I = a$ $x = r - a - b$ $V_{MTG} = t\left(r^2 - a^2\right)\pi$
Clamped Joint , Outside Flange		$r_O = a + b$ $r_I = r - B$ $x = a - r$ $V_{MTG} = t\left((a+b)^2 - (r-B)^2\right)\pi$ $+ \frac{1}{2}h\left(r^2 - (r-B)^2\right)\pi$
Bolted Joint, Inside Flange		$r_O = a + b$ $r_I = r - \frac{1}{2}d_N$ $x = a - r$ $V_{MTG} = t\left((a+b)^2 - (r - \frac{1}{2}d_N)^2\right)\pi$

4.3.3 Module and Stretched Strategy Product Platform Portfolios

The four-step process presented in Section 4.1 is used to determine the optimal component product platform portfolio for the two proposed platform yoke models. The objective function is given by Eq. 4.8. A large penalty P is included that is added when any component platform is not used on its own artifact, i.e., $C_i \neq i$ using the notation defined previously in Section 4.1. Although the examples consider it necessary that the artifact associated with the platform use its own platform, this is not mandatory for implementing the methodology; however, imposing this necessity is reasonable as it assures that the instantiation involving the platform's source artifact will optimally meet the target design criteria.

$$F = T + P$$

where:

$$P = 10(A_{FP}+A_{VP}) \text{ if } C_i \neq i \qquad 4.8$$
$$P = 0 \text{ otherwise}$$

An interesting fixed cost is the design database overhead fixed cost, C_O, which is common to all artifact types. It denotes the cost required to maintain the database of design information such as design drawings and the paperwork required to order raw material and manufacture a yoke. Since it is common to all types, its net cost for the platform portfolio is a direct function of the number of required platforms (N). Then, this cost could be removed from the tradeoff metric and instead applied as a weight on the platform quantity (*N*) in the general four-step optimization process objective function. Then, Eq. 4.9 is an alternative objective function that could be employed.

$$F = NC_O + T + P \qquad 4.9$$

The simple cost model is applied to the optimized yoke valve artifacts of the example market segmentation grid. In preparation for applying the four-step process, each market segmentation grid artifact is assigned an ordinal as shown in Table 4-10. In order to demonstrate the flexibility of the process, it is assumed that several artifacts should not be included in the optimization, and twelve gaps exist corresponding to the excluded artifacts. Such artifact exclusions may be desired for several reasons: because they do not currently exists, are not worth salvaging as a portfolio member, or involve fundamentally different design philosophies. This grid considers only gasketed bolted flanges (the un-shaded artifact numbers) and clamped type bonnet joints (the shaded black artifact numbers) as reflected in Table 4-9. For three of the excluded artifacts, the bonnet joint is the threaded type, and for the other nine, the design is not available for production at the target manufacturing facility. The threaded joint artifacts could be included by adding a forth option to Table 4-9. Alternatively, a platform could be created separately for the threaded joint artifacts using the presented methodology. Similarly, the bolted bonnet and clamped valve artifacts could be separated, and a component-based product platform portfolio created for each.

Table 4-10: Market Segmentation Grid Artifact Ordinals With Exclusions

		Size					
Type	Class	3	4	6	8	10	12
DD	150	1		3	4	5	6
	300	7	8	9	10	11	12
	600	13	14	15	16	17	18
	900	19		21	22	23	24
	1500		26	27	28	29	30
FW	150			33	34	35	
	300			39	40	41	
	600	43	44	45	46	47	
	900	49	50	51	52	53	54
	1500	55		57		59	60

Although the employed Simulated Annealing (SA) Algorithm optimizer yields good results, the global optimal solution is not guaranteed. In an attempt to reach the best solution in a reasonable time and without interaction, the optimization process is performed twenty times in succession automatically. The twenty-run sequence was conducted several times during the search for the best solution. For about half of the sequences, the initial design variables were set so that the initial used platform ordinals equal their corresponding artifacts; in equation form, using the notation developed during the definition of the four-step optimization process, $C(X^P(1))=1$, $C(X^P(2))=2$, and so on, noting that the design variables are given by the vector Y, which contains the indices into the platform matrix C such that $C(X^P)$ defines the artifact ordinals to use as platforms. For the other sequences, the initial design variables were set at random. There was no noticeable difference in solution time or process performance due to the initial starting point.

The following tables and figure summarize the optimization results for the best solutions (i.e., maximum commonality and maximum relative cost savings). Table 4-11 gives a sample iteration history from the best solution for the module cost model, and this table shows that a single optimization takes about 3 minutes to complete and requires about 600,000 function calls. Figure 4-3 shows how the SA temperature parameter, the objective function and the number of function calls trend with time for the Table 4-11 iteration history. Table 4-12 and Table 4-13 give cost statistics from the best solutions for the module and stretched cost models, respectively, and Table 4-14 and Table 4-15 are corresponding pivot tables that provide a good visualization of the respective platform distributions.

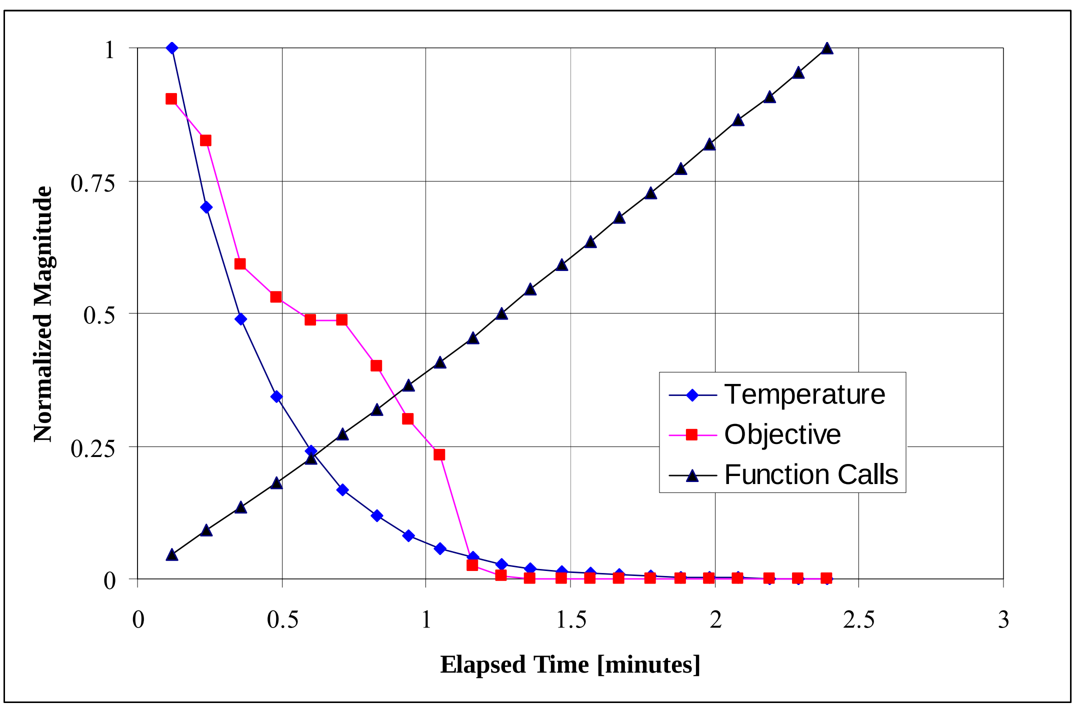


Figure 4-3: Sample Iteration History Trends

Table 4-11: Sample Solution SA Algorithm Iteration History

Temperature	Objective, F	Elapsed Minutes	Total Function Calls
10000	-1976.868	.12	28801
7000	-3541.752	.24	57601
4900	-8167.545	.36	86401
3430	-9447.786	.48	115201
2401	-10316.7	.6	144001
1680.7	-10323.51	.71	172801
1176.49	-12070.08	.83	201601
823.543	-14077.82	.94	230401
576.4801	-15426.23	1.05	259201
403.5361	-19596.79	1.16	288001
282.4753	-19965.3	1.26	316801
197.7327	-20072.82	1.36	345601
138.4129	-20072.82	1.47	374401
96.88901	-20072.82	1.57	403201
67.8223	-20072.82	1.67	432001
47.47562	-20072.82	1.78	460801
33.23293	-20072.82	1.88	489601
23.26305	-20072.82	1.98	518401
16.28414	-20072.82	2.08	547201
11.3989	-20072.82	2.19	576001
7.979227	-20072.82	2.29	604801
5.585459	-20072.82	2.39	633601

Table 4-12: Optimal Module Cost Model Statistics

Used Platform	Quantity Used	Platform Cost ($)		Baseline Cost ($)		Savings ($)
		Fixed Cost	Subtotal Variable Cost	Subtotal Fixed Cost	Subtotal Variable Cost	
13	4	2000	920.89	1400	2550.15	1029.26
15	8	2800	1846.59	3300	5339.40	3992.82
26	6	2400	2028.89	1100	4316.58	987.69
28	3	1800	2543.84	800	4156.54	612.70
30	8	2800	11862.64	3800	16460.59	5597.94
47	10	3200	6493.03	2500	10985.89	3792.86
51	9	3000	3820.01	2900	7979.55	4059.54
Totals	7 platforms	18000	29516	15800	51789	20073

Table 4-13: Optimal Stretched Cost Model Statistics

Used Platform	Quantity Used	Platform Cost ($)		Baseline Cost ($)		Savings ($)
		Fixed Cost	Subtotal Variable Cost	Subtotal Fixed Cost	Subtotal Variable Cost	
5	3	1400	1600.75	800	2227.71	26.96
15	3	1400	1027.53	1300	1923.65	796.12
22	5	1400	3898.23	1500	4790.98	992.75
26	5	1400	2768.87	1500	3535.82	866.95
28	2	1400	2602.48	200	2892.35	-910.13
29	2	1400	3641.09	700	3721.31	-619.78
30	3	1400	7787.18	1300	7109.21	-777.96
40	5	1400	2053.30	2000	3608.52	2155.21
44	4	1400	1117.53	1400	2431.38	1313.85
47	3	1400	2751.63	300	2366.18	-1485.45
51	6	1400	4431.31	1600	6031.54	1800.24
52	3	1400	1911.47	1300	4332.30	2320.83
54	3	1400	4363.62	1300	4386.92	-76.69
60	1	1400	2130.84	600	2430.84	-500
Totals	14 platforms	19600	42086	15800	51789	5903

Table 4-14: Optimal Module Cost Model Pivot Table

Type	Class	Size 3	4	6	8	10	12
DD	150	47		51	26	51	28
	300	15	15	15	26	47	47
	600	13	15	15	47	47	30
	900	26		26	47	28	30
	1500		26	47	28	30	30
FW	150			51	51	26	
	300			15	15	51	
	600	13	13	15	47	47	
	900	13	51	51	47	30	30
	1500	51		51		30	30

Ordinal	Cross-Section Source	Qty
13	3-600-DD	4
15	6-600-DD	8
26	4-1500-DD	6
28	8-1500-DD	3
30	12-1500-DD	8
47	10-600-FW	10
51	6-900-FW	9

Table 4-15: Optimal Stretched Cost Model Pivot Table

Type	Class	Size 3	4	6	8	10	12
DD	150	22		51	26	5	51
	300	40	15	15	47	22	22
	600	5	5	15	47	54	30
	900	26		26	22	28	30
	1500		26	22	28	29	30
FW	150			40	51	40	
	300			40	40	51	
	600	44	44	26	52	47	
	900	44	44	51	52	54	54
	1500	51		52		29	60

Ordinal	Cross-Section Source	Qty
5	10-150-DD	3
15	6-600-DD	3
22	8-900-DD	5
26	4-1500-DD	5
28	8-1500-DD	2
29	10-1500-DD	2
30	12-1500-DD	3
40	8-300-FW	5
44	4-600-FW	4
47	10-600-FW	3
51	6-900-FW	6
52	8-900-FW	3
54	12-900-FW	3
60	12-1500-FW	1

These results show that the module cost model mandates seven platforms to span the market segmentation grid, and the stretched model requires fourteen platforms. Although both models yield a relative cost savings over the baseline standard, the savings for the module model is significantly greater ($20073 verses $5903). Then, the module model is the clear winner, given the assumed relative costs from Table 4-8. For this example (1) the commonality introduced by the platforms results in a platform portfolio fixed cost comparable to the baseline standard fixed cost, (2) due to the use of the optimal yoke leg cross-sections and to the more efficient setup cost, platform portfolio variable cost is significantly less than for the baseline standard, but (3) the extra artifact mounting flange machining variable cost in the stretched cost model must tradeoff with the fixed cost savings. In addition, it is evident that, because the platform portfolio variable cost is less than the total baseline standard variable cost, an increase in turns (t) would further increase cost savings.

If the module strategy is employed, Table 4-12 gives the cost savings ($20073) for the production of one complete set of market segmentation grid artifacts (i.e., one turn as described in Section 4.3.1.2). Notice that a cost savings is realized even though the fixed cost for the platform portfolio is greater than that for the baseline standard, and this cost difference ($2200 for the module model) represents the maximum risk in not realizing the production volume assumption inherent in the turns parameter, t, which is not significant in this case. The current cost model does not include the cost of developing the methodology, as this is considered a sunk cost (i.e., the methodology exists as of this writing). The cost (e.g., man-hours) to assemble and implement a redesign team is included in the design database overhead cost coefficient (C_O) from Table 4-8, and for this example, the database overhead cost is the same for both the platform and the baseline standard. This is reasonable given the premise that the baseline standard will require modification, and in addition, it is very probable that the proactive redesign effort (i.e., man-hours) required to create a component platform yoke is comparable to the effort required to reactively modify a baseline standard. In fact, it may be argued that reactive modification is inefficient (i.e., more costly) compared to proactive redesign due to the "emergency atmosphere" that often develops during the reactive approach, which requires special treatment (e.g., overtime). Therefore, the results show that implementing the platform methodology is feasible given the cost and turns assumptions.

It is possible that the project cannot be justified in some cases. For instance, Marion, et al. (2007) describe an example where the cost of outsourcing saves more money than implementing a product platform in-house. If the yoke redesign project had not shown a cost savings, then the project would be aborted, and the redesign team effort to date would be a loss; however, the effort may not be a complete loss as some of the work may still have value. For example, a baseline standard product line may emerge that did not formally exist previously, or a developed ABC model could improve future cost estimation. In general, the risk is acceptable given the potential benefits, either in full or only partial. In addition, the effort required to reach this critical decision point is not excessive, even for a small company with limited resources. In particular, the redesign team's required tasks, except perhaps for ABC model development, are not significantly different from their normal job functions, and since an entire product line is involved, there is potential for batching their effort, e.g., if four man-hours are required to evaluate a single yoke, then the cost of evaluating ten yokes might be twenty hours or less, a savings of nearly half the effort in terms of man-hours.

For comparison, the optimization process was performed while considering commonality alone without cost. This is accomplished by setting C_O equal to unity and setting all other cost parameters to zero. This effectively makes the objective function as per Eq. 4.10. Table 4-16 gives the resulting platform portfolio statistics and shows that the required number of platforms equals seven. It is interesting that this number is the same as for the module cost model. This shows that, although platform-artifact usage is different, the module model results make maximum use of commonality.

$$F = N + P \tag{4.10}$$

Table 4-16: Optimal Portfolio Statistics Considering Commonality Only

Platform Used	Quantity Used
23	9
29	12
30	7
46	8
49	4
54	4
55	4
Totals	7 platforms

Obviously, the given results are sensitive to the assumed relative cost model employed, and it is possible that a small change in the model could significantly change the optimal platform portfolio solution. Therefore, it is recommended that any real-world design team should consider relative cost sensitivity, as results of a sensitivity analysis could influence design decisions. In the example problem for instance, small changes in relative costs could significantly influence the cost difference between the module and stretched models, even to the extent that implementing a product platform portfolio cannot be justified. However, the strategy and analysis involved with a sensitivity analysis is left for future work as data regarding cost variability is not readily available for the example problem.

4.4 Chapter Summary

This chapter presents a methodology for determining an optimal product platform portfolio from a subset of candidate component platforms that were developed using the component-based platform redesign methodology presented in Chapter 3. The methodology is presented as a four-step process centered on an optimization procedure with the goal of minimizing manufacturing cost without sacrificing product performance or customer perceived variety.

With a targeted market segmentation grid as a precursor, the process proceeds in four steps. In Step 1, a set of candidate component platforms is developed, and application of the methodology presented in Chapter 3 meets the requirements of this step. In Step 2, the feasibility of using each candidate on each artifact is tested, and what results is a collection of candidates, one collection for each artifact, that satisfy constraints for that artifact. In Step 3, the optimization problem is formulated with one design variable associated with each artifact, and the value of the variable points to the candidate to use as a platform for that artifact. In Step 4, the optimization problem is solved to yield a product platform portfolio, and a zero-order method is required because the design variables are constrained to integers and the objective function is not guaranteed to be a continuous function.

Although the generalized objective function from Step 3 involves the tradeoff between cost and performance, an example is presented using the valve yoke example from Chapter 3 that simply minimizes commonality to clearly demonstrate the basic procedure step-by-step. It is concluded that 7 is the minimum number of platforms required to span the 60-member market segmentation grid, based on commonality alone.

