

AN APPROACH TO DESIGNING SUSTAINABLE ENTERPRISE SYSTEMS

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ABSTRACT

The complexity of a large-scale enterprise makes it difficult to implement a strategic plan for developing the enterprise. To address complexity we divide the enterprise into approximate, inter-related areas of responsibility – organization design, product design and manufacturing process design – and use decisions as integrators. In this paper, we propose a coherent, decision-based method for correlating these different types of design. Strategies in each area of responsibility are developed with the appropriate consideration of overall enterprise goals. This is made possible by an integrated approach to decision making based on the mathematically-rigorous, domain-independent foundation of the compromise Decision Support Problem. Making the decision to use this decision-making framework falls under the general heading of organization design, which we assume to be given. The remainder of the paper deals with the design of product/manufacturing process platforms. Designing platforms of products or processes provides the foundation for the development of streams of products and serves to integrate other aspects of the enterprise around that platform – whether it is a manufacturing process platform or a product platform. We discuss both top-down and bottom-up decision-based approaches to designing product platforms and a method for product or manufacturing process platform development method based on the compromise Decision Support Problem, hierarchy theory and constructal theory.

1 FRAME OF REFERENCE

In complex manufacturing organizations there are at least three distinct design areas: product design, manufacturing process design, and design of the organization itself. Historically these activities have been carried out in relative isolation, by separate people on different timelines. What if they could all be brought together into a domain-independent design process? We capture this prospect by using the term enterprise design.

The three distinct areas in complex enterprise design which we seek to integrate are:

- **Organization design** refers to the design of the organization itself, through the setting of variables which are under management control. These variables include the organization structure (boundaries, levels), technologies (both product and process), people (hiring, training), tasks (work design), reward systems, information systems, and decision-making processes (Hanna 1988), Section 2.
- **Product design** is defined as the process by which customer requirements are transformed into a physical artifact that fulfills the customers' stated needs, Section 4.
- **Manufacturing process design** includes facility location and layout, the purchasing of new equipment and technology, and the planning, scheduling and operation of manufacturing facilities. This idea is captured well by the field of operations management,

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which may be defined as “the design, operation, and improvement of the production systems that create the firm’s primary products or services” (Chase and Aquilano 1995), Section 5.

Currently these design activities proceed independently, as shown in Figure 1.

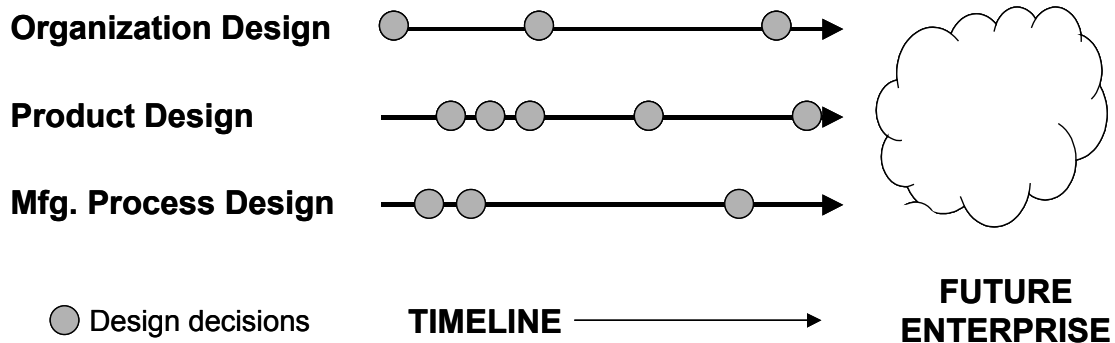


Figure 1. The development over time of an enterprise system – the current paradigm.

We present a unified foundation for the design of complex enterprise systems by adopting a decision-based perspective (Mistree, Smith et al. 1990), so that the enterprise as a whole moves toward a target, as shown in Figure 2. We assert that the making of decisions is a central and key activity in the design of products, in the design and operation of manufacturing processes, and in a significant fraction of all managerial and executive activity that encompasses organization design and that a coherent framework for decision-making can integrate the enterprise, and that decision making over time can help us integrate complex enterprise systems. The notion of decision making as the common thread that runs throughout all of these activities is offered eloquently by Simon, 1987, as he argues that:

“...a great deal of real-world decision making -- perhaps most of it -- is concerned with creating alternatives among which choices can be made. The activities that create new alternatives are usually called design activities, and although we most often apply the term *design* to the work of engineers and architects, it is equally central to the work of managers. Companies and the organizational structures within them must be designed. Investment alternatives must be discovered, that is, designed. Products and product lines must be designed.”

An enterprise is the sum total of its people and the jobs and tasks they perform, its products, its processes and facilities, its information systems and flows, and so on. Clearly all of these aspects of an enterprise come into being at some time, and then remain dynamic, changing over time. We therefore say that the enterprise as a whole is designed, either implicitly or explicitly. As voiced by Hanna, 1988, “all organizations are perfectly designed to get the results they get.” However, because of the potentially overwhelming complexity of dealing with enterprises in their entirety, the design of each aspect is often treated separately. Functional departments such as product design, research and development, production and distribution, human resources and strategic planning are created to design separate aspects of an enterprise somewhat independently.

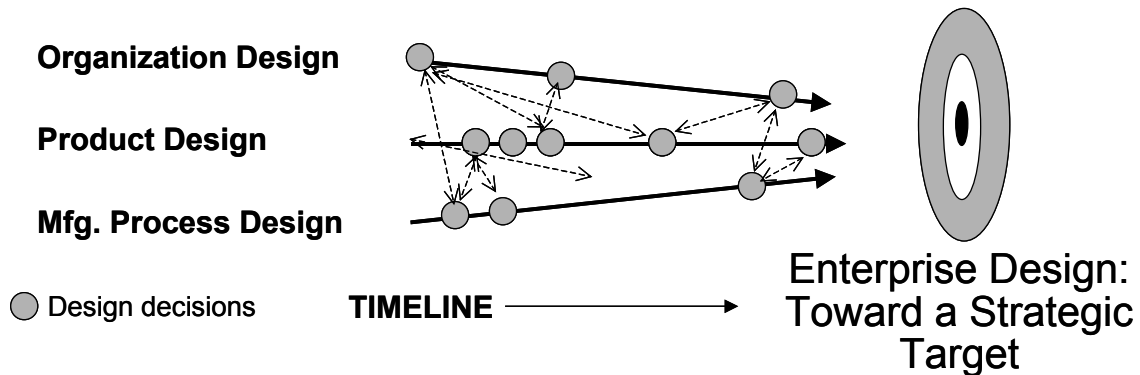


Figure 2. Enterprise design unifies organization design, product design and manufacturing process design. Decisions bind these disparate areas and integrate the enterprise as it moves toward a strategic target if an effort is made to incorporate information from the various aspects of the enterprise into the decisions.

Regardless of how many groups formulate designs/decisions, there are some similarities. Each decision formulation is equivalent in that courses of action are selected from competing alternatives (represented as design variables) to satisfy as much as possible a set of prioritized goals. These goals may be shared across decisions; for example a low-cost product may be a common enterprise goal that is affected by decisions across product design, production, and distribution. It is very likely that these decisions will be made both by different people and at different points in time. The concept of designing sustainable enterprises therefore becomes:

- Identifying and assessing the enterprise-wide effects of each local decision,
- Identifying and assessing the effects of other external decisions on the local decision at hand, and
- Making each decision to satisfy as many of the enterprise-wide goals as possible, while being as robust as possible to external decisions that are beyond the decision-maker's control.

In effect, formulating these decisions fosters the integration of enterprise design activities and thus the design of sustainable enterprises. However, in practice, it is necessary to recognize the limitations on the size of any one decision, based on Simon's concept of bounded rationality (Simon 1996), thus we advocate robust design, and especially the design of robust product platforms which may be particularized to produce a stream of mass customized products.

2 CHANGING INDUSTRIAL CHALLENGES

To understand what is happening in industry today, we focus on a "worst case scenario", a company whose business strategy is to lead the market with short-lived, relatively expensive products. For these companies, the business landscape has changed tremendously in the last five years due to competition from Asia. We believe that a similar – perhaps attenuated - trend will occur for longer-lived products. Also this changing climate will set the boundaries for those whose business strategies are to be fast-followers rather than leaders in innovation.

As shown in Figure 3, the VCR was introduced in 1973 and, at that time, very few units were produced and the selling price was high. Over the succeeding 25 years, new technology was introduced and new models were developed. Eventually the selling price dropped to the point at which this product has become a commodity – it is widely available and the profit margin shrank accordingly. With the VCR, there were many generations in which to improve and develop the product. The DVD was introduced about 1995 and it became a commodity in about 4 years. The RW-DVD was introduced in 2001 and became a commodity in 18 months.

This compaction of the product life cycle introduces substantial new challenges for the business community. These include:

- A reduced interval between the introduction of a product and the time it becomes a commodity (when the profit margin becomes low); this implies:
 - That there are at most 2-3 generations before the commoditization of the product so there is tremendous pressure to “get it right the first time”.
 - That as the product is being introduced, the second or third generation of the product must already be well into the design cycle.
- Multiple product configurations are desired/desirable (mass customization).
- The enterprise is distributed, and effective management of supply chains is essential
- Increased business risk. Several factors play a role in this increased risk:
 - Uncertainty in the economic environment and demand
 - The required substantial investment in inventory and manufacturing facilities before there is any return on investment
 - Investments in new technologies will need to be made well in advance of product development, well before any return on this investment is possible.

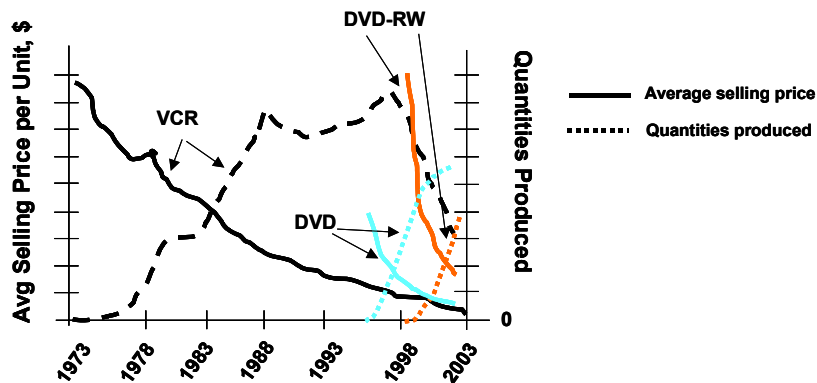


Figure 3. The commoditization of electronic goods. (Minderhoud 2003)

To be effective in this environment, a coherent design process, recognized across the firm is an advantage, and this design process is part of the design of the organization. We focus next on decision making and enterprise design.

3 DECISION MAKING IN ENTERPRISE DESIGN

Decisions are central to any design process. They serve as process-milestones and define the structure of a design process even as it is being compressed in real time. We identify two major types of decisions, selection decisions and compromise decisions (Mistree, Smith et al. 1990). Selection decisions indicate preference, based on multiple attributes, for one among several alternatives. With compromise decision, we seek the improvement of an alternative through modification. the improvement of an alternative through modification. Both selection and compromise decision may be coupled, networked or solved hierarchically. For each of these types of decisions, in order to support designers in their search for superior solutions, we have developed mathematical constructs, the selection and compromise Decision Support Problems, DSPs. As appropriate, these mathematical constructs may be coupled, networked or arranged in hierarchies.

The compromise DSP is a multiobjective decision model which is a hybrid formulation based on Mathematical Programming and Goal Programming (Mistree, Hughes et al. 1993). It is used to determine the values of design variables that satisfy a set of constraints while achieving a set of conflicting goals as well as possible. The mathematical form of the compromise DSP is shown in Figure 4. The system descriptors, namely, system and deviation variables, system constraints,

system goals, bounds and the deviation function are described in detail elsewhere (Mistree, Hughes et al. 1993) and are therefore this description is not repeated here. In the compromise DSP, multiple goals are combined in a deviation function either with Archimedean weightings or preemptively (lexicographically). The solution algorithm for Decision Support Problems is the Adaptive Linear Programming (ALP) Algorithm (Mistree, Hughes et al. 1993). Decision Support Problems and the ALP Algorithm are based on the notion of satisficing solutions, or solutions that are *good enough*, as opposed to *optimizing* solutions (Simon 1996). We believe that these rigorous mathematical decision tools are domain independent enough to be used in all phases of enterprise design and the mathematical commonality between decisions from the different domains will foster their integration into a common enterprise design timeline.

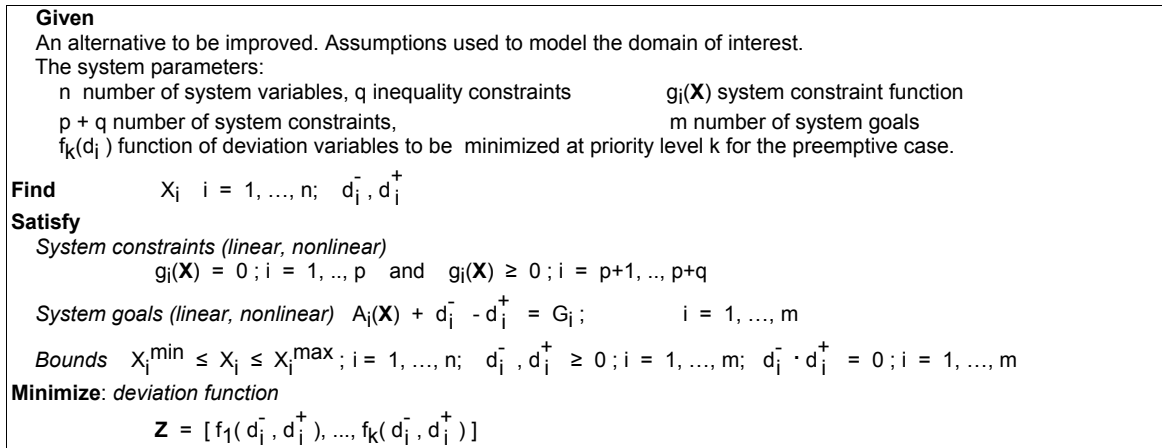


Figure 4. The mathematical form of the compromise Decision Support Problem (Mistree, Hughes et al. 1993)

We envision enterprise design as an extension of the formulation and solution of a compromise Decisions Support Problem(s). Our vision of the process of enterprise design has been developed with industry partners. To develop this approach, the pervasive decision-making process was established across the domains of designing, engineering and management and each element of our approach to enterprise design is developed without the constraints of any specific design context, and no element is dependent on knowledge from any specific design domain. Our approach to enterprise design is shown in Figure 5 (Peplinski 1997).

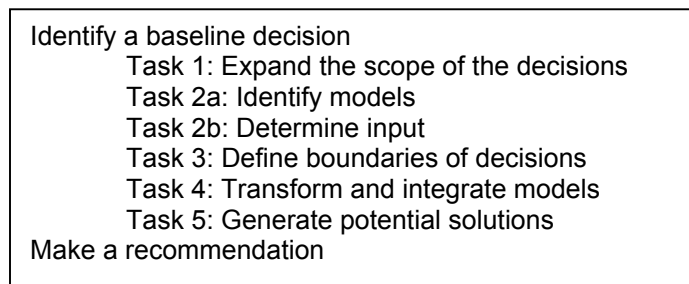


Figure 5: Steps of enterprise design (Peplinski 1997)

In enterprise design, a designer begins with a decision represented in terms of design variables, goals and constraints and models for analysis. This decision is likely geared toward local measures of merit and may not capture its enterprise-wide implications. Task 1 of the method is to explore the potential enterprise-wide impact of this baseline decision. This may be accomplished with various ideation methods, e.g., brainstorming, and with an awareness of

customer requirements. During Tasks 2a and 2b, modeling schemes are identified to quantify the relationships between the baseline design variables and any additional goals generated in Task 1. Tasks 2a and 2b are separated to emphasize that there may be a process of iteration; modeling techniques are modeled both by examining the goals (from the top down) and by examining design variables (from the bottom up). Inconsistencies may be resolved by iteration. In Task 3, we determine the limits on the size of the problem we choose to solve. Based on Simon's concept of bounded rationality, we do recognize that there are limitations of scope for any design decision. Further, because of empowerment it is not necessarily desirable to gather all decisions under centralized control, so appropriate boundaries for the decision must be chosen. In Task 4, to speed solution, it may be necessary to build surrogate statistical models and/or to incorporate robust goals into the decision model. In Task 5, the enterprise design decision is formulated mathematically in terms of a compromise Decision Support Problem and solved. Solution occurs through an in-depth process of exercising the formulation by changing parameters, testing assumptions, and exploring "what-if" scenarios. Sets of potential solutions are generated. In the end, one solution is selected that satisfies as many of the enterprise-wide goals as possible and one that is as robust as possible to the effects of external decisions outside of the designer's control. This solution is then the recommendation submitted for implementation. As we can see, enterprise integration is information driven; in our case it is driven by decisions.

Here we assume one particular type of decision making process – based on the use of Decision Support Problems. A major portion of organization design is selecting the decision-making process, thus we have pre-empted a large part of the organization design portion of enterprise design. Therefore our focus in this work is primarily on product design and manufacturing process design, specifically we focus on the design of product/manufacturing process platforms.

4 PRODUCT PLATFORMS

Producers must offer a variety of products in addition to enhanced system flexibility in order to remain competitive in the marketplace. In the last decade, one method for accomplishing this has been to develop families of products based on product platforms which can be modified or modules exchanged to create "mass customized" goods. In practice, product platforms provide the foundation for streams of products and serve to integrate manufacturing processes and organization around the common core of the product platform.