The valve yoke example is revisited, but this time, the objective function includes manufacturing cost including the cost associated with implementing the stretching/scaling strategy described in Section 3.2.6.1. This requires a custom ABC model and an automatic yoke mounting flange design methodology, and these are presented before implementing the four-step process. The stretching/scaling strategy includes two alternatives, the module and stretched models, and one goal of the example is to determine which is better. Some artifacts from the original market segmentation grid are removed in the revisited example before proceeding with the optimization, and this demonstrates some flexibility inherent in the process. It is concluded that the module model is better, as it requires only 7-platforms whereas the stretched model requires 14. In addition, it is shown that 7-platforms is the minimum number required considering commonality alone when considering the reduced number of candidate platforms, and thus, it is concluded that the module model is capable of achieving maximum possible commonality.

The proposed four-step product platform portfolio optimization methodology shows promise for creating a product platform portfolio from a set of candidate component platforms that is most cost effective within an existing product line. The methodology allows for arbitrary leveraging as it does not rely on the traditional vertical, horizontal, or beachhead strategies advocated for the market segmentation grid, and this is especially beneficial when applied to an existing product line that was develop one-at-a-time time such that artifact designs are inconsistent from one to another.

In the next chapter, an algorithm is presented for implementing a product platform portfolio through a web-based interface, and the optimal module model portfolio developed in this chapter is used there as an example implementation.

Chapter 5

Web-Based Product Platform Portfolio Implementation

This chapter presents an algorithm for implementing a web-based interface to facilitate the implementation of a product platform portfolio for low volume highly customized products such as what results from applying the procedure discussed in Chapter 4. What results is a web-based virtual product family, which does not require the existence of a physical product line. Rather, a product platform variant is produced on-demand from a product platform portfolio that meets the customer's specific requirements. Using a strategic design process, the web-based interface queries a design parameter database, which represents a virtual product platform portfolio, and determines a portfolio instantiation that meets the user's custom request. The web-based interface could be used directly by a customer - or more realistically by a sales engineer - to interactively specify custom design requirements, and it would provide a valuable sales and marketing tool.

There are currently many web-based interfaces that allow a user to customize a product; however, these are typically for high volume products for which the possible variety has been strategically targeted in advance to meet the needs of specific market segments, and for which substantial product inventory exists. For these products, the manufacture remains in control of the product specification such as a specific color palette or a choice of a limited number of option packages or modules. For example, Dell Computer allows customers to custom design a computer from a limited set of add-ons, and most automobile companies allow a web user to select from a limited set such as colors, interior styles, and suspension packages. This is assemble-to-order customization.

The web-interface proposes a different approach. Rather than assemble-to-order, the algorithm includes a strategy for engineer-to-order customization, where key features of the product are designed on-demand to meet custom requirements. In addition, the algorithm includes strategy that invites the user to compromise performance requirements in exchange for cost and/or lead-time savings. The resulting design flexibility can benefit the marketing of highly customized products with low volume where the product specification is not known in advance, and it is not practical to stock inventory.

The combination of a web-based product platform portfolio implementation and an engineer-to-order design and compromise strategy streamlines the design process overall and can reduce manufacturing cost and lead-time by taking full advantage of the savings inherent in platform leveraging and the flexibility inherent in engineer-to-order customization. In addition, an implementation introduces custom requirements at the initial stages of the product ordering process, which has potential benefits of avoiding costly rework due to overlooked requirements, and of increased customer goodwill due to improved performance overall. A goal is to give the user or sales engineer full control over the design specification, which is fundamentally different from the typical custom design web site. What can result is a powerful sales and marketing tool that improves customer good will through a streamlined and interactive product procurement process.

5.1 The Web-Based Interface Algorithm

The proposed algorithm for the web-based interface is outlined in Figure 5-1, and is organized as a hierarchy of options. It assumes the existence of a product platform portfolio, an engineer-to-order design strategy and an algorithm for modifying a basic product platform member to flexibly meet custom requirements, and possibly a baseline standard product line. The algorithm starts with user supplied custom specification input that defines performance requirements and then proceeds with a series of tests and user dialogues to determine option feasibility.

Part of the strategy is to transform the baseline standard product line into a fully instantiated product platform portfolio, and parts of the algorithm involving this transformation are highlighted with dashed lines. The transformation occurs over time as the need for product platform instantiation arises in order to meet custom specifications, and once the transformation is complete, the highlighted portion is no longer implemented. In addition, it is optional to abandon the baseline standard from the start, in which case, the highlighted portion may drop out from the start. However, it may be useful to retain the baseline standard implementation to allow in-service evaluation of artifacts that are produced using the baseline standard.

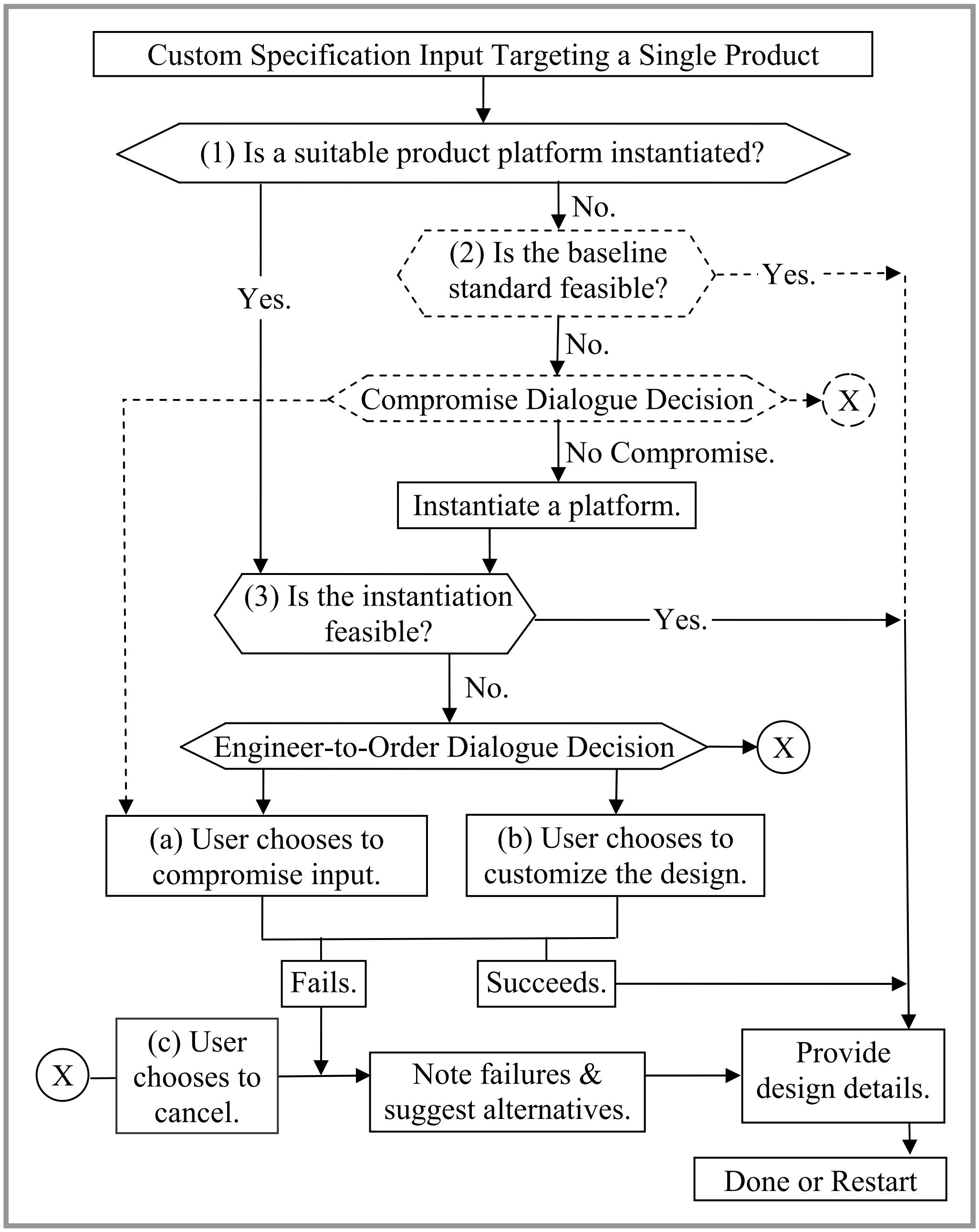


Figure 5-1: Web-based Interface Algorithm

The user input must be constrained, with drop-down boxes for instance, such that only a single product platform member is targeted at any time. Then on request, three possible tests are performed, as numbered in Figure 5-1. Test (1) determines whether the applicable product platform was previously instantiated, Test (2) checks the feasibility of using the baseline standard artifact if no previous instantiation occurred, and Test (3) checks the feasibility of using an instantiated platform when the opportunity presents itself. Production history regarding the product platform portfolio instantiation must be tracked to support the testing at least until the entire portfolio is instantiated. If the baseline standard is feasible, then it is presented as the design choice, and design details are output to the user, and the algorithm is done. In the same way, if the instantiated platform meets requirements, then details are presented to the user. However, an engineer-to-order process must be implemented when requirements are extreme and neither is feasible.

The engineer-to-order portion of the algorithm contains three options: (a) compromise, (b) customize, or (c) cancel, as labeled in Figure 5-1, and the choice is presented to the user through a dialogue box. With the compromise option, which is described in Section 5.1.1, the user is requested to compromise on input requirements in order to make a basic design feasible, whereas with the customize option, which is described in Section 5.1.2, key design features are changed or added through a flexible design strategy. The user may choose to cancel either the engineer-to-order process or the baseline standard compromise, which triggers the presentation of design details for the infeasible design including information regarding associated failures, and this presentation can provide a useful reference that (1) can help decide on how to proceed toward a feasible solution, (2) allows the user to explore the design space fully, and (3) allows for the assessment of unexpected in-service overload of production artifacts. A user is invited to invoke the compromise option when either the baseline standard is infeasible or when the instantiated platform is infeasible. The customize option is presented only when the instantiated platform is infeasible because it is difficult to implement on a baseline standard that does not include a consistent design strategy like a product platform portfolio.

As indicated by the 'succeeds' box in Figure 5-1, if the chosen engineer-to-order option succeeds in determining a feasible design, details for that design are provided. The amount of detail must be sufficient to completely define the resulting design so that it can be manufactured when required. For completeness, marketing details should be included such as a sales price and instructions on placing an order. Presented results represent an instantiated member of the virtual product family that can be potentially manufactured.

It is possible that the custom specification input is so severe that it is impossible to compromise input or customize design features. When the engineer-to-order process fails, which is indicated by the 'fails' box, the failures are noted and alternative options are given. For instance, the user could be invited to contact a sales representative for help in collaborating on a radical redesign or on a completely new design. This presentation leg of the algorithm is similar to that for the cancel option discussed above; however, with the cancel option, it is not necessary to present alternatives, but this subtle difference is not indicated in Figure 5-1.

In summary, a web-based interface can (1) introduce the voice of the customer early into the design process, (2) implement a virtual product family, (3) achieve engineer-to-order customization, and (4) provide an integrated design and marketing tool.

Implementation of the algorithm is demonstrated in Section 5.2 through an example involving the valve yoke component product platform portfolio discussed in Section 4.3.

5.1.1 The Compromise Engineer-to-Order Strategy

With the compromise option, the user is invited to select replacement custom specification input, which is based on a feasible design point from the selected platform's feasible design space. Since the choice requires the user to sacrifice desired performance, an incentive to compromise must be offered, and the most natural and common incentives are reduced price and reduced production lead-time. In addition, a compromise is beneficial to the producer if (1) an instantiated platform with no modifications can be manufactured with a better profit margin than one that requires modification and/or (2) there is evidence that offering this option increases good will with the customer, which may lead to increased sales. Conversely, the compromise option should not be offered if a benefit cannot be justified, and it is a job for the redesign team to make an informed decision as to whether to offer it, and the decision can be subjective since intangibles such as good will are involved. As advocated in Chapter 3, an ABC model should be part of the component-based product platform portfolio development, and it is further advocated here to include this model in the procedure for determining price and profit margin. Then, the keys to successful implementation of the compromise option are, as a minimum, (1) a method for the user to perceive the feasible design space, which is further discussed below, (2) a method to determine price, lead-time, and profit margin, and (3) evidence that a compromise is sufficiently beneficial to both the buyer and seller.

The compromise problem is similar to a multi-objective optimization (MO) problem, where the custom specification input variables involved in the compromise may be considered objective functions within a MO problem. The solution to the MO problem is often called the Pareto frontier, which is defined as the set of solutions where any improvement in one objective (a compromise input) can only take place if at least one other objective (a compromise input) worsens. A Pareto Frontier Plot (Abbass, et al. 2001; Messac, et al. 2003) can be useful for visualization, and Figure 5-2 illustrates a simple example involving two objectives showing both the feasible design space and the Pareto frontier.

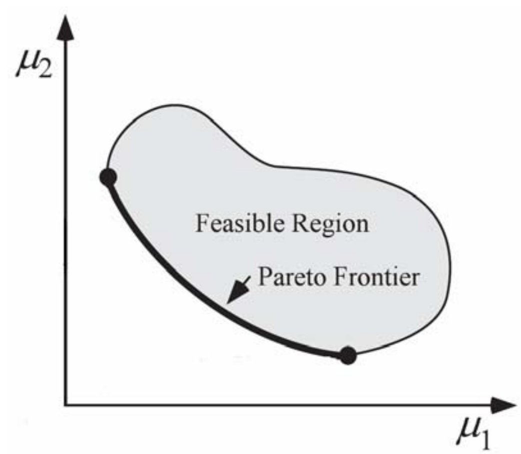


Figure 5-2: An Example Pareto Frontier Plot Adapted from Messac et al. (2003)

When more than two variables are involved, it is more difficult to present the design space and the Pareto frontier, and specialized algorithms may be required. For example, Stump, et al. (2002) discuss the glyph plot and the scatter matrix, and Yukish and Simpson (2004) critique the divide & conquer algorithm for displaying Pareto points. When many compromise inputs are involved, the complexity of the presentation can become overwhelming to the user, and therefore, it is best to limit the number of compromise variables, and perhaps the user can be given the choice of which few from the many to include in the compromise.

It is important to realize that, since the user's selected platform was design *a priori,* it is possible to create a Pareto frontier plot *a priori*, and this could significantly improve processing time over creating plots *in situ.* Similarly, as mentioned in (Yukish and Simpson 2004) many thousands of Pareto-optimal solutions could be generated *a priori* and stored in a database for *a posteriori* choosing by the user.

5.1.2 The Customize Engineer-to-Order Strategy

Choosing the customize option invokes an automatic procedure that determines the value of key design parameters to transform the user's selected platform, which is initially infeasible, into a feasible design. The customization process presents an opportunity to implement a multi-tiered platform strategy as advocated in the discussion near the end of Section 3.1.2. The best customization procedure is one that starts with a basic platform, i.e., one that can meet the majority of expected custom design specifications, and then adds design features through a strategy consisting of the addition of modules, and/or the stretching and/or scaling of design parameters. In order to minimize the effort of determining the features to add that yields a feasible design, all potential design features can be designed in advance, and a select collection of them can be considered a platform tier. Employing such a multi-tiered strategy can avoid over-designed components yet provide a flexible design strategy capable of responding to a super-majority of expected or even unexpected custom design specifications.

The process of determining added design features needed to achieve feasibility can be automated by employing an optimization algorithm. The objective for the optimization problem is to achieve a feasible design at minimal cost, the design space for the problem is the collection of potential design features that make up platform tiers, and the design variables consist of indices into the collections and possibly parameters that define stretching/scaling of certain features. A zero-order optimization algorithm is recommended, such as the Simulated Annealing (SA) or Genetic algorithms (GA), as these can easily implement the indices with integers. In addition, these algorithms are good at finding an optimum for ill-behaved objective functions. By definition, the customization process starts with an infeasible design, which presents a challenge for some optimization algorithms, but both SA and GA can address an infeasible start with a penalty function. Although the *a priori* design of added features and the use of optimization techniques make the customization process efficient, it could still require significant processing time, and is courteous to warn the user when solution times are long.

Assuming the design space of the potential added features is small, say one hundred or fewer, the potential for finding a feasible design at minimal cost is generally excellent. However, as mentioned previously, it could be impossible to find a feasible solution when the custom specification input is extremely severe. Since failure is a possibility, a final step of the customization strategy is to check for feasibility of the resulting solution, and if feasible, the ‘succeed’ leg of the web-based interface algorithm is followed, and if infeasible, then the ‘failed’ leg is followed.

5.2 The Web-Based Valve Virtual Product Line

The example web-based interface implements a virtual product line based on a valve component product platform portfolio described in Section 4.3. The interface was developed using Microsoft’s Visual Web Developer 2005 Express Edition Version 8.0, which employs Microsoft’s ASP .NET Version 2.0 that is a set of web application development technologies. A single web page provides the interface and changes interactively upon user action under the control of a system of Microsoft Visual Basic routines.

For simplicity, the baseline standard product line is not considered in the example, and only the module-model product platform portfolio is implemented, which is the winner over the stretched-model as described in Section 4.3. In addition, platform instantiation is not tracked, as this is a simple book-keeping function that would not contribute to understanding the example better. The stretched portfolio is created from the collection of spreadsheets for the baseline model by changing the baseline yoke leg cross-section parameters to the appropriate yoke component platform parameters in accordance with Table 4-14, and what results is a new collection of spreadsheets, i.e., a workbook, that defines the portfolio.