Wheelwright and Clark, 1992, suggest designing "platform projects" which are capable of meeting the needs of a core group of customers but are easily modified into derivatives through addition, substitution, or removal of features. Nelson, Parkinson and coauthors, 1999, define a product platform as, "a set of common components, modules or parts from which a stream of derivative products is created." The motivation behind platform design is to reduce part variety by standardizing components so as to reduce manufacturing variability and costs, which are enterprise considerations. The challenge is to synthesize parts that will be shared by multiple product variants while minimizing the loss of performance of the individual products that result from part sharing. A key element for the efficient production goods is platform design, (Anderson 1997). Uzumeri and Sanderson, 1995, emphasize standardization and flexibility as a means for enhancing product flexibility, as do McDermott and Stock, 1994; Collier, 1981; and Kota and Sethuraman, 1998. The Design for Variety work by Martin and Ishii, 1996 and Ishii and coauthors, 1995, provides qualitative guides for developing products that incur minimal variety cost. Chen and her coauthors, 1994, suggest designing flexible products which can be readily adapted in response to large changes in customer requirements by changing a small number of components or modules. Rosen, 1996; Siddique and Rosen, 2001; Dahmus and coauthors, 2000; and Gonzalez-Zugasti and Otto, 2000 advocate modular product architecture as a means of achieving product variety. This idea is further expanded by Simpson, 1995, who introduces open engineering systems are introduced; these are systems which are readily adaptable to changes in

their environment and enable producers to remain competitive through indefinite growth and continuous improvement of an existing technological base.

Simpson, 1998, classifies methods for designing platforms as top-down or bottom-up. Bottom-up design refers to the redesign and consolidation of existing products to create more competitive product families by reducing part variety and standardizing components, the top-down approach is used for the *de novo* creation of product variety. This is a useful distinction and we will expand on it in what follows.

4.1 Top Down Approaches to Product Platform Design

Our early efforts in the area of product platform design were based on the observation that robust designs are a means of improving system flexibility, (Rothwell and Gardiner 1988). They assert that robust designs have sufficient inherent design flexibility or "technological slack" to enable them to evolve into a design family of variants which meet a variety of changing market requirements. This is a form of top-down platform design characterized by an up-front decision to develop a product family based on a common core and thus reduce redesign cost.

Simpson and coauthors (Simpson, Chen et al. 1999) (Simpson, Maier et al. 2001) propose combining robust design techniques with multi-objective solution methods to explore platform concepts. This facilitates the synthesis and exploration of a common product platform concept that can be *scaled* into a family of products. Input to Simpson's Product Platform Concept Exploration Method is a set of overall product family design requirements; the output is a portfolio of products based upon a common product platform. Nayak and coauthors, 2000, follow a similar approach with their Variation-Based Platform Design Methodology, wherein commonalization is performed only on a set of carefully chosen (robust) variables; this somewhat reduces the effect of commonalization on product performance. Variations, extensions and applications of these methods include (Chen, Atul et al. 2000), (Conner (Seepersad), DeKroon et al. 1999) and (Hernandez, Allen et al. 2001).

Ericsson and Erixon, 1999, deal with platform design from a modularity standpoint by identifying a series of module drivers that form the base of Modular Function Deployment - a structured method for finding modular designs. Using state-of-the-art engineering design theory and methodologies, Tseng and Jiao, 1998, developed a method that addresses the functional, behavioral, and structural domains of product family design. Stone, Wood and Crawford, 1999, propose quantitative function models for developing product families based on the functional analysis of existing products, which in turn, are used to group products together.

Essentially, these are all "top-down" approaches to designing product platforms in which product family designs are developed *de novo*. There are two major limitations of top-down approaches - the first is related to the "extent" of commonality, the second, to the number of varied specifications. Regarding the first limitation, top-down approaches have been used to commonalize features or components across an entire product family (that is, the feature is made common to all the relevant product variants). It can also be difficult to anticipate demand for a new product. Commonalization can result in a significant loss of performance of individual products, and it is important to insure that the platform does not incorporate too many or too few products. With regard to the second limitation, in an effective platform strategy, we should be able to specify different levels of commonality for the various features and components of the

product family in order to reduce the impact of commonality on performance. Understanding these limitations of top-down design of product platforms, we turn to the bottom-up design of product platforms.

4.2 Standardization in a Portfolio of Products: Bottom-up Approaches to the Design of Product Platforms

In bottom-up design methods for product platforms, to the redesign and consolidation of existing products to create more competitive product families by reducing part variety and standardizing components. Anderson, 1997 suggests determining part commonality by analyzing Pareto plots on the parts that are used in greatest quantity, in the most products and which have consistent usage over many years. Kalpajian, 1997, suggests using group technology to form part families with members that use similar processes to prevent design proliferation. Stone, Wood and Crawford, 1999, propose quantitative function models for developing product families based on the functional analysis of existing products, which in turn, is used to group products together.

Siddique and Rosen, 2001, propose a Product Family Reasoning System for replacing an existing product family with an improved one. Specifically, they focus on the components in a product family, and their arrangements and relationships through configuration reasoning methods. They show that, for combinatorial problems in engineering, a discrete mathematical space can be developed that models a hierarchical arrangement of configurations (typically representing solutions to the combinatorial problem). The space will have a mathematical structure that can be exploited to enable the explicit representation of the feasible region of the space. They demonstrate this work on coffee maker and automotive platform design problems.

In general, the main advantage of bottom-up approaches is the ability to build on existing knowledge of parts and processes. The main disadvantage of bottom-up systems is that product rationalization is achieved after a number of products have been designed and manufactured, and the platform design is based on history rather than on the future.

Pedersen (Pedersen 1999) and (Pedersen, Allen et al. 2001) proposes an approach in which product platforms are designed hierarchically. Pedersen's work is based on the method of numerical taxonomy, (Sneath and Sokal 1973). Numerical taxonomy has primarily been used to classify biological organisms based on their overall similarity to (a) create groups for categorization and/or (b) study lineages and evolution. At first glance, it may seem that there is no similarity between evolution and product platform development. However, a product platform taxonomy can be constructed where each junction becomes a potential product platform, and where junctions at higher level taxa represents product platforms for an increasing number of products. Consequently, we can select product platforms by revealing the 'contours' of this apparently hierarchical organisation by means of investigating the similarities at various levels of assembly for a group of products anticipated to share many of the same features. We demonstrate this approach in the context of vessels to exploit marginal sub-sea oilfields. We build on information available about three types of ship-shaped vessels designed for three different field development applications; oil storage (FSU), oil production and storage (FPSO), and oil transportation (shuttle tanker). In addition to being designed for different applications, the vessels are large and complex (160 – 450 million USD); they are made to order systems (specification varies from location to location); they are fabricated in small numbers (in 1998 11 vessels where contracted world wide); and they share much of the same technology (especially the hull midship-sections) (Torma 1998).

In Figure 6, an *Assembly Taxonomy* is on the left - this is a hierarchical representation of construction assemblies – on the right is the *Standardization Taxonomy* corresponding to phylogenetic taxonomies which show lines of evolution. The assembly taxonomy can be understood when vessels themselves are partitioned. Note that evolutionists seek to reveal historical connections whereas 'standardisationists' are trying to reveal future ones. Hence, basing product platforms solely on existing designs may impose constraints that are historically anchored and are not applicable for contemporary / future designs.

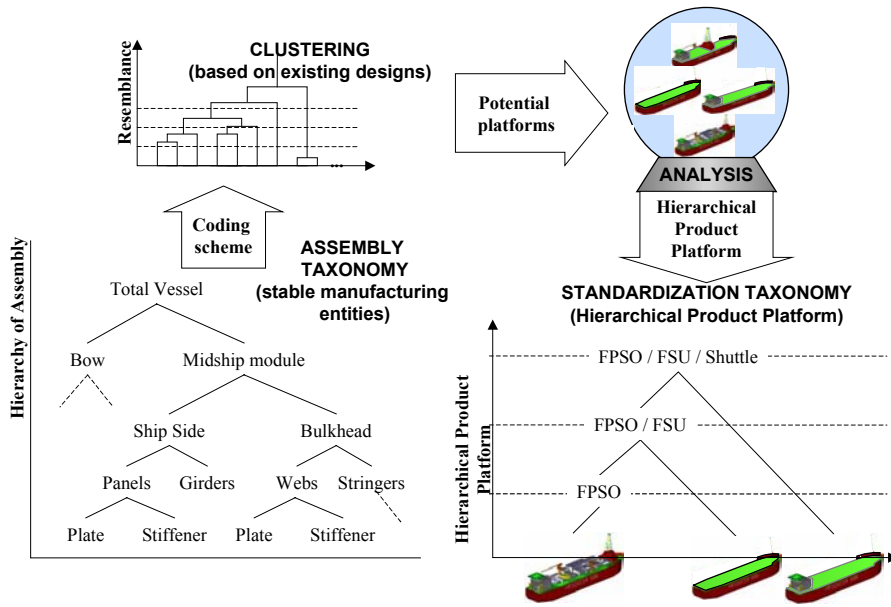


Figure 6. Numerical Taxonomy used to define product platforms.