In addition to the portfolio workbook, the implementation employs a supporting Microsoft Access database, and although Excel and Access are not robust web-server databases, the .NET framework makes it simple to work with them and helps avoid this weakness. The implementation also requires Visual Basic for Applications macros to perform design evaluations, and these are part of the baseline standard design analysis methodology. These macros require conversion to the .NET version of Visual Basic, and although this takes some effort, the effort is greatly reduced by turning off the explicit variable definition compiler option, which is acceptable since the converted code is well established.

Figure 5-3 is a screenshot of the example valve custom specification input form. The top portion consists of a drop-down list of all artifacts of the targeted market segmentation grid. The middle portion, which contains three segments, allows the user to input the custom specification roughly corresponding to the parameters from Table 3-5 noted by (1), (3), and (4). For simplicity, component materials cannot be specified as this would unnecessarily complicate the example with the need to define user-defined material (e.g., with a sub form). The middle segment defines the actuator, which may be specified three ways: (1) by direct user input, (2) by selecting a standard motor actuator from the provided drop-down list, and (3) by an automatic sizing procedure from the standard design methodology. Given a complete form, the ‘Evaluate’ button starts the algorithm, and in this case, the platform member does not meet the specification without engineer-to-order customization, which is described in Section 5.2.2.

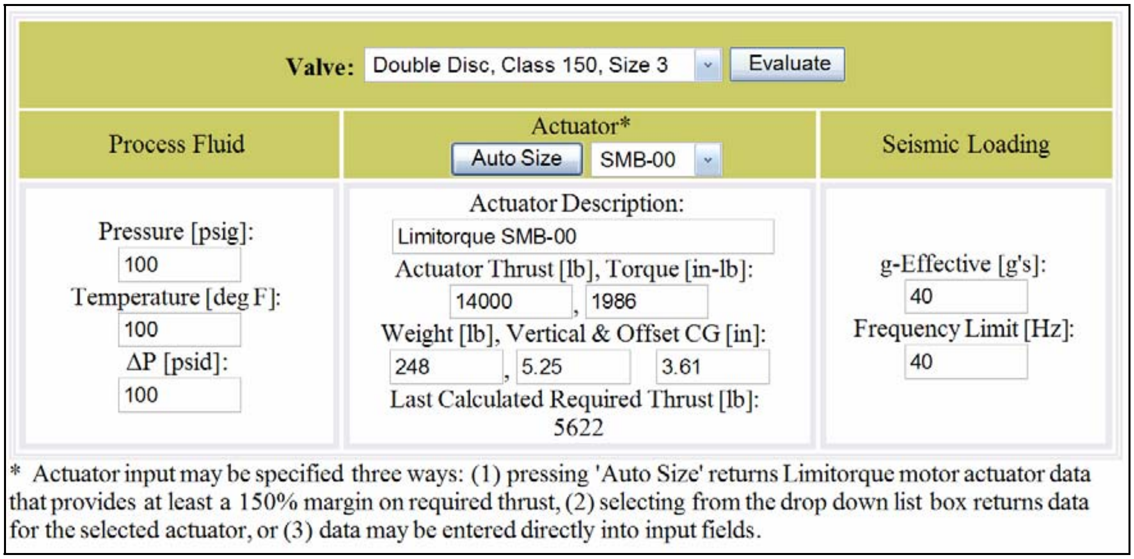


Figure 5-3: Valve Custom Specification Input Form

Before the customization process is demonstrated, another similar input form is presented, but with less severe loading. This time, the platform member meets requirements, and selected design details are presented after pushing ‘Evaluate’. Figure 5-4 shows the input form and the associated design details. The details are limited in the example problem, and the summary shows results associated only with the yoke design, which is the focus of the example problem. In addition, cross-section property results are given for all components of the valve extended structure. These results could be much more extensive; for instance, a complete set of design data similar to that in Appendix A could be provided, or a cost and lead-time quote and an invitation to purchase could be offered.

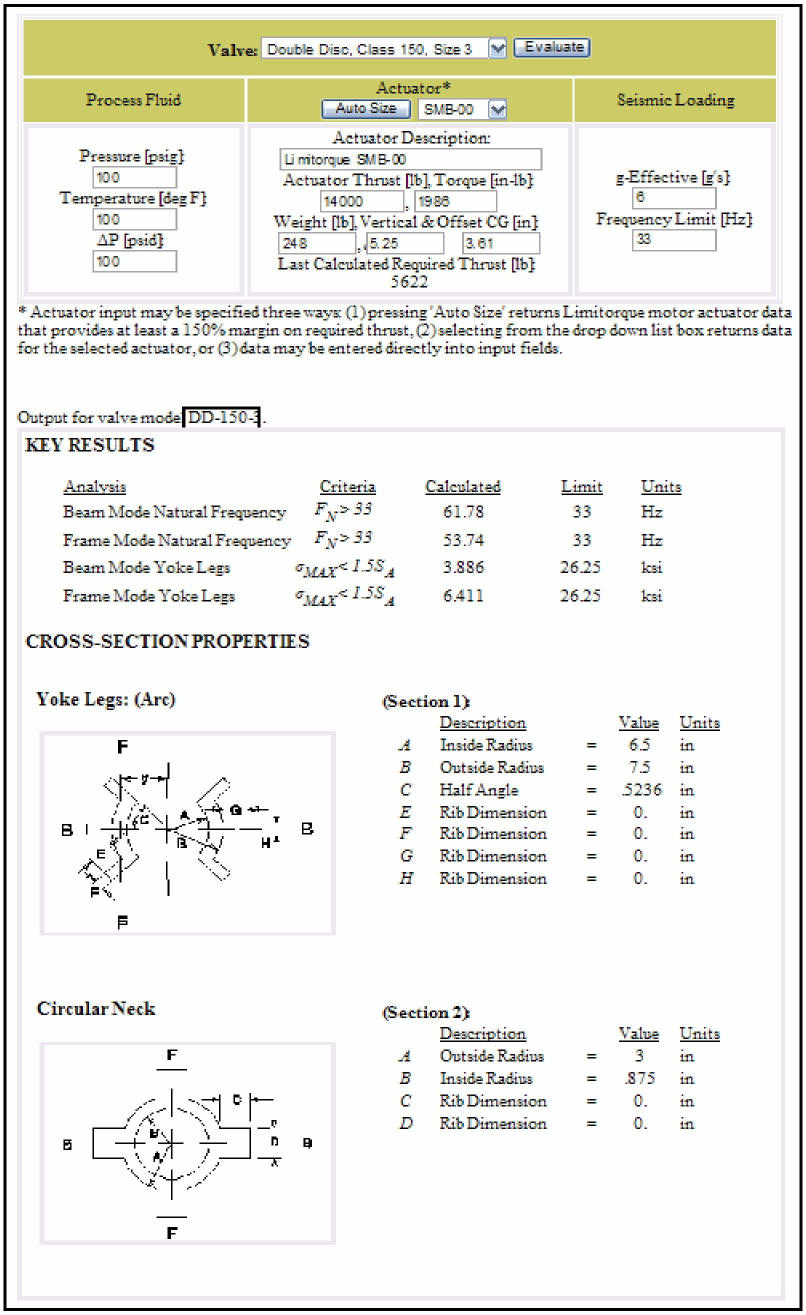


Figure 5-4: Example Valve Result Details

When the form in Figure 5-3 is evaluated, the dialogue shown in Figure 5-5 appears, indicating failure of the standard valve, i.e., standard product platform. The compromise question dialogue resolves by choosing 'yes' to attempt to compromise on input (See Section 5.2.1), 'no' to proceed with the custom design of reinforcement ribs (See Section 5.2.2), or 'cancel', which displays results and notes criteria failures (See Figure 5-6 for an example) and is useful for assessing how to proceed toward feasibility, for exploring the design space, and for assessing in-service overloads as discussed in Section 5.1.

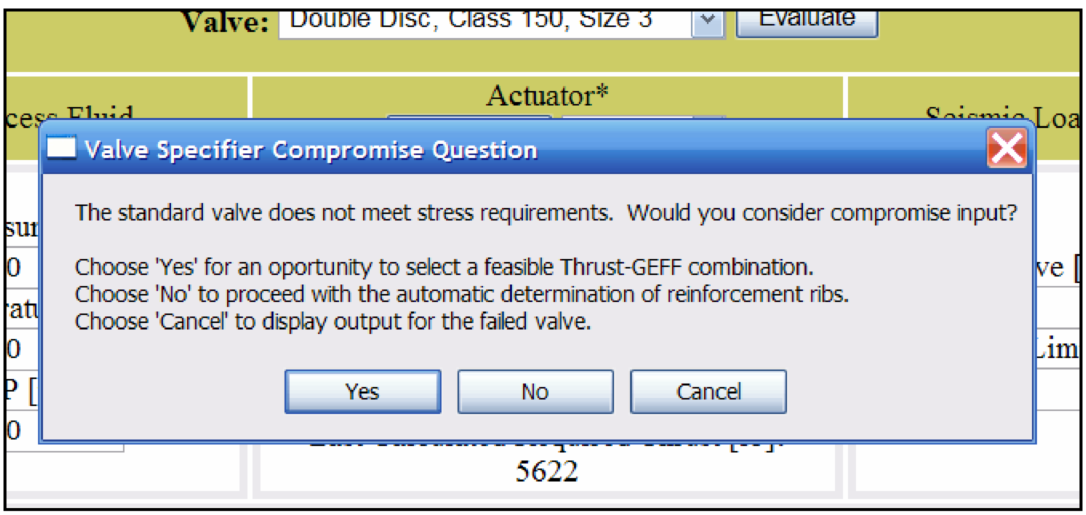


Figure 5-5: Compromise Question for the Valve Example

Frame Mode Yoke Legs Stress=FAIL,
Output for valve model DD-150-3.

KEY RESULTS

Analysis	Criteria	Calculated	Limit	Units	
Beam Mode Natural Frequency	$F_N > 40$	61.78	40	Hz	
Frame Mode Natural Frequency	$F_N > 40$	53.74	40	Hz	
Beam Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	20	26.25	ksi	
Frame Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	36.8	26.25	ksi	FAIL

CROSS-SECTION PROPERTIES

Figure 5-6: Example Output Showing a Noted Criteria Failure

Engineer-to-order customization is included through a two-part strategy: (1) a compromise input strategy implemented by a Pareto Frontier Plot that allows the user to choose automatically between conflicting input parameters as described in Section 5.2.1, and (2) an automatic reinforcement rib sizing strategy implemented through optimization techniques as described in Section 5.2.2.

5.2.1 The Compromise Input Strategy

Choosing 'Yes' from the compromise question dialogue box initiates the compromise input strategy. For this example, the user is given a tool for automatically choosing a compromise between the effective seismic load (G_{EFF}) and the actuator thrust, as evident by the dialogue box text, and this combination is useful because it is known that these parameters challenge valve performance most typically. The automated choice is implemented using a Pareto Frontier Plot, and Figure 5-7 shows the plot for this example.

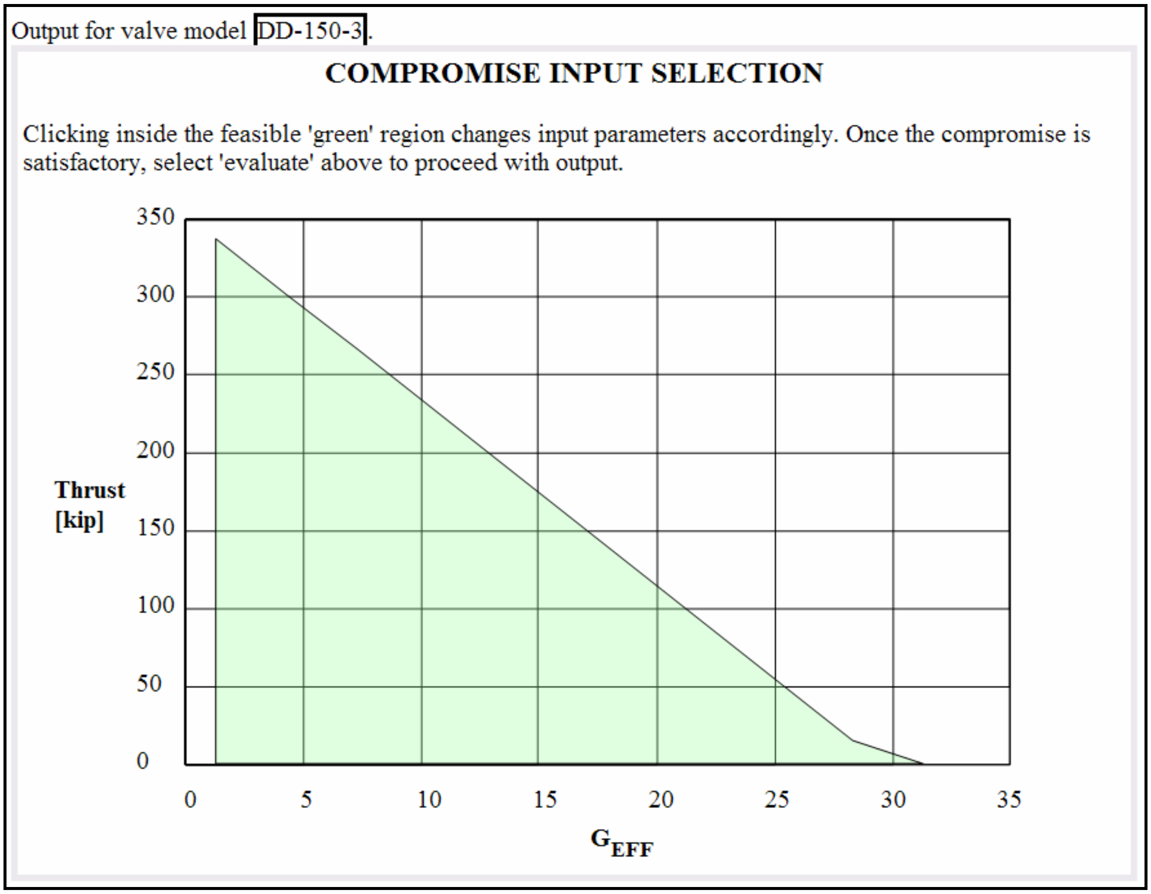


Figure 5-7: Valve Example Pareto Frontier Plot

Input for the plot is obtained by evaluating valve performance at ten values of G_{EFF}, and for each, a goal seek iteration is performed on actuator thrust until the corresponding maximum allowed thrust value is obtained that does not violate performance constraints. Since only two variables are involved in the goal seek, a simple optimality criteria algorithm is sufficient. As a precursor however, the upper extreme value of G_{EFF} is determined from a similar goal seek with actuator thrust set equal to zero, and this results in an eleventh point. In addition, the lowest value of G_{EFF} equals one, which corresponds to valve component dead weight loading. The enclosed shaded region in Figure 5-7, which represents a feasible design space, is created from plotting the eleven points, adding a twelfth point at (1,0) to close the loop.

As can be seen in Figure 5-7, the user is instructed to click inside the feasible region to change the input form according to the clicked location point, and Figure 5-8 shows the response to a click inside this region, where a simple dialogue box indicates the (G_{EFF}, thrust) pair used to update the form, and the '*' shows the location of the point, which is close to the Pareto frontier. Although the example clicked location was placed near the Pareto frontier, input can be obtained by clicking anywhere within the region, and this allows the user complete freedom in exploring the design space.