Applying the methods of numerical taxonomy, we have clustered the brackets from the three midship sections of the various vessels based on their cross-section modulus I [m⁴] and their weights [kg]. The representation is called a dendrogram and the formation of clusters is determined by the Taxonomic Level (TL): TL = 0.50 yields only one cluster, TL = 0.25 yields 3 clusters, and so on. The choice of TL is subject to a designer's discretion based on the purpose of the taxonomy. In this context, the dendrogram is an attention-directing tool -- it is supposed to point a designer to where there might be a potential for standardisation. Based on knowledge and insight a designer chooses a TL, and the resulting clustering (representing future standard products) is then evaluated against technical and economic criteria. Based on the dendrogram, we propose a hierarchical set of product platforms for standardized shipsides and bulkheads (transverse as well as longitudinal) for all three vessel types, FPSOs, FSUs and Shuttle tankers, Figure 7. The hierarchy is represented as product platform levels, where Level 1 is a platform integral to all products in a study, Level 2 is a platform integral to all but one product, and so forth. Based on this we evaluated the technical and economic ramifications of using standardization on the three vessel types (a Level 1 platform). Further, we evaluated the technical and economic ramifications of using standardised modules for the FPSO and the FSU (a Level 2 platform) and thus are able to balance the costs and benefits of developing product platforms (Pedersen 1999),

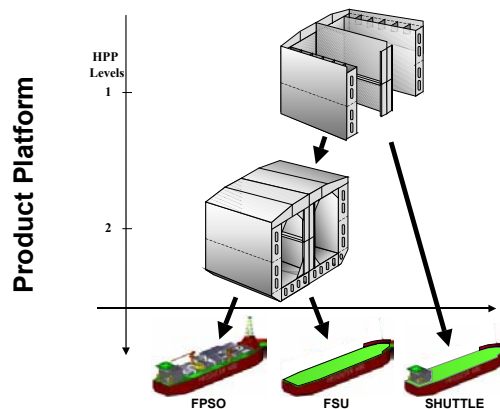


Figure 7. Product Platform Development Based on Market Demand (Pedersen 1999)

In this typical bottom-up approach to the design of product platforms, we relied on extensive knowledge about the product being designed and related products. A database of the dimensions of existing ships was available and recommendations were developed based on this knowledge – inevitably this ties future products to the past. Clearly there are both advantages and limitations of linking the future to the past in this way.

5 AN INTEGRATED PRODUCT OR MANUFACTURING PROCESS PLATFORM DEVELOPMENT STRATEGY BASED ON CONSTRUCTAL THEORY

A good platform strategy should allow us to specify different levels of commonality for the various features and components of the product family in order to reduce the impact of commonality on performance. Here, we formulate the design of platforms for customizable products as a problem of optimization of access in a geometric demand-space based on Constructal Theory (Bejan 2000). This approach allows us to develop systematically hierarchic product and process platforms with multiple levels of commonality.

Our approach to product platform design relies on the work of Herbert Simon (Simon 1996) and (Simon 1987). Herbert Simon argues that complex structures grow and evolve more efficiently when organized hierarchically. It is not assembly of components, *per se*, but hierarchic structure produced either by assembly or specialization that enables complex systems to adapt and respond to changes in the environment. This leads to our first two posits:

Posit 1 Potential for rapid adaptation and/or response is higher in complex systems when they are organized hierarchically.

Posit 2 In hierarchically organized systems, the high-frequency (short run) responses tend to be associated with the lowest levels of the hierarchy and the low-frequency (long run) ones with the interactions of these subsystems, i.e., the higher levels of the hierarchic organization.

A third posit is necessary, based on constructal theory (Bejan 2000).

Posit 3 Systems complexity results from a natural process of providing paths of easier access.

These three posits constitute the theoretic underpinning for developing an effective approach to manage complexity which can be used in designing product architectures for mass customization, that is customizing products to satisfy individual customer specifications while maintaining costs and speeds close to those of mass production (Pine II 1993). This, in turn, is one aspect of managing an enterprise system. From a designer's perspective, the advantages of constructal theory based product/process platform development method include:

- *Cost-Effectiveness.* The method offers a rigorous approach for balancing effectively the tradeoff between the various costs involved in product/process customization and linking market and design capability forecasts to design decisions and plans for product portfolios.
- *Suitable for small or large variety in the product specifications.* The method can be applied to a small number of product/process variants by formulating the space of customization as a discrete one or to a large number of variants - as is typically the case in mass customization - by formulating the space of customization as a continuous one.
- *Adaptability.* It is possible to alter product/process designs for portions of the space of customization without affecting other products of the family that are not in the same branch of the hierarchic construct.

The starting point to manage the complexity created by mass customization is, based on the basic principle of constructal theory, to determine the intersection of the demand and technically feasible designs and then to formulate a problem of optimization of access. We do so by

modeling the set of all feasible combinations of values of specifications that a manufacturing enterprise is willing to satisfy as a geometric space, which we call a space of customization. In this model, one particular combination of specifications is represented as a point in this geometric space. In addition, we refer to any generic approach embedded in a design for systematically achieving customizations (such as parametric design) as a mode for managing product variety. The modes for managing product variety can be seen as the “vehicles” by which we “travel” the space of customization.

Mathematically, let N be the number of quantitative parameters that define the requirements of a product. Let r_i represent these parameters, where $i=1, \dots, N$. Then the space of customization, M^N , is the set:

$$M^N \equiv \{(r_1, r_2, \dots, r_N)\}$$

It should be noted that a space of customization is not limited to continuous variables; it can be formed by continuous, discrete or mixed-valued requirements. Based on this mathematical definition of space of customization, a product i can be represented by a unique specification of product requirements in an N -dimensional space of customization, i.e., a vector $r_i(r_{i1}, \dots, r_{iN})$:

$$r_i = r_{i1}\hat{e}_1 + r_{i2}\hat{e}_2 + \dots + r_{iN}\hat{e}_N$$

where \hat{e}_k is the unit vector in each direction k of the space of customization. Using this representation of a product, the derivation of a new product, r_j , based on an existing product, r_i , is referred in this work as a “product customization,” represented by a vector in the space of customization:

$$\Delta r_{ji} = \sum_{k=1}^N (r_{jk} - r_{ik})\hat{e}_k = \sum_{k=1}^N \Delta r_{jki}\hat{e}_k$$

This representation of product customization is illustrated in Figure 8. We refer to generic approaches to “access” points in the space of customization, i.e., to achieve product customizations from a baseline design, as shown in Figure 8, as modes for managing product customization. A mode for managing product customization is any generic approach in a product design or its manufacturing process for systematically achieving a product customization.

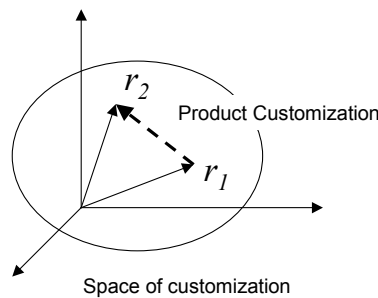


Figure 8. Product platform development as a problem of access in a geometric space

Common modes for managing product customization include, but are not limited to, modular design, platform design and standardization, robust design, and dimensional customization. With the introduction of these definitions, the problem of designing a platform for customizable products/processes becomes an effort to define a baseline set of components (the product platform) from which we can access all the points of a space of customization through the systematic use of a series of modes for managing customization, and optimizing some given objective (e.g., cost, profit, customer service, etc). Following hierarchic systems theory, we propose to solve this access problem through the hierarchic application of modes for managing

variety. Our approach to do so is based on constructal theory developed by Adrian Bejan (Bejan 2000).

Bejan’s constructal theory embodies the notion that the hierarchic organization we observe in nature is the result of a sequential optimization of access. For example, the formation of tree networks (like blood vessels) is explained as a hierarchic process of optimization: the shape that optimizes “access” at the most elementary volume occurs first, followed by an assembly of these innermost “volumes” into a second – larger - shape, which in turn are assembled into a third volume, and so on. This sequential process continues until all relevant volume is connected, as shown schematically in Figure 9.

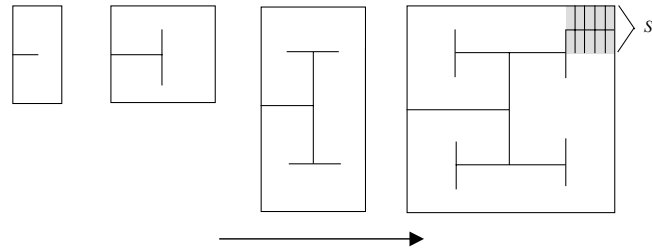


Figure 9 – Organization in nature as a process of access optimization (adapted from (Hernandez 2001))

Using these concepts, the problem of designing customizable products using multiple modes for managing product variety can be formulated as a mathematical optimization problem as: how to access in the most effective manner all the points of a space of customization by combining a limited number of modes for managing product variety?