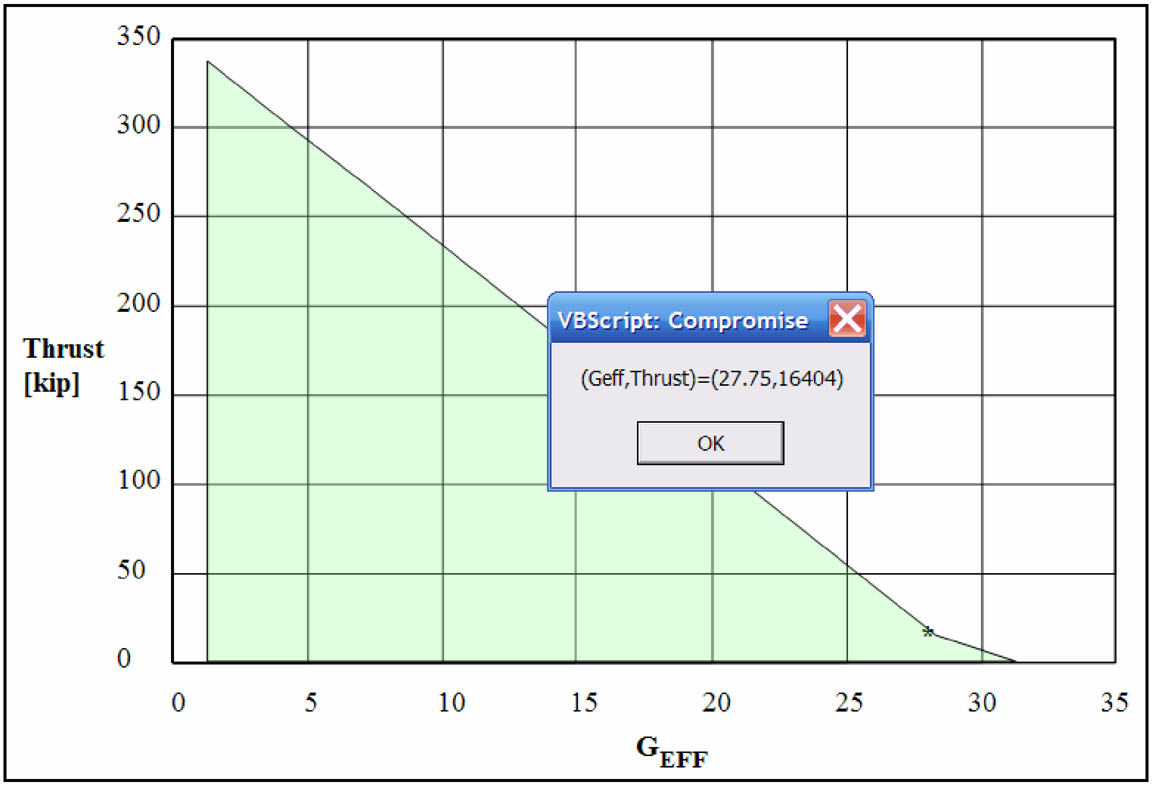
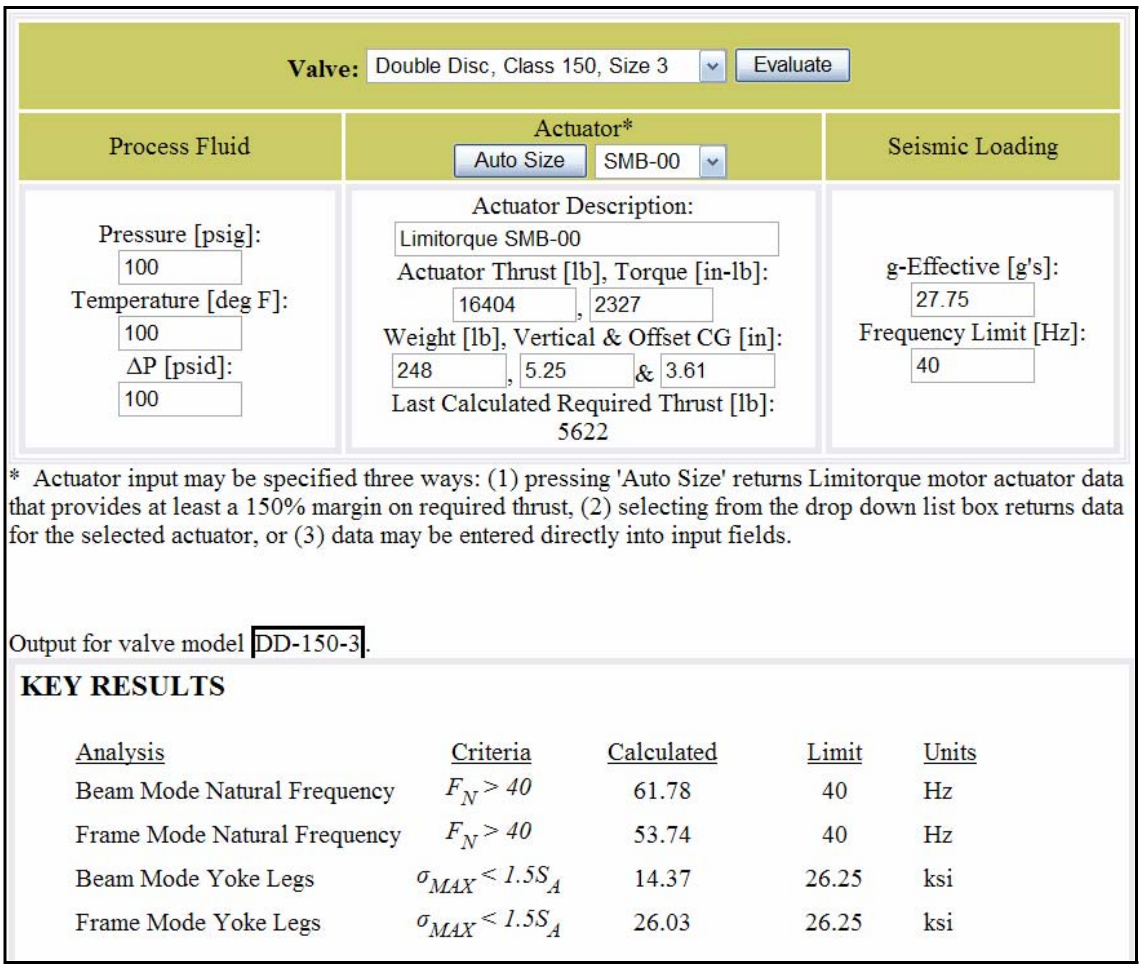


Figure 5-8: Example Compromise Input Selection

Plot construction is performed using VML (Vector Markup Language), which is a XML schema that can be implemented in Windows Internet Explorer™. Although VML has weaknesses, such as poor documentation, inconsistent performance, and dwindling support, it is used to develop this example because it is easy to program within an HTML document. It is recognized that better approaches exists, such as SGV (Scalable Vector Graphics), which is another XML schema, but SGV graphics must reside in a separate file, which adds off-topic development complications. As future work, perhaps a better-suited web-based graphing approach can be identified, or a SVG solution can be developed.

Figure 5-9 shows posted output obtained from clicking 'Evaluate' on the input form after clicking 'OK' on the dialogue shown in Figure 5-8. The actuator torque is changed along with the thrust and G_{EFF} as thrust and torque are related through valve stem power transmission threads. Since the selected input from Figure 5-8 is close to the Pareto frontier, it is expected that at least one limit criterion should be close to the allowable, and as can be seen, this is true for the frame mode yoke legs stress.



Valve: Double Disc, Class 150, Size 3 [Evaluate]

Process Fluid	Actuator* [Auto Size] SMB-00	Seismic Loading
Pressure [psig]: 100 Temperature [deg F]: 100 ΔP [psid]: 100	Actuator Description: Limitorque SMB-00 Actuator Thrust [lb], Torque [in-lb]: 16404 , 2327 Weight [lb], Vertical & Offset CG [in]: 248 , 5.25 & 3.61 Last Calculated Required Thrust [lb]: 5622	g-Effective [g's]: 27.75 Frequency Limit [Hz]: 40

* Actuator input may be specified three ways: (1) pressing 'Auto Size' returns Limitorque motor actuator data that provides at least a 150% margin on required thrust, (2) selecting from the drop down list box returns data for the selected actuator, or (3) data may be entered directly into input fields.

Output for valve model DD-150-3.

KEY RESULTS

Analysis	Criteria	Calculated	Limit	Units
Beam Mode Natural Frequency	$F_N > 40$	61.78	40	Hz
Frame Mode Natural Frequency	$F_N > 40$	53.74	40	Hz
Beam Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	14.37	26.25	ksi
Frame Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	26.03	26.25	ksi

Figure 5-9: Posted Output for the Compromise Input Example

5.2.2 The Reinforcement Rib Sizing Customization Strategy

Choosing 'No' from the compromise question dialogue box initiates the reinforcement rib sizing strategy, and Figure 5-10 shows typical reinforcement ribs on a yoke leg cross-section and on a general neck cross-section used to model other valve extended structure sections. The strategy is to determine automatically the size of the ribs, i.e., width (*w*) and height (*h*), considering all applicable extended structure sections.

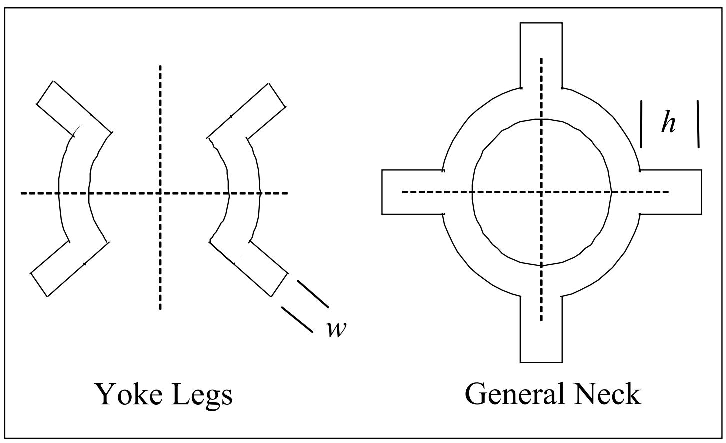


Figure 5-10: Cross-Section Rib Design Strategy

The heart of the strategy is to limit rib dimensions to those given in Table 5-1 and to employ an optimization algorithm that determines the ribs needed to meet custom requirements. By limiting the choice of ribs, the optimization process is simplified, which increases its chance of success. Full-penetration welds attach the ribs along the length of the extended structure section, and the available rib selection reflects the tradeoff between a narrow width, which is better for welding, and a small height, which minimizes their effect on overall valve enveloping dimensions.

Table 5-1: Cross-Section Rib Database

Index	Width (w), [in]	Height (h), [in]
1	0.25	1
2	0.25	2
3	0.5	2
4	0.5	3
5	0.75	2
6	0.75	3
7	1	3
8	1	4
9	1.5	4
10	1.5	5
11	0	0

For the example rib strategy, the optimization problem is given by Eq. 5.1. A simple ABC model is employed as the objective function, where the cost of adding ribs is summed over all extended structure sections (N_{MAX}). The cost for a given section of the extended structure (N) equals the sum of a fixed cost, which is the first product in the equation, and a variable cost, which is given by the remaining terms. The coefficient c_N tracks whether a rib is specified for the section, and when a rib is not specified, the cost equals zero. The performance constraints (P) are the same as for the yoke component class optimization problem given by Eq. 3.1. Bounds constraints, if any, are likely different than those considered in Chapter 3, but no bounds constraints are considered for the sake of simplicity here. One design variable is required for each section (N), and a single design variable value, which is given by $X^I(N)$, is limited to one of the Index integers from Table 5-1, which specifies a unique rib cross-section. Relative cost parameters that define the ABC model are presented in Table 5-2, and as discussed in Section 4.3.1.2, costs are given in dollars ($) although true cost magnitudes are masked to protect confidential sources.

$$F(\mathrm{X}^I) = \sum_{N}^{N_{MAX}} c_N C_{WS} + L_N \left(C_R wh + C_W w^2\right) \qquad 5.1$$

where:

$c_N = 0$, if $X_N^I = 11$, i.e., no rib for section *N*.

$c_N = 1$, otherwise, i.e., a rib is specified for section *N*.

Subject to:

$$\mathrm{P}_1 = (1 - f_1(\mathrm{X}^\mathrm{I}) / f_{\mathrm{MIN}}) \leq 0$$

$$\mathrm{P}_2 = (1 - f_2(\mathrm{X}^\mathrm{I}) / f_{\mathrm{MIN}}) \leq 0$$

$$\mathrm{P}_3 = (\sigma_1(\mathrm{X}^\mathrm{I}) / S_\mathrm{A} - 1) \leq 0$$

$$\mathrm{P}_4 = (\sigma_2(\mathrm{X}^\mathrm{I}) / S_\mathrm{A} - 1) \leq 0$$

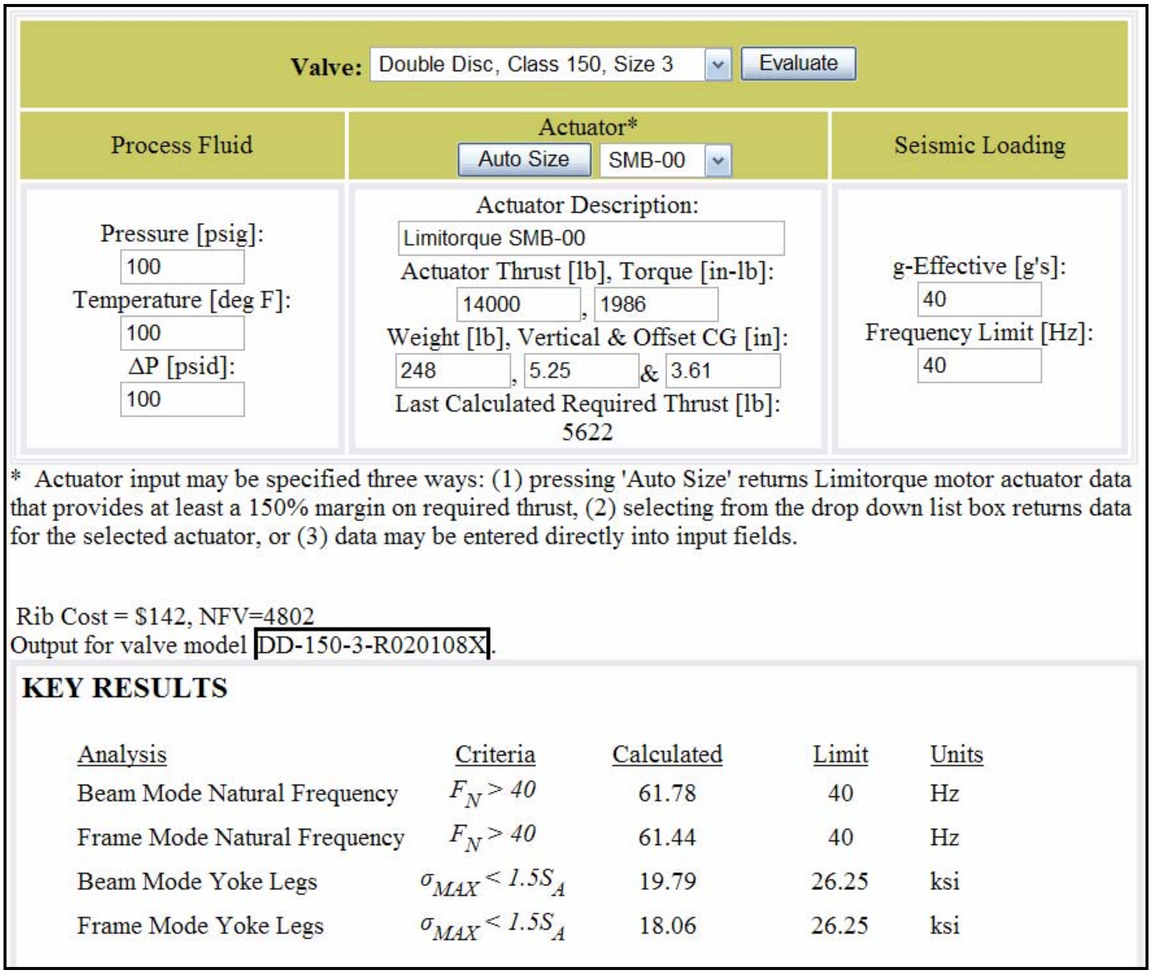
$$\mathrm{X}^\mathrm{I}(N) \in \{1,2, \ldots, 11\}$$

Table 5-2: Rib ABC Model Parameters

Symbol	**Variable or Fixed Cost**	**Value**	**Description**
C_{WS}	Fixed	75	Welding Setup Cost [$/weld]
C_W	Variable	4	Weld Raw Material Cost per Unit Volume [$/in^3]
C_R	Variable	2	Rib Raw Material Cost per Unit Volume [$/in^3]

Because the design variables (X^I) are integers and the objective function is not continuous, the SA algorithm is employed, which is well suited for such problems. The SA implementation used in Chapter 4 was converted to the .NET version of Visual Basic for this example. Problem solution is robust because the design space is well constrained. A typical problem with three extended structure sections ($N_{MAX} = 3$) has only 1331 (11^3) possible optimal solutions (X^I*).

Once the SA algorithm is complete, the resulting solution is checked for feasibility, and if feasible, i.e., every $P_i(X^I*)$ is less than or equal to zero, rib sizing is a success, and the resulting solution is posted to the form. Figure 5-11 reiterates the sample input from Figure 5-3 and gives the key results summary portion of the posted output that shows that all constraints are satisfied. In addition, the output includes the manufacturing cost for the required ribs ($142) and a valve model number (DD-150-3-R020108X), and these have potential use for preparing a quotation and identifying the required rib modifications. The ‘R020108X’ portion of the model number is coded such that ‘02’ indicates the rib Index from Table 5-1, ‘01’ indicates the extended structure section to receive the rib, and ‘08’ indicates the rib placement on the cross-section. The posted output also includes the number of function evaluations (NFV) required to perform the SA optimization. For this case, 4802 evaluations are required, which is not at all excessive, and the corresponding computation time is only about fifteen seconds.



Valve: Double Disc, Class 150, Size 3 | Evaluate

Process Fluid	Actuator*	Seismic Loading
Pressure [psig]: 100	Auto Size, SMB-00	g-Effective [g's]: 40
Temperature [deg F]: 100	Actuator Description: Limitorque SMB-00	Frequency Limit [Hz]: 40
ΔP [psid]: 100	Actuator Thrust [lb], Torque [in-lb]: 14000, 1986	
	Weight [lb], Vertical & Offset CG [in]: 248, 5.25 & 3.61	
	Last Calculated Required Thrust [lb]: 5622	

* Actuator input may be specified three ways: (1) pressing 'Auto Size' returns Limitorque motor actuator data that provides at least a 150% margin on required thrust, (2) selecting from the drop down list box returns data for the selected actuator, or (3) data may be entered directly into input fields.

Rib Cost = $142, NFV=4802
Output for valve model DD-150-3-R020108X.

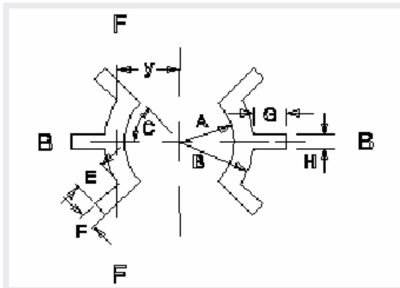
KEY RESULTS

Analysis	Criteria	Calculated	Limit	Units
Beam Mode Natural Frequency	$F_N > 40$	61.78	40	Hz
Frame Mode Natural Frequency	$F_N > 40$	61.44	40	Hz
Beam Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	19.79	26.25	ksi
Frame Mode Yoke Legs	$\sigma_{MAX} < 1.5S_A$	18.06	26.25	ksi

Figure 5-11: Automatic Rib Design Example Key Results

Figure 5-12 shows the portion of the posted output that lists cross-section parameters including the required ribs. As can be seen, only the yoke legs (extended structure Section 1) require ribs to satisfy the performance constraints of natural frequency and stress.

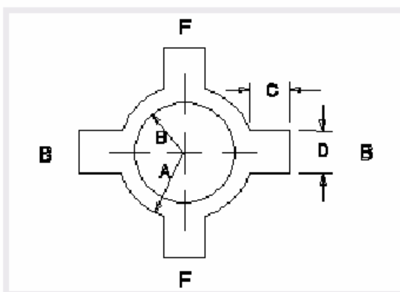
Yoke Legs: (Arc)



(Section 1):

	Description		Value	Units
A	Inside Radius	=	6.5	in
B	Outside Radius	=	7.5	in
C	Half Angle	=	.5236	in
E	Rib Dimension	=	0.	in
F	Rib Dimension	=	0.	in
G	Rib Dimension	=	2	in
H	Rib Dimension	=	.25	in

Circular Neck



(Section 2):

	Description		Value	Units
A	Outside Radius	=	3	in
B	Inside Radius	=	.875	in
C	Rib Dimension	=	0.	in
D	Rib Dimension	=	0.	in

Figure 5-12: Automatic Rib Design Example Cross-Section Parameters

5.3 Chapter Summary

In this chapter, an algorithm, which is summarized in Figure 5-1, is presented for implementing a web-based virtual product platform portfolio that does not require the existence of a physical product line, but is instantiated on-demand to meet user specified custom requirements. The algorithm considers the strategic transformation of a baseline standard product line into a product platform portfolio. In addition, it includes a strategy for implementing an engineer-to-order customization procedure where key design features are engineered on-demand, which is fundamentally different from most web-based interfaces that employ an assemble-to-order strategy targeted toward high volume products where variety is limited to what has been designed in advance. The engineer-to-order customization procedure also includes a strategy for inviting the user to consider a performance compromise in exchange for cost and/or lead time savings, which further adds to design flexibility. Finally, the algorithm allows for the complete exploration of a product platform member's feasible design space, which is useful for assessing how to proceed toward feasibility, for generally exploring the design space, and for assessing in-service overloads.

As an example, the algorithm is applied to the module model valve component product platform portfolio developed in the example from Chapter 4. A single web page exists that demonstrates key portions of the algorithm including a user interface that constrains input toward a single valve artifact, an output section that provides design details upon determination of a satisfactory design, a compromise input strategy implemented by a Pareto Frontier Plot, and a custom yoke leg reinforcement rib sizing strategy. The rib sizing is automated using an SA optimization algorithm with an objective function based on a simple ABC formulation. Several screen shots are presented to demonstrate the implementation.

As a result of implementing the algorithm, the voice of the customer and custom design requirements are introduced and addressed early in the design process, the potential for overlooked requirements and misunderstandings is greatly reduced, and the design specification process is improved overall.

Chapter 6

Conclusion and Future Work

This dissertation presents a methodology that fulfills the research objectives that are embodied in three fundamental questions: (1) in what ways can platform-based product development benefit small companies who produce highly customized products at low volumes?, (2) how should product platform design differ from current research for such products, and what factors are important for defining the best platform design strategy?, and (3) how can the World Wide Web be used to facilitate customized product design for low volume products? The methodology employs a bottom-up component platform redesign strategy to transform an existing product line into a virtual product platform portfolio with the goal of improving manufacturing cost and reducing production lead time through the introduction of design commonality. Part of the strategy is the implementation of a resulting virtual product platform portfolio through a web-based interface that allows the incorporation of user-specified custom design requirements early into the design process and allows for engineer-to-order customization on-demand if necessary.

6.1 Dissertation Summary

As discussed in Chapter 1 of this dissertation, the presented methodology is motivated by the need to improve commonality in a highly customized low volume product line whose members were originally developed one-at-a-time to meet specific customer requirements, as it can be difficult to achieve and maintain commonality under this scenario. The methodology builds upon existing research as outlined in Chapter 2, and a specific focus is on extending the Product Platform Concept Exploration Method using bottom-up product platform design techniques. Chapter 3 and Chapter 4 present detailed methodologies for transforming an existing product line of low volume highly customized products into a virtual product platform portfolio through targeted component redesign. Finally, Chapter 5 presents an algorithm for implementing a resulting virtual portfolio through a web-based interface that allows the early incorporation of custom design requirements into the design process. Details on each contribution follow.

6.1.1 Bottom-Up Platform Design Methodology

Chapter 3 presents a methodology for redesigning an existing line of low volume highly customized products using a bottom-up product platform development approach that is based on the PPCEM. Rather than redesign an entire product line, the focus is on the redesign of a limited set of components with the highest potential for cost savings, and when applied across the product line, a *component-based* product platform portfolio results.

The methodology involves three phases of redesign team activity. In Phase 1, design knowledge and history is collected about every aspect of the existing product line, which is employed throughout the redesign process. In Phase 2, a baseline standard product line is constructed that provides a reference to compare with any redesign effort, and this involves defining a targeted market segmentation grid and targeted components for redesign, aggregating design inputs, and defining the baseline standard. In Phase 3, critical component performance functions are aggregated, and targeted component classes are developed that are then instantiated to yield candidate component platforms. Then, the redesign involves developing a baseline standard redesign strategy around common component classes.

Candidate component platforms are created by instantiating the component classes, and a product platform portfolio is created by replacing baseline standard components with a select subset of candidate platforms by stretching and/or scaling key platform parameters. Chapter 4 provides a methodology for optimizing the cost effectiveness of the portfolio.

To be effective, a component class must adequately address cost, and the methodology proposes the use of Activity-Based Costing (ABC) to define the relationship between design parameters and cost. A generalized ABC model is presented under a low volume production scenario, and a tradeoff metric is formulated that is used to capture potential cost savings between a proposed product platform portfolio and the baseline standard product line.

6.1.2 Component Product Platform Portfolio Optimization

Chapter 4 presents a methodology for determining an optimal product platform portfolio from a subset of candidate component platforms that were developed using the component-based platform redesign methodology presented in Chapter 3. The methodology is built around an optimization procedure with the goal of minimizing manufacturing cost without sacrificing product performance or customer perceived variety.

With a targeted market segmentation grid as a precursor, the process proceeds in four steps. In Step 1, a set of candidate component platforms is developed, and although not a necessity, application of the methodology presented in Chapter 3 meets the requirements for this step. In Step 2, the feasibility of using each candidate on each artifact is tested, and what results is a collection of candidates for each artifact that satisfy constraints for that artifact. Step 3 is the formulation of an optimization problem with one design variable associated with each artifact that points to the candidate to use as a platform for that artifact. The optimization problem is solved in Step 4 to yield a product platform portfolio, and a zero-order method is required because the design variables are constrained to integers and the objective function is not guaranteed to be a continuous function.

The presented methodology can create the most cost-effective product platform portfolio from a set of candidate component platforms. The resulting portfolio does not rely on traditional vertical, horizontal, or beachhead leveraging strategies across the market segmentation grid, and this is especially beneficial for a product line that was developed one-at-a-time with designs that may be inconsistent from one to another.

6.1.3 Web-Based Product Platform Portfolio Implementation

In Chapter 5, an algorithm is presented for implementing a web-based virtual product platform portfolio that does not require the existence of a physical product line but is instantiated on demand to meet user specified custom requirements. The algorithm considers the strategic transformation of a baseline standard product line into a product platform portfolio. In addition, it includes strategy for implementing an engineer-to-order customization procedure where key design features are engineered on-demand, which is fundamentally different from most web-based interfaces that employ an assemble-to-order strategy targeted toward high volume products where variety is limited to what has been designed in advance. The algorithm also includes a strategy for inviting a user to consider a performance compromise in exchange for cost and/or lead-time savings, which further increases design flexibility.

As a result of implementing the algorithm, the voice of the customer and custom design requirements are introduced and addressed early in the design process, the potential for overlooked requirements and misunderstandings is greatly reduced, and the design specification process is improved overall.

6.1.4 The Valve Yoke Redesign Example Problem

The methodologies presented in Chapters 3-5 are illustrated with a single example involving the redesign of yokes on a product line of nuclear-grade valves, which is very representative of a low volume highly customized product line. In Chapter 3, the valve product line is introduced, and the component platform redesign methodology is applied toward it step-by-step. A targeted market segmentation grid is defined, a baseline standard product line is defined from existing artifacts and from existing product knowledge, a redesign strategy is presented involving a yoke component class and two alternative yoke mounting interface models, and finally, the yoke component class is instantiated for each member of the targeted market segmentation grid to yield a set of candidate component platforms.

The example is continued in Chapter 4 where the product platform portfolio optimization methodology is employed to create a valve product platform portfolio from a subset of the instantiated candidate platforms. The optimization methodology is illustrated in two ways. First, component platform commonality alone is the focus for simplicity, where the minimum number of platforms required to span the targeted market segmentation grid is determined without consideration of the interface with each artifact, and this provides a clear demonstration of the basic optimization procedure step-by-step. With the second example, interfacing flange design strategies and a custom ABC model are considered to create a realistic tradeoff metric that properly addresses manufacturing cost in the optimization problem objective function.

Two alternative yoke mounting interface stretching/scaling strategies are proposed in Chapter 3, which are the module and stretched models, and a goal of the second example in Chapter 2 is to determine which is better. In this second example, some artifacts from the original market segmentation grid are removed before proceeding with the optimization, and this demonstrates some flexibility inherent in the process. Not only is it concluded that the module model is better, it is demonstrated capable of achieving maximum possible commonality; however, a caveat is that the sensitivity of results to cost model parameters is a topic for future study.

In Chapter 5, the presented web-based implementation algorithm is applied to the module model valve component-based product platform portfolio from the Chapter 4 example. A single web page is created that demonstrates key portions of the algorithm, including a user interface that constrains input toward a single valve artifact, an output section that provides design details upon determination of a satisfactory design, a duel-option engineer-to-order strategy consisting of a compromise input strategy implemented by a Pareto Frontier Plot, and a custom yoke leg reinforcement rib sizing strategy. The rib sizing is automated using an SA optimization algorithm with an objective function based on a simple ABC formulation.

6.2 Research Contributions

The methodologies and algorithms presented in this thesis build upon existing research regarding product platform portfolio design, i.e., the Product Platform Concept Exploration Method, and extend it to bottom-up design techniques. A detailed methodology is presented for the specific focus for transforming an existing product line of low volume highly customized products into a virtual product platform portfolio through targeted component redesign. In addition, an algorithm is presented for implementing a virtual product platform portfolio through a web-based interface that allows the early incorporation of custom design requirements into the design process and includes strategies for custom design features on demand through an engineer-to-order approach. Implementing a virtual product platform portfolio improves the specification of low volume highly customized products as it avoids the stocking of inventory yet allows for quick response to custom requests.

The methodology also introduces the concept of a component class that is instantiated to yield candidate component platforms for replacing components from an existing product line with the greatest potential for cost savings from a redesign effort. In addition, an innovative method is presented for creating a component-based product platform portfolio that spans a targeted market segmentation grid with optimal cost effectiveness without relying on traditional leveraging strategies.

In conclusion, Table 6-1 summarizes the research contributions side-by-side with the corresponding motivating research questions from the summary of research questions and objectives in Table 1-1.

Table 6-1: Summary of Research Contributions

Research Questions	Research Contributions
How can product platforms benefit the design of low volume highly customized products?	Bottom-up methodology and targeted component redesign as an extension of the PPCEM. Component class, component platform, and component-based product platform portfolio concepts.
How should product platform design differ from current research, and what factors are important?	A portfolio optimization methodology that does not rely on traditional leveraging strategies. A portfolio manufacturing cost model that employs Activity Based Costing methodology.
How can the Web be used to facilitate product platform portfolio implementation?	An algorithm for virtual portfolio implementation and early custom specification evaluation. Strategy to transform a baseline standard product line into a product platform portfolio. Engineer-to-order ‘customize’ and ‘compromise’ methodology. An integrated design and marketing tool that can improve cost, lead-time, and customer goodwill.

6.3 Research Limitations

The presented methodology is intended for the redesign of an existing product line that is produced in low volumes and often must adapt to varied and unknown future custom design requirements. In addition, the focus is on a product line that was created one-at-a-time to respond to specific requirements without considering the product line as a whole. Such a product line can lack commonality of features leading to high development and production costs that are difficult to predict and to long and uncertain production times. Applying the proposed methodology can transform an exiting line by adding commonality to key components that often require redesign resulting in cost savings from a more streamlined production process and by incorporating custom requirements early into the design process that potentially reduces costly rework and missed requirements.

Although only one product line example is given for applying the methodology, the example is highly representative of the type of product that is the focus of the methodology. The example is presented in detail such that all aspects of the methodology are demonstrated. A realistic redesign project could potentially result in a voluminous amount of detail that is beyond the scope of a typical thesis, but the example purposely limits details to a manageable level so as not to detract from demonstrating the underlying methodology. In addition, although the valve product line is real, the yoke redesign example does not reflect a real redesign project, and details such as the choice of the targeted market segmentation grid or the module verses stretched mounting flange interface design strategy are strictly the creation of the researcher and not the effort of a realistic redesign team consisting of all aspects of the business. Finally, a real-world design team could potentially identify additional improvements and cost savings that were not readily apparent with the documented example using the methodology as they would benefit from having different perspectives on the team (e.g., manufacturing, marketing, management).

There are other limitations that were discovered during work on the example problem. For instance, the SA algorithm used in Chapter 4, which solves the optimization problem associated with the product platform portfolio non-traditional market segmentation grid leveraging strategy, is not sufficiently robust to give consistent results. In addition, since a real-world design team was not assembled, data collection resources were limited, which makes it impossible to apply robust design techniques as advocated in Section 3.1.1.

These limitations provide some of the motivation for potential future work, which is the final topic for discussion, and which is presented next.

6.4 Potential Future Research

The presented methodology provides a strong foundation for addressing the focused intent of redesigning an existing line of low volume highly customized products, and of implementing a resulting product platform portfolio. However, there is potential for strengthening and reinforcing the utility of the underlying methods, and some thoughts for improvement and for extending the work to other research areas are presented in these final paragraphs.

Implementation of the product platform portfolio optimization procedure given in Chapter 4 can benefit from an improved zero-order optimizer. The SA algorithm employed in the example does not yield consistent results, and the inconsistency increases with the number of candidate component platforms. As an alternative to or concurrent with a better portfolio optimizer, a strategy for dividing the targeted market segmentation grid into more manageable sub-segments could improve consistency; however, sub-segmenting could reduce the generality of results. As another alternative, perhaps a hybrid between the proposed arbitrary leveraging strategy and traditional leveraging could prove acceptable, and traditional horizontal, vertical, or beachhead leveraging could be employed in a way that is natural for the product line.

The underlying premises behind the presented methodology could be strengthened through the preparation of other example problems. By its very nature, low volume highly customized products can include varied design challenges, and addressing other examples could bring to the surface other design needs that were not readily apparent during development of the methodology. The best examples are real-world projects conducted by a redesign team consisting of all aspects of the targeted product line from sales and marketing to design and manufacturing. Without the need to present a methodology, a real-world project could concentrate on the redesign task at hand and provide interesting detail on topics such as formation of the redesign team, how to compromise on design strategy among the team members, or successful manufacture of an instantiated virtual product platform member. Typically, heavy industrial equipment used for material processing, manufacturing, or power production are produced in low volume and require customization, and thus, they could benefit from application of the methodology. Some specific examples of products discussed in the literature that could benefit are hydraulic cylinders (Shirley 1990), absorption chillers (Seepersad, et al. 2000; 2002), and refiner plates (Simpson, et al. 2003).

A few specific enhancements to the presented methodology are worthy of mention. A real-world project could present opportunities to apply robust design techniques as advocated in Section 3.1.1, and to develop a sensitivity analysis strategy as recommended in Section 4.3.3. With a real-world project, the final tangible product is the web-based interface described in Chapter 5, and a real-world interface could benefit from additional features. For instance, a help system could be supplied to guide the user in interface navigation, or supporting web pages could be created to enhance its utility. With the valve yoke redesign example problem for example, supporting pages could be added to allow the choice of different material specifications and different allowable stress criteria, and a detailed sales price and an invitation to purchase could be presented along with final design details. In addition, other analysis procedures could be included such as the stress analysis of other components (e.g., the stem, the discs, and the actuator mounting flange). Finally, other component platforms could be developed (e.g., for the stem). A real-world web-based interface may benefit from access control (e.g., a login system) that could help track usage and sales and could protect against damaging use by competitors (e.g., inside information leading to unfair advantage when bidding for jobs).

A real-world project could reveal unforeseen hurdles, and the first hurdle is getting a project off the ground. An important area of future work is to determine the best way to introduce such a redesign project to management. For example, at Flowserve Corporation, which is the source of the example product line, the policy is that all capital is procured through Black Belt projects. The proposed methodology could appear radical to some, which could hinder project approval as management may require information regarding a successful example implementation, and perhaps a small project (i.e., one that does not require significant resources or commitment and has low risk) could be proposed and implemented and later used to springboard larger, more radical projects.