Mathematically, the application of these principles yields the following formulation of the access problem as multi-stage optimization problem, where each stage of the optimization problem corresponds to a level of the hierarchic utilization of modes for managing product customization:

Given	An N -dimensional space of customization $M^N \equiv \{(r_1, r_2, \dots, r_N)\}$ n Modes for Managing Product Variety k Stages
Find	The decision variables for each stage $\Delta r(1), \Delta r(2), \dots, \Delta r(k)$ where $\Delta r(i) = [\Delta r_1(i), \Delta r_2(i), \dots, \Delta r_N(i)]$
Satisfy	Constraints $\Delta r_j(i+1) \geq \Delta r_j(i) \quad j=1, \dots, N; \quad i=1, \dots, k-1$ Bounds $\Delta r_{j \min} \leq \Delta r_j(i) \leq \Delta r_{j \max}$
Minimize	An objective function f

In the preceding formulation, $\Delta r(i)$ represents a vector of N decision variables that define the organization of the space of customization (the size and shape of the space elements) at stage i :

$$\Delta r(i) = [\Delta r_1(i), \Delta r_2(i), \dots, \Delta r_N(i)]$$

The constraint $\Delta r_j(i+1) \geq \Delta r_j(i)$ in the above formulation is required to enforce the sequential solution to be a hierarchic assembly (Hernandez 2001).

We have demonstrated this approach for the design of product platforms of electric motors, pressure vessels, and beverage merchandisers (Hernandez 2001), (Hernandez, Allen et al. 2002), (Carone 2003) and (Carone 2003; Williams 2003). However, here we discuss the design of a manufacturing process platform. This example is based on the process of manufacturing

customized hearing-aid shells (Williams, Panchal et al. 2003) and Williams, 2003. Consider a manufacturer of customized hearing aid shells who seeks a competitive advantage over other manufacturers through offering personalized hearing aids. The manufacturer has developed the following plan to customize the hearing aid shells: after consulting with a doctor, a clay impression of the patient's ear canal is created. Using 3D laser scanning technology, the impression is digitized and converted into a CAD file. The CAD file is then modified to model a personalized hearing aid shell and individualized hearing aid shells are to be manufactured using the process of fused deposition modeling (FDM), a type of rapid prototyping (Stratasys 2003).

Each hearing aid shell consists of a hollow, negative impression of the customer's ear canal. The exterior geometry is unique to the customer, however the internal void in the part must be large enough to house a common set of electronic components. For this reason, the majority of the hearing aid shells are of the same overall dimensions. For the problem of determining a process platform to make these hearing aid shells, each hearing aid shell is approximated by a general platform design of a truncated elliptical cone, Figure 10. This generic hearing aid shell can be thought of as a hearing aid shell platform. This example is based on an actual current product line produced in a collaboration between Siemens and Phonak.

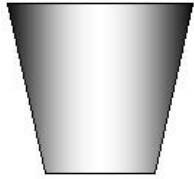
 <p>GENERIC HEARING AID SHELL MODEL</p>	Upper Ellipse Minor Diameter 10.72 mm	Upper Ellipse Major Diameter 18.7 mm
	Lower Ellipse Minor Diameter 6.36 mm	Lower Ellipse Major Diameter 10.5 mm
	Part Height 21.78 mm	Wall Thickness 1.11 mm
	Volume of Material 229 mm ³	

Figure 10. Hearing Aid Shell Average Dimensions (Williams, Panchal et al. 2003)

Although the plan for customizing the product has been developed, the specific plan for configuring the manufacturing process must be determined. (Specifically, the manufacturer must determine an appropriate batch size, layer thickness, road width (width of scanning beam), type of FDM machine and appropriate number of machines for specific levels of product demand. These choices affect three desirable, but conflicting objectives: minimization of production cost, minimization of production time and maximization of the quality of each part. The goals of minimizing production cost and time clearly are a part of organization design and product design as well as manufacturing process design, the examples are formulated by considering labor costs and equipment costs as well as technical parameters. The goal of quality maximization certainly affects product design as well as manufacturing process design. Further information about modeling these objectives is available in the Appendix. It is clear that for this example, enterprise design considerations have been considered. In what follows, we follow the steps of enterprise design suggested in Figure 5.

The manufacturer faces a serious production constraint, the parts must be completed no more than one week from the date they were ordered. Further, the marketing department assures the manufacturer that the demand for customized hearing aid shells is highly non-uniform. Therefore the manufacturer needs to design a manufacturing process platform in which certain process parameters are commonalized across a range of capacity so that the production process will not have to be drastically reconfigured for changes in demand. Possible modes of managing the manufacturing process variety are shown in Figure 11. Details about the variables and the mathematical formulation of this problem are given in the Appendix and in Williams, 2003. A general method for the iterative solution of this problem is given in Figure 12.

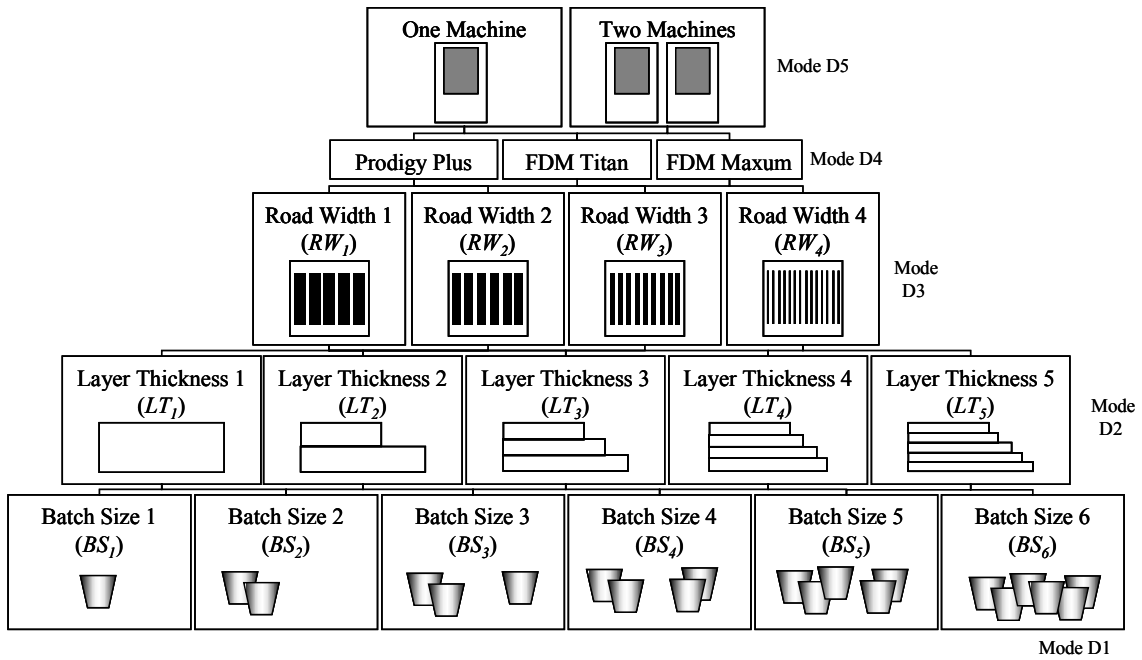


Figure 11. Hierarchic organization of the modes for managing process customization for the hearing aid example (Williams 2003)

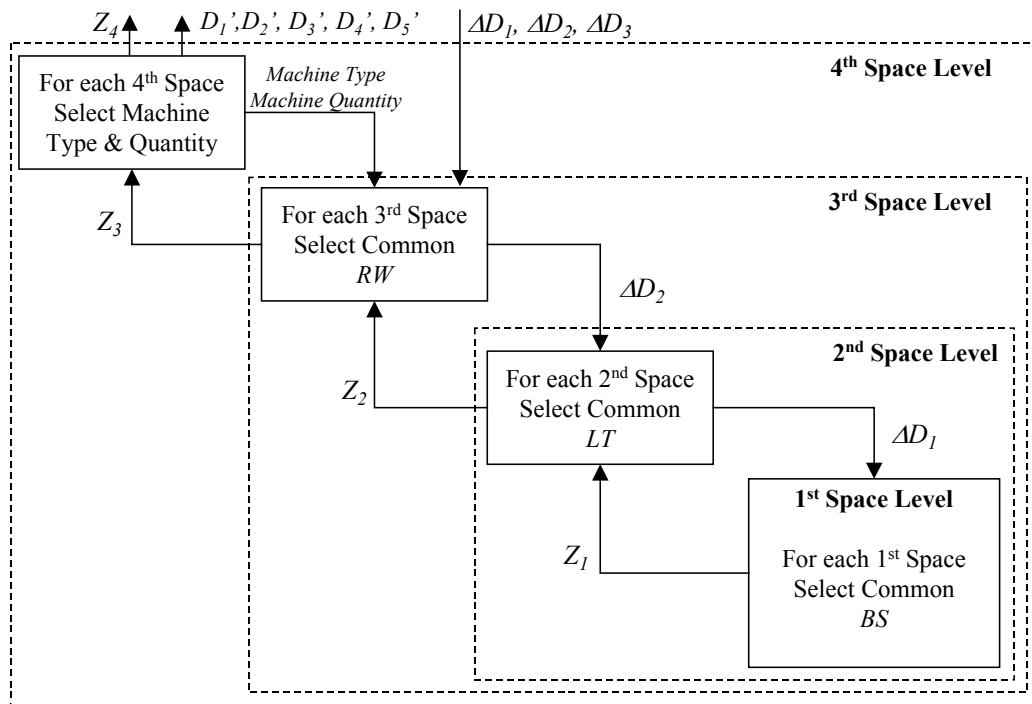


Figure 12. General iterative solution scheme for designing the process platform for manufacturing hearing aid shells (Williams 2003)

The best combination of the first three modes of managing process customization for each machine is presented in Figure 13. The maximum capacity in the table represents the maximum number of parts per day that each machine combination can feasibly build. A sample of the mapping between the process platform and the parameters for one FDM machine is given in the Appendix in Figure A.6.