Perhaps portions of the methodology could be applied to the general design or redesign of various products in an emerging or existing product platform portfolio. For example, the product platform optimization procedure outlined in Chapter 4 is presented as a stand-alone process that could be applied to an existing product line without implementing the overall methodology. For instance, given a product line that currently requires multiple size fasteners, the platform portfolio optimization process could be used, perhaps with minor modification, to design a portfolio of fasteners that improves size commonality.

There is potential to extend the research in several areas. The ABC model could be expanded beyond manufacturing cost to include, for example, inventory, decreased design cost due to the streamlined process, decreased lead time, mistake avoidance, or improved quality. The minimum commonality example in Chapter 4 is a type of minimum cover problem that could be solved using an integer programming algorithm, leading to improved convergence rates. Another interesting future research topic is how to extend the methodology to redesign multiple components, especially when there are common interfaces that must be considered to reduce cost and increase performance.

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Appendix A

Seismic Analysis Example

A.1 Discussion

This is an example seismic analysis that is prepared to demonstrate implementation of analysis methodology and the application of input parameters based on the aggregation of known custom specifications. Analysis is limited to the determination of minimum natural frequency of the valve extended structure, actuator sizing calculations, and stress in the yoke legs. Although other analyses are appropriate in practice such as stress analysis of other sections of the valve extended structure, the ones documented are adequate to demonstrate methodology in support of the yoke component platform redesign example discussed throughout this thesis. Aggregate input loading employed is given in Table A-1, and in addition, aggregate yoke material and allowable stress criteria is employed when evaluating yoke stress. The subject artifact is the Class 150, Size 4 Double Disc Gate Valve.

Table A-1: Aggregate Specification Input Parameters

	Description		Value	Units	Ref.
P	Internal Pressure	=	290.	psi	
	Metal Temperature	=	100.	^{O}F	
T_A	Actuator Induced Stem Thrust	=	8000.	kip	
Q_A	Actuator Induced Stem Torque	=	1000.	Ft-kip	
G_{H1}	Horizontal Seismic Coefficient	=	6.	g's	
G_{H2}	Horizontal Seismic Coefficient	=	6.	g's	
G_V	Vertical Seismic Coefficient	=	6.	g's	
G_{EFF}	Effective Seismic Coefficient	=	11.	g's	
	Natural Frequency Limit	=	33	Hz	
	Valve Factor	=	.35		

Table A-2 provides a highlight summary of the results obtained that demonstrates comparison of calculated results with established criteria. For this example, the criterion is met in all cases.

Table A-2: Summary of Performance

Analysis	Criteria	Calculated	Limit	Units
Required Actuator Thrust	$F_{ACT}<T_A$	2.771	8.	kip
Beam Mode Natural Frequency	$F_N>33.$	62.37	33.	Hz
Frame Mode Natural Frequency	$F_N>33.$	70.55	33.	Hz
Beam Mode Yoke Legs	$\sigma_{MAX}<1.5S_A$	10.68	26.25	ksi
Frame Mode Yoke Legs	$\sigma_{MAX}<1.5S_A$	15.47	26.25	ksi

Figure A-1 is a sketch of the valve that shows extended structure section lengths L_0 through L_3 and the corresponding distribution of component weights that are assumed lumped at their center of gravity. The extended structure is the portion of the valve that extends away from the connecting piping, and for this valve, this includes the body neck, the bonnet and yoke, and the actuator.

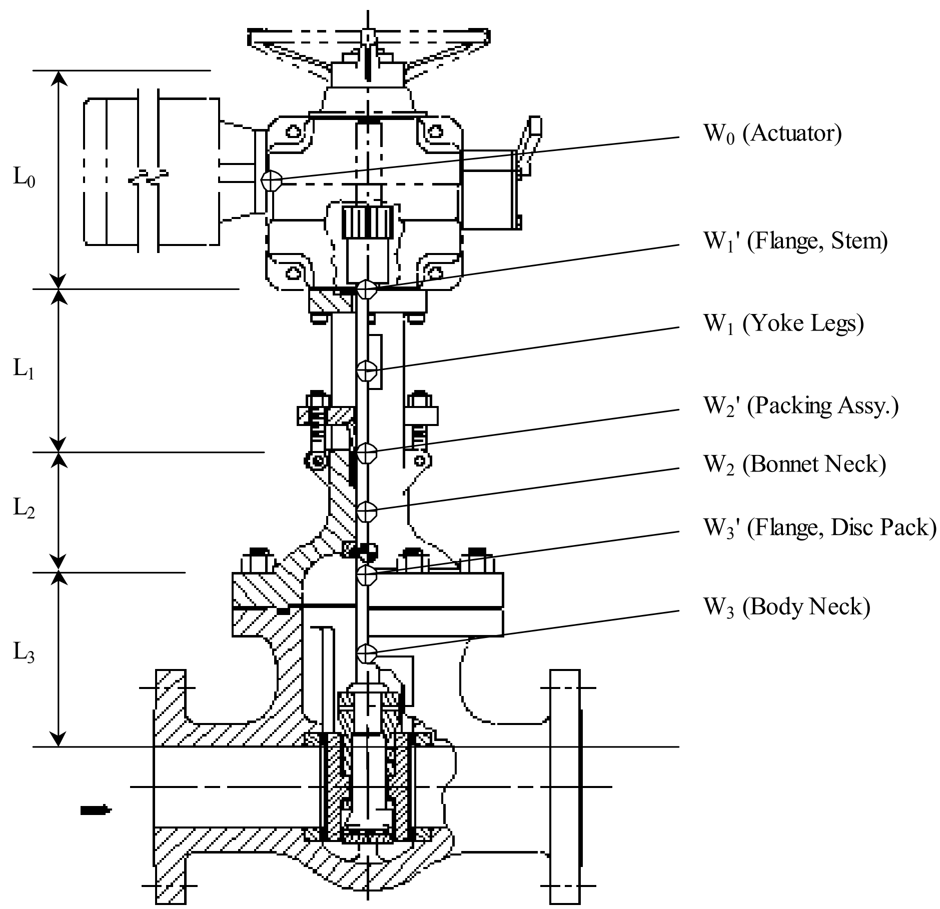


Figure A-1: Extended Structure Model

The extended structure model consists of a rigid actuator section, and three flexible sections each with associated sectional properties including section and node weights, section lengths, and cross-section properties, and Table A-3 provides applicable data. Section A.2 provides cross-section property calculation details. Except for the yoke legs, the sections are modeled as simple cantilever beams. The yoke legs section is modeled as both a cantilever beam and a cantilever frame, and two separate deflection and stress modes result that are denoted as the beam and frame modes, respectively.

Table A-3: Extended Structure Model Parameters

	Section/Node	0.	1.	2.	3.	Units
W	Section Weight	149.	20.	25.	35.	lb
W'	Node Weight	0.	30.	5.	45.	lb
L	SectionLength	7.	7.5	4.5	9.	in
E	Elastic Modulus	0.	28.3	28.3	28.3	msi
X	W Offset	4.6	0.	0.	0.	in
X'	W' Offset	0.	0.	0.	0.	in
P	No. Legs	n/a	2.	1.	1.	
A_{CS}	Section Area	n/a	3.275	10.65	8.655	in^2
I_B	Beam Inertia	n/a	3.619	4.291	39.53	in^4
I_F	Frame Inertia	n/a	.2749	44.84	19.31	in^4
Y	Leg Centroid	n/a	2.895	n/a	n/a	in

Section A.3 describes the standard approach for determining actuator induced stem thrust required to operate the valve. In the redesign methodology in Chapter 3, the required basic actuator size is determined using this approach, and the chosen actuator is the smallest and lightest one that can provide the calculated required thrust with an additional 50% margin. The actuator torque is related to thrust through a standard ‘valve factor’ that quantifies the action of the valve stem power threads in converting actuator induced torque into available stem thrust for valve operation.

Section A.4 provides analysis of extended structure natural frequencies for cantilever beam and frame modes respectively. The minimum natural frequency is required to be above 33 Hz, which is the established aggregate based on the custom specifications.

Section A.5 determines reaction forces at the nodes of the valve extended structure model due to a combination of actuator induced stem thrust and torque and seismic inertia loading. Seismic loading is included in the form of static coefficients applied to component weights. Again, the loading is determined from aggregation of known custom specifications.

Finally, Section A.6 provides stress analysis of the yoke legs resulting from seismic and actuator induced loading

Analysis techniques are based on classical statics, dynamics, and strength of materials theory. The methods used are considered nuclear power industry standard and have been used for the design and qualification of many valves for a variety of power utilities. The presented methodology is a good example of the existing methodology that forms part of a baseline standard product line.

A.2 Extended Structure Cross-Section Properties

Equations are presented here that are used to calculate extended structure cross-section properties, and calculation details are provided in Table A-4 where one set of results is given for each extended structure section. For each applicable cross-section model, a sketch is provided that shows key dimensions that is followed by applicable equations.

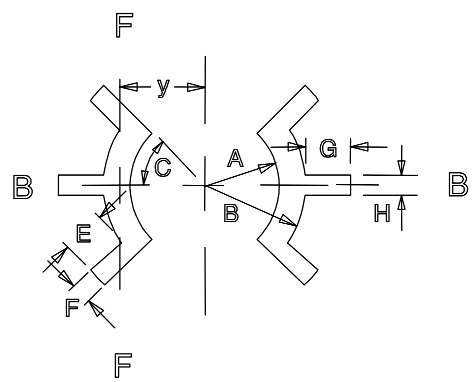


Figure A-2: Arc Yoke Legs Cross-Section

Arc Yoke Leg Area:

$$A_{CS} = C(B^2 - A^2) + GH + 2EF \qquad \text{A.1}$$

Arc Yoke Leg Beam-Mode Inertia for One Leg:

$$I_B = \tfrac{1}{4}(B^4 - A^4)(C - \sin C \cos C) + \tfrac{1}{12} GH^3 + 2I_V$$

$$I_V = \tfrac{1}{12} FE(F^2 \cos^2 C + E^2 \sin^2 C) + EFV^2 \qquad \text{A.2}$$

$$V = B \sin C + \tfrac{1}{2}\sqrt{E^2 + F^2} \cos\left(C + \arctan\left(\frac{E}{F}\right)\right)$$

Arc Yoke Leg Frame-Mode Inertia for One Leg:

$$I_F = \tfrac{1}{4}(B^4 - A^4)(C + \sin C \cos C) - A_{CS}Y^2 + \tfrac{1}{3}HG^3 + BGH(B+G) + 2I_U$$

$$I_U = \tfrac{1}{12}FE(E^2\cos^2 C + F^2\sin^2 C) + EFU^2 \qquad \text{A.3}$$

$$U = B\cos C + \tfrac{1}{2}\sqrt{E^2 + F^2}\sin\left(C + \arctan\left(\frac{E}{F}\right)\right)$$

Arc Yoke Leg Centroid:

$$Y = \frac{1}{A_{CS}}\left[\tfrac{2}{3}\sin C\left(B^3 - A^3\right) + \left(B + \tfrac{1}{2}G\right)GH + 2EFU\right] \qquad \text{A.4}$$

Arc Yoke Leg Beam-Mode Extreme Fiber Distance:

$$X_B = (B+E)\sin C \qquad \text{A.5}$$

Arc Yoke Leg Frame-Mode Extreme Fiber Distance:

$$X_F \max\{B + G, Y - A\cos C, 2U - B\cos C - Y\} \qquad \text{A.6}$$

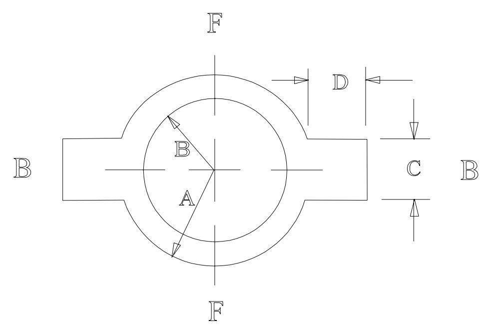


Figure A-3: Single Ribbed Circular Neck

Single Ribbed Circular Neck Area:

$$A = \pi(A^2 - B^2) + 2CD \qquad \text{A.7}$$

Single Ribbed Circular Neck Beam-Mode Inertia

$$I_B = \tfrac{1}{4}\pi(A^4 - B^4) + \tfrac{1}{6}CD^3 \qquad \text{A.8}$$

Single Ribbed Circular Neck Frame-Mode Inertia:

$$I_F = \tfrac{1}{4}\pi(A^4 - B^4) + 2CD\left(\tfrac{1}{3}C^2 + A^2 + AC\right) \qquad \text{A.9}$$

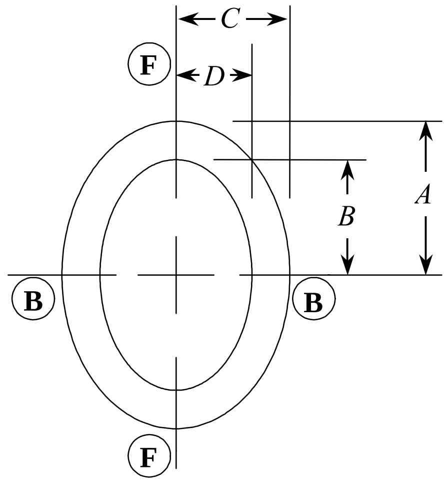


Figure A-4: Oval Neck

Oval Neck Area:

$$A = \pi(AC - BD) \quad \text{A.10}$$

Oval Neck Beam-Mode Inertia:

$$I_B = \tfrac{1}{4}\pi(A^3C - B^3D) \quad \text{A.11}$$

Oval Neck Frame-Mode Inertia

$$I_F = \tfrac{1}{4}\pi(C^3A - D^3B) \quad \text{A.12}$$

Table A-4: Section Property Results

Arc Yoke Legs (Extended Structure Section 1):

	Description		Value	Units	Ref.
A	Leg Inside Radius	=	2.625	in	
B	Leg Outside Radius	=	3.5	in	
C	Leg Half Angle	=	.611	in	
E	Rib Dimension	=	0.	in	
F	Rib Dimension	=	0.	in	
G	Rib Dimension	=	0.	in	
H	Rib Dimension	=	0.	in	
A_{CS}	Area	=	3.275	in^2	Eq. A.1
I_B	Beam Mode Inertia	=	3.619	in^4	Eq. A.2
I_F	Frame Mode Inertia	=	.2749	in^4	Eq. A.3
Y	Distance to Leg Centroid	=	2.895	in	Eq. A.4
X_B	Beam Mode Extreme Fiber Distance	=	2.008	in	Eq. A.5
X_F	Frame Mode Extreme Fiber Distance	=	.745	in	Eq. A.6

Single Ribbed Circular Neck (Extended Structure Section 2):

	Description		Value	Units	Ref.
A	Neck Outside Radius	=	1.5	in	
B	Neck Inside Radius	=	.75	in	
C	Rib Dimension	=	2.375	in	
D	Rib Dimension	=	1.125	in	
A_{CS}	Area	=	10.65	in^2	Eq. A.7
I_B	Beam Mode Inertia	=	4.291	in^4	Eq. A.8
I_F	Frame Mode Inertia	=	44.84	in^4	Eq. A.9

Oval Neck (Extended Structure Section 3):

	Description		Value	Units	Ref.
A	Major Outside Radius	=	3.469	in	
B	Minor Outside Radius	=	2.25	in	
C	Major Inside Radius	=	2.938	in	
D	Minor Inside Radius	=	1.719	in	
A_{CS}	Area	=	8.655	in^2	Eq. A.10
I_B	Beam Mode Inertia	=	39.53	in^4	Eq. A.11
I_F	Frame Mode Inertia	=	19.31	in^4	Eq. A.12

A.3 Required Stem Thrust

This section presents an analysis for predicting the minimum thrust required to close and to seal the valve under design flow conditions. Applicable forces include packing drag, stem end load due to internal pressure (*P*), disc drag due to differential pressure (*△P*), and required seating force. The employed valve factor takes into consideration both frictional and flow induced drag.

The basic equations used in the analysis, and analysis results are given in Table A-5.

Differential pressure force on the disc:

$$F_{DISC} = \tfrac{1}{4}\pi D_{SEAT}^2 \Delta P \qquad \text{A.13}$$

Stem end load (rejection load):

$$F_{STEM} = \tfrac{1}{4}\pi D_{STEM}^2 P \qquad \text{A.14}$$

Required seating differential pressure is a function of seating surface contact width and the seat bearing stress required to seal. Required bearing stress is determined by test on moderately worn seats.

Force required to seat:

$$F_{SEAT} = \tfrac{1}{4}\pi D_{SEAT}^2 \Delta P_{REQ} \qquad \text{A.15}$$

Approximate packing load:

$$F_{PACK} = 1000 D_{STEM} \qquad \text{A.16}$$

The term ($F_{SEAT} - F_{DISC}$) represents the force the actuator must contribute to affect a seal. It conservatively approximates the transfer of stem thrust to seat force when industry standard valve factors can be assumed.

Gate Valve Required Actuator Thrust:

$$F_{ACT} = \max\{(F_{SEAT} - F_{DISC}), f_V F_{DISC}\} + F_{PACK} + F_{STEM} \qquad \text{A.17}$$

Table A-5: Required Stem Thrust Results

Input:

	Parameter Description		Value	Units
D_{SEAT}	Seat Contact Surface Diameter	=	4.4	in
D_{STEM}	Stem Basic Diameter	=	1.	in
f_V	Valve Factor	=	.35	
P	Internal Pressure	=	290.	psi
ΔP	Differential Pressure	=	290.	psi
ΔP_{REQ}	Required Seating Pressure	=	320.	psi

Results:

	Force Description		Value	Units	Ref.
F_{DISC}	Differential Pressure Force on Disc	=	4.41	kip	Eq. A.13
F_{STEM}	Stem End Load	=	.2278	kip	Eq. A.14
F_{SEAT}	Required Seating Force	=	4.866	kip	Eq. A.25
F_{PACK}	Packing Drag	=	1.	kip	Eq. A.16
F_{ACT}	Required Stem Thrust (Gate Valve)	=	2.771	kip	Eq. A.17

A.4 Extended Structure Minimum Natural Frequency

Natural frequencies of the valve extended structure due to bending are considered here. The method used is from the ASME published paper, "A Simplified Method for Calculating the Natural Frequency of Valve Superstructures" (Ezekoye 1978). The method employs Rayleigh's principle which states that the maximum kinetic energy must equal the maximum potential energy in order for the system to satisfy conservation of energy. The approach is to consider two models of the structure: (1) cantilever beam mode which considers deflections normal to the yoke window plane, and (2) cantilever frame mode which considers deflections parallel to the yoke window plane.

Consistent with the extended structure model, the base of the extended structure rigidly fixed, the extended structure components are rigidly connected, and section weights are lumped at their centers of gravity. In addition, it is reasonable to ignore axial and pure shear displacements as they are negligible in comparison to those due to bending since section lengths are sufficiently large.

The theory is presented next and is followed by Table A-6, which presents calculation details and resulting calculated minimum natural frequencies.

Forces at Nodes: (N = Node Number)

$$F_N = \tfrac{1}{3} W_N + \sum_{I=1}^{N} \left(W_{I-1} + W'_{I-1} \right) \qquad \text{A.18}$$

Moments at Nodes:

$$M_N = \sum_{K=1}^{N} \left\{ \sum_{I=K}^{N} \left(W_{K-1} + W'_{K-1} \right) L_{I-1} - \tfrac{1}{2} \left(W_{K-1} L_{K-1} \right) \right\} \qquad \text{A.19}$$

Single Section Slope:

Beam Section:

$$\theta_N = \frac{F_N L_N^2}{2PE_N I_N} + \frac{M_N L_N}{PE_N I_N}$$

Frame Section: A.20

$$\theta_N = \frac{M_N L_N}{2A_N E_N Y_N^2}$$

Single Section Deflection:

Beam Section:

$$\delta_N = \frac{F_N L_N^3}{3PE_N I_N} + \frac{M_N L_N^2}{2PE_N I_N}$$

Frame Section: A.21

$$\delta_N = \tfrac{1}{2}\theta_N L_N + \frac{F_N L_N^3}{24E_N I_N}$$

Slope Deflection:

$$\delta_{\theta N} = L_N \sum_{I=N+1}^{\max N} \theta_I \qquad \text{A.22}$$

Section Node Deflection:

$$\delta_{SN} = \delta_N + \delta_{SN} \qquad \text{A.23}$$

Total Node Deflection:

$$\delta_{TN} = \sum_{K=N}^{\max N} \delta \qquad \text{A.24}$$

Natural Frequency[1]:

$$f_N = \frac{1}{2\pi}\sqrt{\frac{g\sum C_{1N}}{g\sum C_{2N}}} \qquad \text{A.25}$$

$$C_{1N} = (W_N + W'_N)\delta_{TN} \qquad \text{A.26}$$

$$C_{2N} = (W_N + W'_N)\delta_{TN}^2 \qquad \text{A.27}$$

---

[1] In Eq. A.25, '*g*' is acceleration due to gravity and equals 386.4 in/sec^2.

Table A-6: Extended Structure Natural Frequency Results

Beam Mode Frequency Calculation Details:

N	Node	0.	1.	2.	3.	Units	Ref
F_N	Force	0.	185.7	212.3	285.7	lb	Eq. A.18
M_N	Moment	0.	521.5	1939.	2913.	in-lb	Eq. A.19
τ_N	Slope	0.	4.459E-5	8.955E-5	3.378E-5	rad	Eq. A.20
δ_N	Deflection	0.	1.991E-4	2.148E-4	1.675E-4	in	Eq. A.21
$\delta_{\tau N}$	Slope Deflection	1.175E-3	9.25E-4	1.52E-4	0.	in	Eq. A.22
δ_{SN}	Sect. Node Deflection	1.175E-3	1.124E-3	3.668E-4	1.675E-4	in	Eq. A.23
δ_{TN}	Total Node Deflection	2.834E-3	1.658E-3	5.343E-4	1.675E-4	in	Eq. A.24
C_1		.4222	8.292E-2	1.603E-2	1.34E-2	in-lb	Eq. A.26
C_2		1.197E-3	1.375E-4	8.564E-6	2.245E-6	in^2-lb	Eq. A.27

Frame Mode Frequency Calculation Details:

N	Node	0.	1.	2.	3.	Units	Ref
F_N	Force	0.	185.7	212.3	285.7	lb	Eq. A.18
M_N	Moment	0.	521.5	1939.	2913.	in-lb	Eq. A.19
τ_N	Slope	0.	2.518E-6	8.571E-6	6.914E-5	rad	Eq. A.20
δ_N	Deflection	0.	4.289E-4	2.056E-5	3.429E-4	in	Eq. A.21
$\delta_{\tau N}$	Slope Deflection	5.616E-4	5.828E-4	3.111E-4	0.	in	Eq. A.22
δ_{SN}	Sect. Node Deflection	5.616E-4	1.012E-3	3.317E-4	3.429E-4	in	Eq. A.23
δ_{TN}	Total Node Deflection	2.248E-3	1.686E-3	6.746E-4	3.429E-4	in	Eq. A.24
C_1		.3349	8.431E-2	2.024E-2	2.743E-2	in-lb	Eq. A.26
C_2		7.529E-4	1.422E-4	1.365E-5	9.405E-6	in^2-lb	Eq. A.27

Resulting Natural Frequencies:

Description		Value	Units	Ref.
Beam Mode Natural Frequency	=	62.37	Hz	Eq. A.25
Frame Mode Natural Frequency	=	70.55	Hz	Eq. A.25

A.5 Extended Structure Reaction Forces

The generalized equations for the forces at the nodes of the extended structure model are given in this section. In order to qualify an arbitrary valve orientation, the vector sum of the required static load coefficients (G_{EFF}) is imposed on the structure in a conservative manner. Loading in both the valve local horizontal and local vertical directions are considered. The plus one factor accounts for component dead load weights. Table A-7 provides input data and analysis results.

$$G_{EFF} = \sqrt{G_{H1}^2 + G_{H2}^2 + \left(G_V + 1\right)^2} \qquad \text{A.28}$$

Thrust (Vertical Force) at Node N:

$$T_N = G_{EFF} \sum_{I=0}^{N-1} \left\{ \left(W_I + W'_I\right) + W_N \right\} + T_A \qquad \text{A.29}$$

Shear (Horizontal Force) at Node N:

$$V_N = G_{EFF} \sum_{I=0}^{N-1} \left\{ \left(W_I + W'_I\right) + W_N \right\} \qquad \text{A.30}$$

Bending Moment at Node N:

$$M_N = \max \left\{ \begin{array}{l} G_{EFF} \displaystyle\sum_{I=0}^{N-1} \left[\left(W_I + W'_I\right) \sum_{J=I}^{N-1} L_J \right] - \tfrac{1}{2} W_I L_I , \\ G_{EFF} \displaystyle\sum_{I=0}^{N-1} \left(W_I X_I + W'_I X'_I\right) + W_N L_N \end{array} \right\} \qquad \text{A.31}$$

Torsional Moment at Node N:

$$Q_N = G_{EFF} \sum_{I=0}^{N-1} \left(W_I X_I + W'_I X'_I\right) + W_N L_N + Q_A \qquad \text{A.32}$$

Table A-7: Reaction Force Results

Extended Structure Model Parameters:

N	Section	0.	1.	2.	3.	Units
W_N	Weight	149.	20.	25.	35.	lb
W'_N	Weight	0.	30.	5.	45.	lb
L_N	Length	7.	7.5	4.5	9.	in
X_N	Offset	4.6	0.	0.	0.	in
X'_N	Offset	0.	0.	0.	0.	in

Load Conditions:

	Description		Value	Units	Ref.
T_A	Actuator Thrust	=	8000.	lb	
Q_A	Actuator Torque	=	1000.	in-lb	
G_{H1}	Horizontal Seismic Coefficient	=	6.	g's	
G_{H2}	Horizontal Seismic Coefficient	=	6.	g's	
G_V	Vertical Seismic Coefficient	=	6.	g's	
G_{EFF}	Effective Seismic Acceleration	=	11.	g's	Eq. A.28

Reaction Force Calculation Results:

N	Node	1.	2.	3.	4.	Units	Ref
T_N	Thrust	9969.	1.024E+4	1.101E+4	1.14E+4	lb	Eq. A.29
V_N	Shear	1969.	2244.	3014.	3399.	lb	Eq. A.30
M_N	Moment	7539.	2.133E+4	3.205E+4	6.09E+4	in-lb	Eq. A.31
Q_N	Torque	8539.	8539.	8539.	8539.	in-lb	Eq. A.32

A.6 Yoke Legs Stress Analysis

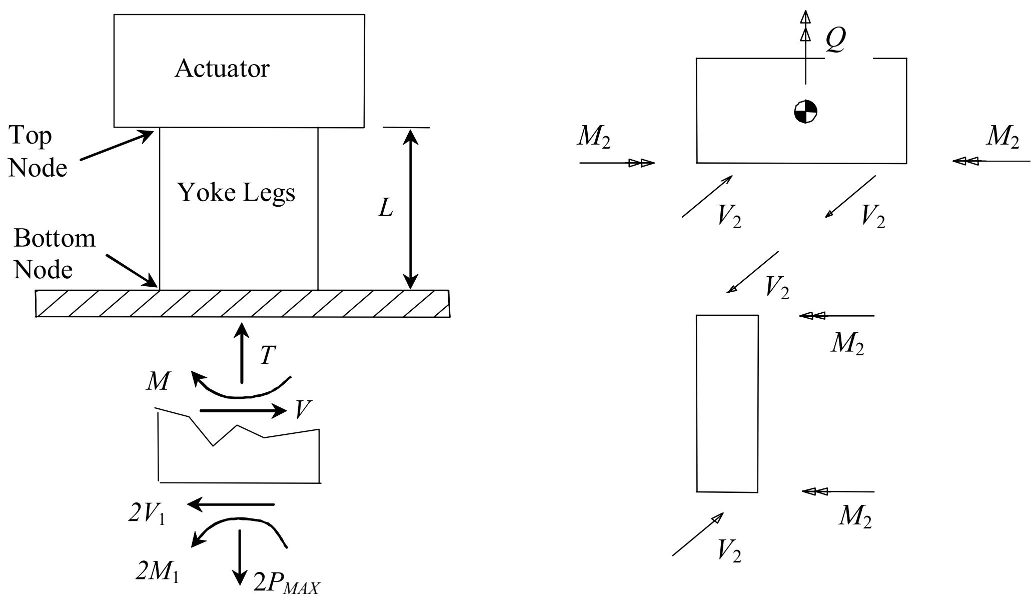
Figure A-5 and Figure A-6 provide free body diagrams that describe the external loading on the yoke legs for the beam and frame modes respectively. The figures are followed by equations for determining applicable forces that result in significant primary stress levels. The equations are followed by Table A-8, which gives results and shows comparison with allowable stress criteria. The method agrees with several cases from Roark and Young (1989).

The beam mode assumes that the external moment and shear act orthogonal to the yoke window so that the legs behave like a cantilever beam. Stress is maximum at the bottom node due to the reaction forces from Table A-7 at the bottom node designated as T (Thrust), V (shear), M (moment), and Q (Torque).

The frame mode assumes that the external moment and shear act parallel with the yoke window so that the legs behave like a cantilever frame. Stress is approximately the same at the top and bottom nodes where it is a maximum. The appropriate reaction forces are T (Thrust at the bottom node), V (shear at the top node), M (moment at the top node), and Q (Torque at the bottom node). Note that Q causes reactions identical to the beam mode.

In order to envelope the majority of customer specifications, yoke leg stress should satisfy the criteria defined in the ASME Boiler and Pressure Vessel Code, Section III, Article NC-3521(a) from valve design rules. Limits are given for primary stress that is defined as stress required to maintain basic force equilibrium, and as such, stress concentrations need not be considered. In particular, primary principal stress is limited to

1.5*S*, where *S* is taken from allowable stress tables included in ASME Code Section II, Volume D.



Reactions to *T*, *V*, and *M*   Reactions to *Q*

Figure A-5: Beam Mode Reactions

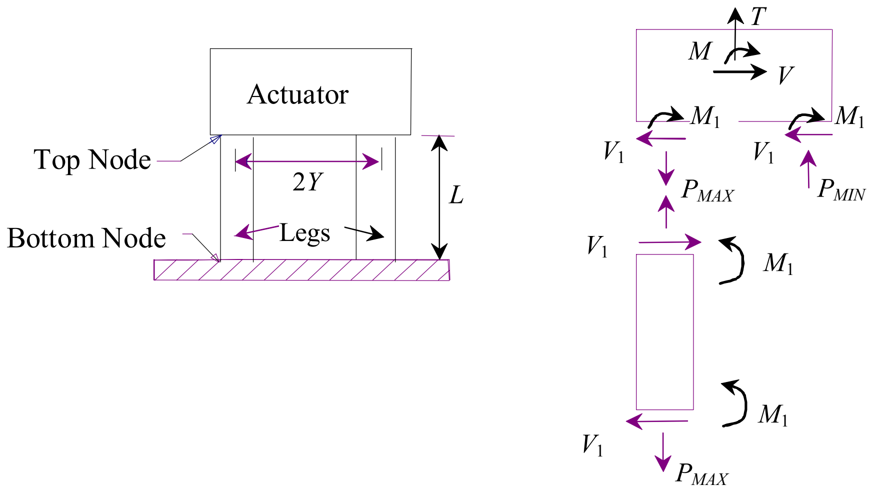


Figure A-6: Frame Mode Reactions to T, V, & M

$$V_1 = \tfrac{1}{2}V$$

$$V_2 = \frac{Q}{2Y}$$

Beam Mode	**Frame Mode**	
$V' = V_1 + V_2$	$V' = \sqrt{V_1^2 + V_2^2}$	A.33
$M_1 = \tfrac{1}{2}M$	$M_1 = \tfrac{1}{2}V_1 L$	A.34
$M_2 = \tfrac{1}{2}V_2 L$	$M_2 = \tfrac{1}{2}V_2 L$	A.35
$M' = M_1 + M_2$	n/a	A.36
$P_{MAX} = \tfrac{1}{2}T$	$P_{MAX} = \frac{VL + M}{2Y} + \tfrac{1}{2}T$	A.37
$\sigma = \frac{P_{MAX}}{A_{CS}} + \frac{M' X_B}{I_B}$	$\sigma = \frac{P_{MAX}}{A_{CS}} + \frac{M_1 X_F}{I_F} + \frac{M_2 X_B}{I_B}$	A.38

$$\tau = \frac{V'}{\tfrac{2}{3} A_{CS}} \quad \text{A.39}$$

$$\sigma_{MAX} = \tfrac{1}{2}\sigma + \sqrt{\tfrac{1}{4}\sigma^2 + \tau^2} \quad \text{A.40}$$

Table A-8: Yoke Legs Analysis Results

Reaction Forces from Table A-7:

	Parameter	At Top	At Bottom	Units	Ref.
	Node	1.	2.		
T	Thrust	9969.	1.024E+4	lb	Eq. A.29
V	Shear	1969.	2244.	lb	Eq. A.30
M	Moment	7539.	2.133E+4	in-lb	Eq. A.31
Q	Torque	8539.	8539.	in-lb	Eq. A.32

Component Input Paramters:

	Parameter Description		Value	Units	Ref.
A_{CS}	Yoke Leg Area	=	3.275	in^2	Eq. A.1
I_B	Beam Mode Inertia	=	3.619	in^4	Eq. A.2
I_F	Frame Mode Inertia	=	.2749	in^4	Eq. A.3
Y	Distance to Leg Centroid	=	2.895	in	Eq. A.4
X_B	Beam Mode Extreme Fiber	=	2.008	in	Eq. A.5
X_F	Frame Mode Extreme Fiber	=	.745	in	Eq. A.6
L	Yoke Window Length	=	7.5	in	

Material Spec. Ref.: SA-351-CF8M (Stainless Steel) @ 100^0F

S	ASME Code Allowable Stress	=	17.5	ksi

(Per ASME Code, Section II, Vol. D)

Stress Results:

	Mode	Beam	Frame	Units	Ref
V'	Resultant Shear	2597.	1773.	lb	Eq. A.33
M_1	Moment	1.066E+4	3692.	in-lb	Eq. A.34
M_2	Moment	5531.	5531.	in-lb	Eq. A.35
M'	Resultant Moment	1.62E+4	N/A	in-lb	Eq. A.36
P_{MAX}	Resultant Thrust	5122.	7699.	lb	Eq. A.37
σ	Normal Stress	10.55	15.42	ksi	Eq. A.38
τ	Shear Stress	1.19	.8123	ksi	Eq. A.39
σ_{MAX}	Principal Stress	10.68	15.47	ksi	Eq. A.40
	Allowable	1.5S	1.5S		
		26.25	26.25	ksi	