Machine Type	Machine Quantity	ΔD_1 (ppd)	ΔD_2 (ppd)	ΔD_3 (ppd)	t_{avg} (hrs)	C_{avg} (\$)	Q_{avg} (mm)	Max Capacity	$E[U(D)]$	d^-	d^+
Prodigy Plus	1	5	44	44	100.65	13,252.83	0.5345	415	0.7325	0.2674	0
	2	5	125	125	92.18	24,667.95	0.5368	865	0.6085	0.2915	0
FDM Titan	1	5	93	80	88.82	14,856.97	0.4664	670	0.7623	0.2376	0
	2	5	440	440	62.59	23,888.68	0.4692	1000	0.6903	0.3097	0
FDM Maxum	1	5	21	21	47.42	11,659.32	0.5090	1000	0.8360	0.1640	0
	2	5	28	28	26.90	18,274.22	0.4760	1000	0.8042	0.1958	0

Figure 13. Range of commonality of the modes of managing process variety for each machine combination of the hearing aid example

Observations of the results of this analysis reveal a number of insights into the consistency of the formulation of this problem:

- Adding an additional machine to the process increases the maximum capacity of each machine and lowers the total time required to produce each level of demand. The cost, however, increases significantly due to the cost of an additional machine and its associated maintenance.
- The average time required to build a certain capacity is much larger for the Prodigy Plus than for the FDM Titan and Maxum. This is consistent with the fact that the lower-end machines have a much slower scan speed than that of the high-end machines. This slower scan speed increases the build time, and thus increases the operation and labor costs of the machine. As a result, the tradeoff between a machine's cost and its performance is not as significant as expected.
- The average quality of the higher-end machines is higher than the lower-end machines. The ability of the FDM Maxum to produce parts faster

The use of this method provides a designer with the ability to synthesize multiple modes of managing process customization hierarchically. Overall, this approach is well suited to enterprise design. It makes it possible to leverage existing technology and infuse new technology into the product or process. Also it makes it possible to choose to leave the maximum possible freedom for future designers – of both products and manufacturing processes.

6 ENTERPRISE DESIGN: WHAT STILL NEEDS TO BE DONE

Although the examples are platform design of products and a manufacturing process and decision formulation retains its product design flavor. There appear to be no intrinsic barriers to implementing this approach across organization design and more extensively across manufacturing process design decisions. At the heart of our approach to the design of complex enterprise systems is the compromise Decision Support Problem. With the compromise DSP, decisions can be formulated mathematically and quantitative solutions can be identified in a rigorous and repeatable manner. In addition, the compromise DSP has been subjected to years of successful applications in the engineering design community. Formulating enterprise engineering design problems rigorously and consistently across the different domains of the enterprise dissolves barriers and makes it possible to more closely integrate and manage the enterprise itself.

With the inevitable increase in computing power, it becomes possible both to gather more information across an enterprise and to compute answers to larger problems. We will be able to push the boundary of bounded rationality. Therefore, enterprise design is becoming more feasible. At the same time, enterprise design is becoming more necessary as intense competition

makes it important for enterprises to become more efficient and to design concrete strategies for success.

In this paper, we record our journey into enterprise design – it is clear that our destination lies in the future and there is much to be done along the way. We invite you to join us on our journey.

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Gabriel Hernandez, PhD 2001, Platform Design for Customizable Products as a Problem of Access in Geometric Space, Siemens Westinghouse.
Kjartan Pedersen, PhD 1998, Designing Platform Families: An Evolutionary Approach to Developing Engineering Systems, Kvaerner Oil & Gas FD.
Jesse Peplinski, PhD 1997, Enterprise Design: Extending Product Design to Include Manufacturing Process Design and Organization Design, Statistical Design Institute.
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Zahed Siddique, PhD 2000 Methods of Product Platform Synthesis, Assistant Professor, University of Oklahoma
Timothy Simpson, PhD 1998, A Concept Exploration Method for Product Platform Design, Currently Associate Professor, Pennsylvania State University.
Christopher Williams, MS 2003 Platform Design for Customizable Products and Processes with Non-Uniform Demand, continuing at Georgia Tech for a PhD.

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APPENDIX
Details on Designing a Process Platform for the Manufacture of Hearing Aid Shells
From Section 5

NOMENCLATURE

C_{batch}	Cost of building a single batch of hearing aid shells; \$
C_{labor}	Cost of labor to operate FDM machines; \$/hr
$C_{machine}$	Cost of purchasing FDM machine; \$
C_{maint}	Annual cost of maintaining FDM machine; \$
$C_{material}$	Cost of FDM material; \$/mm ³
D_d	Demand of hearing aid shells per day
d_i^-, d_i^+	Deviation variables
f	Objective function
f_i	The value of the objective function at the end of stage i
h	Part height; mm
k	Scaling constant of u-cDSP
l	Length of hearing aid shell; mm
N_b	Number of batches to manufacture hearing aid shells
N_l	Number of layers of hearing aid shell
N_{pb}	Number of parts per batch
N_{ppy}	Number of hearing aids produced in one year
N_{setup}	Number of setups of FDM machine
Q	Quality of hearing aid shell; mm
r_i	The i^{th} attribute of a concept
t_{avg}	Average build time of the family of hearing aid shells; sec
t_{base}	Time to build the base of the part; sec
t_{batch}	Total time to build a batch of hearing aid shells; sec
$t_{boundary}$	Time to draw outer and inner boundaries of layer; sec
$t_{cycletime}$	Total time to manufacture a hearing aid shell capacity requirement; sec
t_{fill}	Time to fill the inner portion of the layer via raster scan; sec
t_l	Time to build each layer of hearing aid shell; sec
t_{lower}	Time to move down z-axis one layer thickness; sec
t_s	FDM machine setup time; sec
t_{supp}	Time to draw the support material for this layer; sec
$U(X)$	Overall, multi-attribute utility function
$u_i(A_i(X))$	Utility function for each goal
$V_{material}$	Volume of material used to build one hearing aid shell; mm ³
V_{ss}	Scan speed of FDM machine; mm/s
w_l	Width of lower ellipse diameter
w_{road}	Road width of FDM deposit; mm
w_u	Width of upper ellipse diameter; mm
Z	Deviation function
ΔD	Range of capacity in the hearing aid shell space of capacity
Δr	A derived product realization in the market space
μ	Mean of demand (Gaussian distribution)
σ	Standard deviation of demand (Gaussian distribution)

Details about the mathematical formulation of the problem of designing a platform to manufacture hearing aid shells, discussed in Section 5, are presented in this appendix and in (Williams 2003). Three types of machines are capable of building hearing aid shells. Their capabilities are given in Table A-1. The maximum number of parts is estimated with the knowledge of the average hearing aid dimensions, Figure 10, and the dimension of the build volume of each machine.

Table A.1 – Machine process characteristics (Stratasys 2003)

Machine	Max. Parts	Scan Speed	Layer Thickness	Road Width	Cost
Prodigy Plus	234	64 mm/s	0.178 – 0.33 mm	0.19 – 0.21 mm	\$70,000
Titan	818	127 mm/s	0.24 – 0.26 mm	0.19 – 0.21 mm	\$210,000
Maxum	1703	254 mm/s	0.127 – 0.25 mm	0.193 – 0.965 mm	\$260,000

Production time model

Note that the variables are defined in the nomenclature section of this Appendix. The total time to build a batch of hearing aid shells with FDM is approximated as:

$$t_{batch} = t_s + (t_l N_l + t_{base}) N_{pb} \quad [A.1]$$

The number of layers (N_l) needed to complete a part is the quotient of the height (h) of the part and the layer thickness (t_{layer}).

$$N_l = \frac{h}{t_{layer}} \quad [A.2]$$

The time to build each layer is approximated as:

$$t_l = t_{lower} + t_{boundary} + t_{fill} + t_{supp} \quad [A.3]$$

t_{lower} represents the time for the deposition head to move down one layer. For most FDM machines, the nozzles are cleaned after the deposition of two layers; it is estimated that this cleaning process takes 10 seconds to complete. To calculate the amount of lowering time for one layer, this cleaning time is spread over each layer; thus t_{lower} is estimated to be 5 seconds.