Appendix B

Valve Quantity Count Data by Type, Size, and Class

Double Disc Gate Valves:

Type	Size	Class	Count
DD	1	150	1
DD	1	300	1
DD	1	600	7
DD	1	900	8
DD	1	1500	11
DD	1	1878	39
DD	1	1888	19
DD	1	2500	12
DD	2	150	9
DD	2	300	1
DD	2	600	9
DD	2	900	7
DD	2	1500	24
DD	2	1878	29
DD	2	1888	22
DD	2	2500	19
DD	3	150	13
DD	3	300	2
DD	3	600	8
DD	3	900	24
DD	3	1500	30
DD	3	2500	13
DD	4	150	10
DD	4	300	9
DD	4	600	15
DD	4	900	15
DD	4	1500	10
DD	6	150	9
DD	6	300	6
DD	6	600	6
DD	6	900	27
DD	6	1500	2

Type	Size	Class	Count
DD	8	150	16
DD	8	300	8
DD	8	600	2
DD	8	900	7
DD	8	1500	13
DD	8	2500	1
DD	10	150	2
DD	10	300	12
DD	10	600	9
DD	10	900	17
DD	10	1500	4
DD	12	150	2
DD	12	300	9
DD	12	900	4
DD	12	1500	2
DD	14	150	2
DD	14	300	10
DD	14	600	1
DD	14	900	9
DD	16	150	1
DD	16	300	1
DD	16	900	3
DD	18	150	2
DD	18	300	2
DD	18	600	4
DD	20	600	2
DD	20	900	8
DD	20	2500	3
DD	22	900	2
DD	24	150	1
DD	24	600	12
DD	24	900	1
DD	24	1500	1

Flex Wedge Gate Valves:

Type	Size	Class	Count
FW	1	150	3
FW	1	900	3
FW	2	150	3
FW	2	1500	3
FW	3	150	85
FW	3	300	11
FW	3	600	12
FW	3	900	25
FW	3	1500	17
FW	4	150	54
FW	4	300	23
FW	4	600	23
FW	4	900	71
FW	4	1500	12
FW	6	150	73
FW	6	300	12
FW	6	600	17
FW	6	900	53
FW	6	1500	1
FW	6	2500	1
FW	8	150	46
FW	8	300	7
FW	8	600	6
FW	8	900	14
FW	8	1500	4
FW	10	150	38
FW	10	300	22
FW	10	600	17
FW	10	900	29

Type	Size	Class	Count
FW	12	150	30
FW	12	300	17
FW	12	600	3
FW	12	900	26
FW	12	1500	4
FW	14	150	12
FW	14	300	13
FW	14	600	2
FW	14	900	9
FW	14	1500	3
FW	16	150	21
FW	16	300	8
FW	16	600	1
FW	16	900	3
FW	16	1500	1
FW	18	150	8
FW	18	300	18
FW	18	600	5
FW	18	900	9
FW	20	150	14
FW	20	300	8
FW	20	600	3
FW	20	900	18
FW	20	1500	3
FW	24	150	12
FW	24	300	3
FW	24	900	12
FW	24	1500	3
FW	26	150	1
FW	26	900	1
FW	36	150	1
FW	36	300	1

Appendix C

Artifact Bounds Constraints and Candidate Component Platforms

C.1 Artifact-Specific Bounds Constraints

Artifact	a_{MIN} [in]	a_{MAX} [in]	r_{MAX} [in]	Artifact	a_{MIN} [in]	a_{MAX} [in]	r_{MAX} [in]
1	5.4345	7.818	n/a	31	1.25	2.75	n/a
2	1.5	3	n/a	32	1.3125	2.8125	n/a
3	3.0875	4.85	n/a	33	2.4625	4.225	n/a
4	4.7125	6.475	n/a	34	3.107	5.4905	n/a
5	3.0665	5.141	n/a	35	3.4795	6.793	n/a
6	5.8595	8.243	n/a	36	3.9415	6.016	n/a
7	3.547	5.0005	n/a	37	1.375	2.875	n/a
8	3.672	5.1255	n/a	38	1.5	3	n/a
9	3.922	5.3755	n/a	39	3.3375	5.1	n/a
10	4.7125	6.475	n/a	40	3.3375	5.1	n/a
11	5.504	7.5785	n/a	41	3.0665	5.141	n/a
12	5.5875	7.35	n/a	42	5.5875	7.35	n/a
13	1.8125	n/a	4.3125	43	2.16	n/a	4.02
14	2.665	n/a	6.775	44	2.4065	n/a	5.0305
15	3.442	n/a	7.308	45	3.8435	n/a	6.0935
16	5.14	n/a	9.86	46	3.7655	n/a	7.7035
17	5.69	n/a	11.43	47	5.82	n/a	9.06
18	6.5635	9.5665	n/a	48	2.625	4.125	n/a
19	2.005	n/a	7.245	49	2.062	n/a	4.188
20	1.625	3.125	n/a	50	2.595	n/a	5.215
21	3.573	n/a	6.927	51	3.5	n/a	7
22	5.5875	7.35	n/a	52	4.31	n/a	8.57
23	5.82	n/a	12.56	53	5.375	n/a	10.375
24	7.773	10.467	n/a	54	5.815	n/a	11.315
25	2	3.5	n/a	55	2.6875	n/a	6.4375
26	4.6915	6.766	n/a	56	2.82	6.016	7.28
27	5.701	8.0845	n/a	57	2.594	n/a	8.718
28	6.5665	8.641	n/a	58	3.1875	4.6875	n/a
29	4.81	n/a	11.07	59	3.56	n/a	12.82
30	4.125	n/a	16.125	60	4.115	n/a	14.155

C.2 Candidate Component Platform Solutions

Candidate Platform	*a* [in]	*b* [in]	*c* [rad]	Candidate Platform	*a* [in]	*b* [in]	*c* [rad]
1	5.5	0.625	0.524	31	2.375	0.625	0.524
2	2.625	0.75	0.524	32	2.375	0.625	0.524
3	3.5	1.125	0.524	33	3	0.75	0.524
4	4.75	0.625	0.524	34	5.375	0.75	0.524
5	3.125	1	0.611	35	4.5	0.625	0.524
6	5.875	0.625	0.524	36	4.5	0.875	0.524
7	3.625	0.625	0.524	37	2.375	1.25	0.524
8	3.75	0.625	0.524	38	2.5	0.75	0.524
9	4	0.625	0.524	39	4.375	0.625	0.524
10	4.75	0.625	0.524	40	3.875	0.625	0.524
11	5.625	0.625	0.524	41	4	0.875	0.524
12	5.75	0.875	0.524	42	6.5	0.875	0.524
13	2.875	0.875	0.698	43	2.5	0.75	0.524
14	2.75	1	0.524	44	2.625	1	0.524
15	4	0.875	0.524	45	3.875	1	0.524
16	6.5	1	0.524	46	3.875	1.375	0.524
17	5.75	1.25	0.524	47	5.875	1.25	0.524
18	8.75	1.125	0.524	48	4.125	1.25	0.524
19	2.5	1.125	0.524	49	3.25	0.75	0.611
20	2.375	0.875	0.524	50	3	0.625	0.785
21	3.625	1.125	0.524	51	3.5	0.875	0.873
22	6.625	0.75	0.524	52	4.375	1.25	0.524
23	6.25	0.875	0.524	53	5.375	1.5	0.524
24	9.875	1.125	0.524	54	5.875	1.875	0.524
25	3	0.875	0.524	55	2.75	1.375	0.524
26	4.75	0.875	0.524	56	5.625	0.625	0.524
27	7	0.625	0.524	57	3.125	1.25	0.698
28	7.125	0.875	0.524	58	3.75	1.375	0.524
29	4.875	1.875	0.698	59	4.75	2.125	0.611
30	8	1.75	0.524	60	5.25	2.125	0.524

Appendix D

Product Platform Portfolio Example Supporting Tables

D.1 Example Performance Feasibility Test Matrix

```
*00002000022000220000220002200000000000020000200000002020000
0*0000000000220000220000200000112000210000120000020000200000
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200*02000222000020000020020020000200000000000020000022020022
0021*01111000020000020000200200001200112000220210220000002220
11212*111112111222112222122222111212111121122222112222212222
000200*22200002000002000020020000220022200022020002000000220
0002000*2200002000000000020020000220022200022020002000000220
00020000*200002000000000020020000222002220000002000220000022
200202000*22000020000020020020000200000000000020000022020022
0000020000*2000220000220002200000000000020000200000002020000
00000100001*000220000220001200000000000020000200000002010000
010020100000*10000110000100000111000210000110000110000200000
2022221112222*2000020001200200012120012200022022222200222200
10210211111200*020002020020020000212001120002222002220010220
100001000011000*20000110001102000100000010000200000022010002
0000010000010001*2000112001102000000000010000200000002000000
00000000000000000*000100001102000000000000000000000000000000
212122111122212020*12020120020111212211120112222122220222220
0200200000002200002*0000200000112000210000120000020000202000
10010111111200100000*000020020000111001110002202000220010220
000001000012000220000*20001200000000000020000200000002010000
0000010000000002020002*2001202000000000020000200000002000000
00000000000000000100000*000002000000000000000000000000000000
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000000000000000000000100001*02000000000000000000000000000000
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10010100011100011100011101111*000111001001000011000111010011
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0200000000000200002200000000002*0000220000220000000000200000
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002110111100001000002000020020000*12001110002202102220002222
2022021112220022200022200200200002*2001222002222002222020222
10010100111200102000000002002000021*001110000022000222010022
010000000000021000011000000000011000*10000110000000000200000
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00000100001100022000011000120000000000000*000200000002010000
020000000000022000022000020000011200022000*20000220000000000
0120201110002220002020001000000010000112201*2000222000202000
00010000110000200000000002000000001200112000*202000200000000
100101001111001220000110011020000111001111001*21000220010022
0000010000000001000001100011000000000000010000*0000002000000
01101011100011100000100010000000100000011001120*112000102100
010020000000022000021000010000011100021000012000*20000200000
0120201110002220000020002000000010200022200220002*2000202200
10110111111100102000100001002000011100111000120200*220010220
100101000111000220000120011220000111001002000020000*22010022
1000010000110001120001100011020001000000010000100000*2010000
00000100000000010100011200110200000000000100001000000*000000
102110111110111000002000110000001111001110001202112200*12200
1021221111222020200020001200200012120011200022221122200*2220
11111111111111122000111011122000111100111201122111222211*222
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10010100011100011100011101111220011100100100001100011101002*
```

D.2 Example Candidate Arrays and Solution Details

Artifact Ordinal	Candidate Platforms (C)	Max. X^P Index	Solution 1		Solution 2	
			X^P*	$C(X^P*)$	X^P*	$C(X^P*)$
1	1,6,11,12,16,17,22,23,27,28,42,47,54,56	14	8	23	12	47
2	2,13,14,19,20,25,33,37,44,50,55	11	8	37	5	20
3	3,21,46,48,51,52,57,58,59	9	4	48	5	51
4	1,4,6,10,11,12,17,23,26,29,34,47,53,54,56,59,60	17	10	29	9	26
5	3,5,15,21,26,29,36,41,45,46,48,51,52,57,58,59	16	11	48	12	51
6	3,5,6,12,16,17,18,21,22,23,24,26,27,28,29,30,34, 36,42,45,46,47,48,51,52,53,54,55,57,58,59,60	32	16	30	22	47
7	4,7,8,9,10,15,21,26,29,35,36,39,40,41,45,46,48, 52,58,59	20	9	29	8	26
8	4,8,9,10,15,26,29,35,36,39,40,41,45,46,48,52,58, 59	18	7	29	6	26
9	4,9,10,15,26,29,34,35,36,39,40,41,48,52,53, 59,60	17	6	29	5	26
10	1,4,6,10,11,12,17,23,26,29,34,47,53,54,56,59,60	17	8	23	9	26
11	6,11,12,16,17,22,23,27,28,42,47,54,56	13	11	47	11	47
12	12,16,17,22,23,28,42,47,54	9	5	23	8	47
13	5,13,37,55	4	3	37	3	37
14	1,3,4,5,6,10,11,12,13,14,15,21,26,29,34,36,40,41 ,45,46,48,49,50,51,52,55,56,57,58	29	21	48	13	26
15	3,6,12,15,17,21,23,26,29,34,36,41,45,46,47,48,5 1,52,53,58,59	21	9	29	8	26
16	16,17,30,47,53,54,60	7	4	47	3	30
17	17,18,24,30,47,54	6	4	30	4	30
18	18,30	2	2	30	2	30
19	1,3,5,6,11,12,13,15,17,19,21,23,26,29,34,36,37, 41,45,46,47,48,50,51,52,53,55,56,57,58,59	31	12	23	21	47
20	2,5,13,14,19,20,25,33,37,44,50,55,57	13	9	37	6	20
21	12,21,26,29,45,46,48,52,53,58,59	11	4	29	3	26
22	12,16,17,22,23,28,42,47,54	9	5	23	8	47
23	16,18,22,23,24,28,30,42,47,54	10	4	23	7	30
24	24,30	2	2	30	2	30
25	3,5,13,14,19,25,37,44,49,50,51,55,57	13	7	37	7	37
26	12,16,17,22,23,26,29,42,47,53,54,59,60	13	5	23	6	26
27	12,16,17,22,23,27,28,30,42,47,54	11	8	30	8	30
28	28,30	2	2	30	2	30
29	29,30	2	1	29	2	30
30	30	1	1	30	1	30

D.2 Continued

Artifact Ordinal	Candidate Platforms (C)	Max. X^P Index	Solution 1		Solution 2	
			X^P*	$C(X^P*)$	X^P*	$C(X^P*)$
31	2,14,19,20,31,32,37,38,43,44,55	11	7	37	4	20
32	2,14,19,20,31,32,37,38,43,44,55	11	7	37	4	20
33	3,5,7,8,9,13,14,15,19,21,25,33,40,41, 44,45,46,48,49,50,51,55,57,58	24	18	48	16	45
34	3,21,26,29,34,36,45,46,48,51,52,53,57,58, 59,60	16	9	48	7	45
35	1,3,4,6,10,11,12,15,16,17,21,22,23,26,29,34 ,35,36,40,41,42,45,46,47,48,51, 52,53,54,56,58,59,60	33	24	47	14	26
36	12,17,26,29,34,36,47,48,52,53,54,59,60	13	4	29	7	47
37	13,37,55	3	2	37	2	37
38	2,13,14,19,20,25,33,37,38,43,44,50,55	13	8	37	5	20
39	3,4,10,15,21,26,29,35,36,39,40,41,45, 46,48,51,52,58,59	19	7	29	13	45
40	1,6,11,12,15,17,26,29,34,36,40,41,47, 48,52,53,54,56,59,60	20	14	48	7	26
41	3,5,15,21,26,29,36,41,45,46,48,51,52, 57,58,59	16	11	48	5	26
42	16,17,28,42,47,54	6	5	47	5	47
43	2,13,14,19,20,25,33,37,38,43,44,49,50	13	8	37	8	37
44	3,5,13,14,15,19,21,40,41,44,45,49,50, 51,55,57	16	10	44	14	51
45	15,26,36,41,45,46,48,52	8	7	48	5	45
46	16,17,29,46,47,52,53,59,60	9	5	47	5	47
47	47,54	2	1	47	1	47
48	46,48,51,57	4	2	48	3	51
49	5,13,14,19,37,44,49,50,55	9	6	44	5	37
50	3,5,13,14,15,21,25,35,39,40,41,44,45, 49,50,51,55,57,58	19	12	44	16	51
51	17,29,46,48,51,52,53,58,59	9	4	48	5	51
52	16,17,23,28,29,42,47,52,53,54,59,60	12	7	47	7	47
53	18,30,53,54	4	2	30	2	30
54	24,30,54	3	2	30	2	30
55	3,21,46,48,51,52,55,57,58	9	4	48	5	51
56	3,5,6,11,12,13,15,17,21,26,29,34,36,41,45, 46,47,48,51,52,53,56,57,58,59	25	17	47	17	47
57	16,17,28,29,42,46,47,51,52,53,54,57, 58,59,60	15	4	29	7	47
58	46,48,51,52,58	5	2	48	3	51
59	29,30,59	3	1	29	2	30
60	29,30,59,60	4	2	30	2	30

VITA

Ronald Scott Farrell

Ronald Scott Farrell is currently a Senior Engineer for Flowserve Corporation in the research and development department at the Raleigh, North Carolina Plant. For over twenty-five years, he has been involved in the design, analysis, and formal qualification of valves and actuators installed at nuclear power plants located throughout the world. He is well respected by his peers as an expert in valve and actuator design and usage. He is a practicing registered professional engineer, and is a member of the American Society of Mechanical Engineers.

Mr. Farrell earned a Ph.D. degree in Mechanical Engineering in 2007 from The Pennsylvania State University and a M.S. degree in Mechanical Engineering in 1999 from the same university. In 1980 he obtained his B.S. degree in Engineering Science and Mechanics from The Pennsylvania State University as well. As a graduate student, he was inducted into the Tau Beta Pi National Engineering Honors Fraternity, and as an undergraduate, he was inducted into the Pi Mu Epsilon Honorary Mathematics Fraternity.

During his course of studies as a Ph.D. student, Mr. Farrell has co-authored three conference papers, two published journal papers, and one journal paper yet to be published. His academic interests are in the areas of product platform design, mass customization, and information technology related to engineering design.