The time required to draw the boundary of the average part is proportional to the length of the contour. Since the shape of a hearing aid model is represented as a cone, the average circumference is approximated as the product of the average length and width of the model:

$$t_{boundary} = \frac{[(l_u + l_l)/2][(w_u + w_l)/2]}{V_{ss}} \quad [A.4]$$

where u and l are subscripts representing the upper and lower ellipse dimensions of the cone, and V_{ss} represents the scan speed of the machine.

The time to fill the boundaries of each layer is calculated as:

$$t_{fill} = \frac{\text{Cross Sectional Area}}{\text{Road Width} * \text{Scan Velocity}} = \frac{(t_s - 2w_{road})(l + w)}{w_{road} V_{ss}} \quad [A.5]$$

where t_s is the shell thickness of the hearing aid shell, w_{road} is the road width for the fill, and l and w are the average length and width of the shell model.

T_{supp} is the time required to build the support structure for each layer. Support structure is needed because of the overhang present in the hearing aid model. For this example, the time to build the support material is estimated as 25% of the time required to fill each layer (Equation A.6).

$$t_{supp} = 0.25t_{fill} \quad [A.6]$$

While it is naïve to assume that the time to build each layer will be the same for each layer of each hearing aid shell, it is understood that this will not significantly influence the overall results.

The final portion of Equation A.1 yet to be explained is the time required to build the base of each part. Generally, four layers of support material are laid down to provide a solid build foundation for each part. The time required to build these supports is:

$$t_{\text{base}} = 4 \left(\frac{\left(\frac{\text{Support Area}}{\text{Road Width}} \right)}{\text{Scan Velocity}} \right) = 4 \left(\frac{\left(\frac{l_w}{w_{\text{road}}} \right)}{V_{\text{ss}}} \right) \quad [\text{A.7}]$$

Modeling the cost of this production process is heavily dependent on production time. With a manner in which to model production time established, the cost model is now presented.

Production Cost Model

The cost of building a single batch of parts is estimated as:

$$C_{\text{batch}} = (V_{\text{material}} C_{\text{material}}) N_{\text{pb}} + (C_{\text{labor}} + C_{\text{operation}}) t_{\text{batch}} + \left[\frac{(C_{\text{maint}} + C_{\text{machine}}) N_{\text{machine}}}{N_{\text{ppy}}} \right] N_{\text{pb}} \quad [\text{A.8}]$$

For this example, it is assumed that all parts will be made with ABS plastic. The hourly and annual fees for labor, operation, and maintenance are estimates of actual costs.

Quality Model

For many products, quality is a subjective metric. When manufacturing with rapid prototyping, quality can be quantified by the “stair stepping” effect – the inability to produce smoothed surfaces in the z-direction due to the layer-based additive manufacturing method. For the purpose of this example problem, the quality metric is dependent on the selection of the layer thickness (LT) and road width (RW) process parameters. The manner in which different road widths and layer thicknesses affect the “stair stepping” effect is shown in Figure A.1.

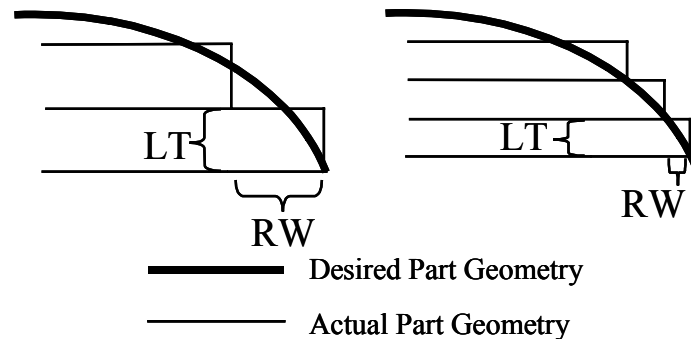


Figure A.1. The effects of different road widths and layer thicknesses affect quality (Williams 2003)

As can be seen, the best quality is achieved with a minimal layer thickness and minimal road width. Without an approximation of the curvature of the surface of each hearing aid shell, the quality metric can be simply modeled as the sum of these two process variables. The engineer would like to reduce this value of the quality metric for obtaining a good quality part. The quality metric, Q , is determined by the equation:

$$Q = t_{\text{layer}} + w_{\text{road}} \quad (\text{mm}) \quad [\text{A.9}]$$

This method of quantifying quality is the most relevant for this application. Ideally one would compare the error between the actual part and the model via an exact representation of the curvature of the hearing aid.

Modeling Demand

The capacity requirement for the production process of this example changes frequently. As such it is beneficial to model demand information in units of demand per day. This simulates an arrival rate of demand to the rapid prototyping machines. Given the batch size and the necessary capacity requirement, one can calculate the number of batches required to meet this demand in one week's time:

$$N_b = \frac{7D_d}{N_{pb}} \quad [A.10]$$

In order to deal with the queuing and batching of the arriving parts, the concept of "wait time" is introduced. The wait time, t_w , is the manner in which the machine's creation of batches are modeled. t_w is the amount of time the manufacturer waits before beginning the production of a single batch. As time passes, more and more parts arrive at the workstation (as a function of demand per day, D_d):

$$t_w = \frac{N_{pb}}{D_d} (24 * 3600) \text{ (s)} \quad [A.11]$$

Through the substitution of these equations into the cost and time equations previously developed, demand and the number of batches are related to time and cost.

Constraints

In order to meet the requirements of the problem statement, the manufacturer imposes four constraints to be certain that:

- (1) the parts are produced within a week of their order arrival
- (2) the batch size is not greater than the maximum allowed in the machine
- (3) the cost of the process is not too expensive
- (4) the parts are of acceptable quality

Establishing the objective function

The focus in this particular step is to define the necessary objective functions. The calculation of average time for the entire process family is based on the amount of time to build one batch, t_{batch} , of a particular capacity requirement from Equation A.1. The average build time of the process family is calculated to be:

$$t_{avg} = \frac{\left(\sum_{i=D_{min}}^{D_{max}} t_{batch,i} N_{batch,i} \right) + \sum_{j=1}^{N_{setup}} t_{setup,j}}{D_{max} - D_{min}} \quad [A.12]$$

where D_{max} and D_{min} represent the upper and lower bounds of the capacity space respectively. This build time metric also includes a time penalty, t_{setup} , of 30 min. This penalty is accrued for each different arrangement of process parameters, N_{setup} , across the process family.

The calculation of the average cost of the process family is performed in a similar fashion. From the cost per batch of a single capacity requirement, C_{batch} (Equation A.8), the average cost is calculated to be:

$$C_{avg} = \frac{\left(\sum_{i=D_{min}}^{D_{max}} C_{batch,i} N_{batch,i} \right) + \left(\sum_{j=1}^{N_{setup}} C_{setup,j} \right)}{D_{max} - D_{min}} \quad [A.13]$$

A penalty for the setup of a different arrangement of process parameters is also added to this metric with C_{setup} , which is equal to \$50.

Finally, the average quality of the process family is calculated using Equation A.9, the quality of a single part:

$$Q_{avg} = \frac{\sum_{i=D_{min}}^{D_{max}} Q_i}{D_{max} - D_{min}} \quad [A.14]$$

Unfortunately, these objectives are inherently contradictory. One cannot maximize one without minimizing another (and vice versa). For example, to maximize the quality, one would set the layer thickness and road width parameters to a minimum. This however, would drastically increase material costs as well as production time. In order to find the best compromise for these tradeoffs among minimization of production cost, minimization of production time and maximization of quality, an engineer must define an expected utility function. Information about the derivation of the utility functions is available in (Williams 2003)

Based on customer preferences, *constants*, k , are determined to determine the relative importance of the various goals. The k -values are used in concert with the individual utility functions for the determination of the overall expected utility, $E[U(D_d)]$.

$$U(D_d) = k_c u(C) + k_t u(t) + k_q u(Q) \quad [A.15]$$

The goal of each objective is to maximize the expected utility value of each individual utility function (i.e., for the value to reach the ideal value, 1).

$$E[u(C_i)] + d_{C_i}^- + d_{C_i}^+ = 1 \quad [A.16]$$

$$E[u(t_i)] + d_{t_i}^- + d_{t_i}^+ = 1 \quad [A.17]$$

$$E[u(q_i)] + d_{q_i}^- + d_{q_i}^+ = 1 \quad [A.18]$$

The deviation function for the multi-attribute utility function of each decision stage, therefore, is to minimize the deviation of the expected utility function from the ideal value:

$$Z_i = 1 - E[U_i(D_d)] = \sum_j^3 k_j (d_j^- + d_j^+) \quad [A.19]$$

In order to formulate the decision for each stage within the range of managing each mode of managing customization, it is necessary to specify a value of the process parameters which satisfies production constraints and also minimized cost and time, and maximizes quality, a detailed analysis is necessary to accomplish this, decision "0", Figure A.2 gives the formulation of this problem. Decision "0" must be solved at each of the decision stages.

<i>Given:</i>	Capacity Requirement; D_d (parts /day) Machine Type; Prodigy Plus, FDM Titan, or FDM Maxum Machine Number; N_{mach}
<i>Find:</i>	Batch Size; N_{pb} Layer Thickness; t_{layer} Road Width; w_{road} Deviation variables; d_i^- and d_i^+
<i>Satisfy:</i>	Bounds: $0 \leq N_{pb} \leq N_{pb,max}$ $t_{layer,min} \leq t_{layer} \leq t_{layer,max}$ $w_{road,min} \leq w_{road} \leq w_{road,max}$ Constraints: $t_{cycletime} \leq 1 \text{ week}$ $d_i^-, d_i^+ \geq 0$ $d_i^- \cdot d_i^+ = 0$ Goals: $E[u(C)] + d_c^- - d_c^+ = 1$; $E[u(t)] + d_t^- - d_t^+ = 1$; $E[u(Q)] + d_q^- - d_q^+ = 1$
<i>Minimize:</i>	$Z = 1 - E[U(D)] = 1 - \left[k_c(d_c^- - d_c^+) + k_t(d_t^- - d_t^+) + k_q(d_q^- - d_q^+) \right]$

Figure A.2 Decision formulation for “Decision 0” of hearing aid example (Williams 2003)

With the general formulation of the utility based compromise DSP for this problem presented, the formulation of the compromise DSPs for each individual stage are given in Figures A-3, A-4, A-5 and A-6.

<i>Given:</i>	The one-dimensional capacity space Mode D1: Customization of the Batch Size
<i>Find:</i>	The value of the decision variable ΔD_1 Deviation variables, $d_c^-, d_c^+, d_t^-, d_t^+, d_q^-, d_q^+$
<i>Satisfy:</i>	Bounds: $0 \leq \Delta D_1 \leq 880$ Constraints: $t_{cycletime} \leq 1 \text{ week}$ $d_i^-, d_i^+ \geq 0$ $d_i^- \cdot d_i^+ = 0$ Goals: $E[u(C)] + d_c^- - d_c^+ = 1$; $E[u(t)] + d_t^- - d_t^+ = 1$; $E[u(Q)] + d_q^- - d_q^+ = 1$
<i>Minimize:</i>	$Z_1 = 1 - E[U(D_d)] = 1 - \left[k_c(d_c^- - d_c^+) + k_t(d_t^- - d_t^+) + k_q(d_q^- - d_q^+) \right]$

Figure A-3. Decision formulation for the first space element (Williams 2003)

<i>Given:</i>	The one-dimensional capacity space Mode D2: Standardization of Layer Thickness The value of ΔD_1
<i>Find:</i>	The value of the decision variable ΔD_2 Deviation variables, $d_c^-, d_c^+, d_t^-, d_t^+, d_q^-, d_q^+$
<i>Satisfy:</i>	Bounds: $0 \leq \Delta D_2 \leq 880$ Constraints: $\Delta D_1 \leq \Delta D_2 \leq 880$ $t_{cycletime} \leq 1 \text{ week}$ $d_i^-, d_i^+ \geq 0$ $d_i^- \cdot d_i^+ = 0$ Goals: $E[u(C)] + d_c^- - d_c^+ = 1$; $E[u(t)] + d_t^- - d_t^+ = 1$; $E[u(Q)] + d_q^- - d_q^+ = 1$
<i>Minimize:</i>	$Z_2 = 1 - E[U(D)] = 1 - \left[k_c(d_c^- - d_c^+) + k_t(d_t^- - d_t^+) + k_q(d_q^- - d_q^+) \right]$

Figure A-4. Decision formulation for the second space element (Williams 2003)

Given:	The one-dimensional capacity space Mode C3: Standardization of Road Width The value of ΔD_1 , The value of ΔD_2
Find:	The value of the decision variable ΔD_3 Deviation variables, $d_C^-, d_C^+, d_t^-, d_t^+, d_Q^-, d_Q^+$
Satisfy:	Bounds: $0 \leq \Delta D_3 \leq 880$ Constraints: $\Delta D_2 \leq \Delta D_3 \leq 880$ $t_{cycletime} \leq 1 \text{ week}$ $d_i^-, d_i^+ \geq 0$ $d_i^- \cdot d_i^+ = 0$ Goals: $E[u(C)] + d_C^- - d_C^+ = 1$; $E[u(t)] + d_t^- - d_t^+ = 1$; $E[u(Q)] + d_Q^- - d_Q^+ = 1$
Minimize:	$Z_3 = 1 - E[U(D)] = 1 - [k_C(d_C^- - d_C^+) + k_t(d_t^- - d_t^+) + k_q(d_q^- - d_q^+)]$

Figure A-5. Decision formulation for the third space element (Williams 2003)

Given:	The one-dimensional capacity space Mode C4: Commonalization of Machine Type Mode C5: Altering the Number of Machines The value of ΔD_1 , The value of ΔD_2 , The value of ΔD_3
Find:	The value of the decision variable ΔD_4 The location of each cutoff point, $D_1', D_2', D_3', D_4', D_5'$ Deviation variables, $d_C^-, d_C^+, d_t^-, d_t^+, d_Q^-, d_Q^+$
Satisfy:	Bounds: $0 \leq \Delta D_4 \leq 880$ Constraints: $\Delta D_3 \leq \Delta D_4 \leq 880$ $t_{cycletime} \leq 1 \text{ week}$ $d_i^-, d_i^+ \geq 0$ $d_i^- \cdot d_i^+ = 0$ Goals: $E[u(C)] + d_C^- - d_C^+ = 1$; $E[u(t)] + d_t^- - d_t^+ = 1$; $E[u(Q)] + d_Q^- - d_Q^+ = 1$
Minimize:	$Z_4 = 1 - E[U(D)] = 1 - [k_C(d_C^- - d_C^+) + k_t(d_t^- - d_t^+) + k_q(d_q^- - d_q^+)]$

Figure A-6. Decision formulation for the fourth space element (Williams 2003)

A sample of the mapping between the process platform and parameters for one FDM Maxum is shown in Figure A-6 on the next page.

Capacity	Batch Size	Road Width (mm)	Layer Thickness (mm)	Cost (\$)	Time (s)	Quality (mm)	E[U]
120	727	0.19	0.15	8765.42	91139	0.340	0.9550454
125	727			8765.42	91139	0.340	0.9550454
130	761			8874.12	94643	0.340	0.9529377
135	777			8984.78	98215	0.340	0.9507826
140	811			9143.48	103520	0.340	0.9476174
145	845		0.16	9033.32	99396	0.350	0.9463987
150	862			9138.04	102762	0.350	0.9443531
155	878			9242.71	106128	0.350	0.942301
160	912		9395.66	111234	0.350	0.9392265	
165	946		0.17	9279.52	106897	0.359	0.938126
170	962			9378.99	110083	0.359	0.9361713
175	979			9478.41	113267	0.359	0.9342107
180	1013		9626.30	118198	0.359	0.9312167	
185	1047		0.18	9506.08	113715	0.369	0.9301953
190	1063			9600.91	116740	0.369	0.928322
195	1080			9695.70	119764	0.369	0.9264432
200	1097		9840.46	124587	0.369	0.9234929	
205	1164		0.22	0.17	9429.54	110302	0.395
210	1181	9513.25			112949	0.395	0.920723
215	1215	9595.69			115552	0.395	0.9191041
220	1232	9679.36			118197	0.395	0.9174555
225	1249	9813.00			122641	0.395	0.9147386
230	1282	0.18		9759.15	120455	0.400	0.9141156
235	1299			9840.89	123033	0.400	0.9124983
240	1316			9922.61	125611	0.400	0.9108768
245	1333	10054.31		129988	0.400	0.9081785	
250	1383	0.19		9911.34	124708	0.410	0.907561
255	1400			9989.58	127165	0.410	0.9060092
260	1417			10067.81	129622	0.410	0.9044535
265	1434	10196.02		133878	0.410	0.9018165	
270	1467	0.19		10137.38	131519	0.415	0.901292
275	1484			10213.98	133920	0.415	0.8997631
280	1518			10289.57	136285	0.415	0.8982517
285	1518	10417.15		140519	0.415	0.8956089	
290	1568	0.20		10271.23	135125	0.425	0.8950539
295	1585		10344.87	137422	0.425	0.8935819	
300	1602		10418.48	139719	0.425	0.8921064	
305	1619	10542.09	143815	0.425	0.8895378		

Figure A.6 A sample of the mapping between the process platform and parameters for one FDM Maxum (Williams 2003)