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Toward Mass Customization in the Age of Information: The Case for Open Engineering Systems

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ABSTRACT *In the Industrial Era, manufacturers used "dedicated" engineering systems to mass produce their products. In today's increasingly competitive markets, the trend is toward mass customization, something that becomes increasingly feasible when modern information technologies are used to create open engineering systems. Our focus is on how designers can provide enhanced product flexibility and variety (if not fully customized products) through the development of open engineering systems. After presenting several industrial examples, we anchor our new systems philosophy with two real engineering applications. We believe that manufactures who adopt open systems will achieve competitive advantage in the Information Age.*

Our Frame of Reference

The United States, despite possessing abundant resources of all kinds and having at one time "made half the manufactured products sold anywhere in the world",[1] now faces an agile and unforgiving global marketplace in which the formerly all-important concept of economies of scale is now a thing of the past. To be effective in today's market, companies must have an intimate *knowledge* of their customers' changing demands and wishes and be flexible enough to quickly respond to them; *flexibility only comes when information feeds the ability to exploit it.*[2] It is only with the advent of the Information Revolution that we have begun to harness the power of the nearly limitless amounts of information which exist. Take for instance Kao Corporation, Japan's biggest soap and cosmetics company and the sixth largest in the world. Kao's network and information system allows them to deliver goods within 24 hours to any of 280,000 shops, whose average order is just seven items. Their network virtually eliminates the lag between an event in the market and the arrival of news to the company.[3]

One of the consequences of the Information Revolution is that information is virtually limitless. Given that we can access the necessary information then, we as designers must ask ourselves, *how can companies such as Kao provide increased product variety at less cost in a highly competitive, rapidly changing marketplace?* We believe that the key to future U.S. competitiveness lies in the development of open engineering systems and the infrastructure to sustain them. We define open engineering systems as follows.

> *Open engineering systems are systems of industrial products, services, and/or processes that are readily adaptable to changes in their environment which enable producers to remain competitive in a global marketplace through continuous improvement and indefinite growth of an existing technological base.*

We believe that inherent benefits of designing open engineering systems include *increased quality, decreased time-to-market, improved customization,* and *increased return on investment* which are enhanced through the system's capability to be adapted to change.

Consider the following analogy: like a species that cannot adapt itself to a changing environment, a system that cannot be adapted to changing customer demands becomes extinct, Figure 1. In the figure, the behavior of open and closed engineering systems is depicted in the context of a marketplace with rapidly changing consumer demands. When customer demands

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change, the company producing open engineering systems can quickly adapt their products to meet these new demands; the company producing closed engineering systems must create entirely new systems. The flexibility of open engineering systems enables them to satisfy a variety of customer demands, and their adaptability eliminates the need for new systems to be produced to accommodate a shift or change in the market. In addition, the company producing open engineering systems has the advantage of *quickly*, and more importantly *economically*, adapting to change and responding to the new market than does a company producing closed engineering systems. The *capability to adapt* enables the company producing open engineering systems to decrease its time-to-market and increase its return on investment while also increasing quality.

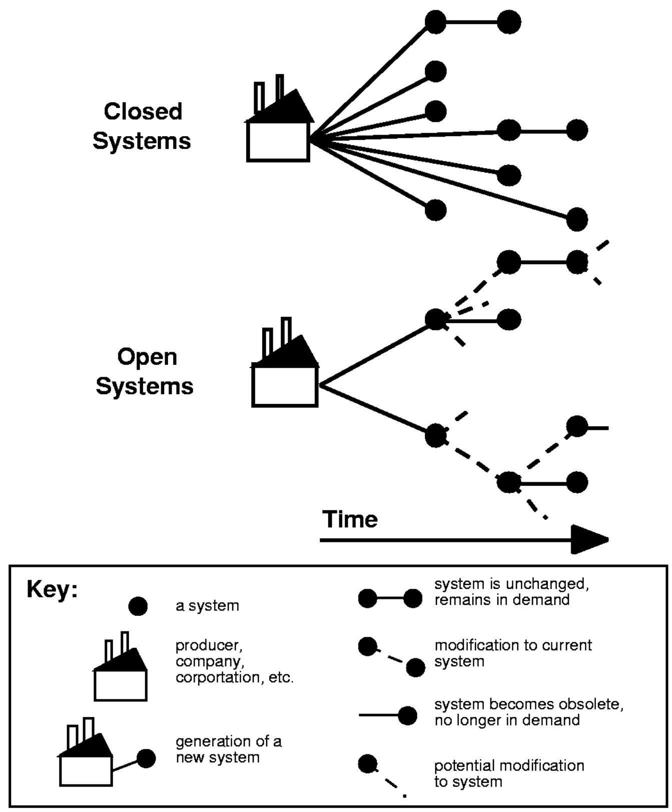


Figure 1. Open and Closed Engineering Systems

Our Foundation for Open Engineering Systems

Examples of the Open Engineering Systems Philosophy in the Literature

Our philosophy of open engineering systems is echoed throughout the literature, whether it be in operations research, computer science, marketing and management, or design itself.[4] In design for example, Wheelwright and Clark[5] 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. Similarly, Uzumeri and Sanderson[6] emphasize standardization and flexibility as a means for enhancing *product flexibility*. At Black & Decker, marketing executive Gary T. DiCamillo stresses that the key is *commonality;* "We don't need to reinvent the power tool in every country, but rather, we have a common product and adapt it to individual markets."[7] Take for example the Black & Decker heatgun which, in its third generation, evolved into a comprehensive design family of variants, ranging from a basic single temperature/air flow version to a top of the line version with several controllable heat settings and airflow rates.[8]

The variety importance-cost map was introduced recently by Ishii and his coauthors[9] to help minimize the life-cycle cost associated with offering product variety. This work has been further elaborated to include metrics for measuring the costs of offering product variety.[10] Chen and her coauthors[11] 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. Meanwhile, Rothwell and Gardiner[12] advocate robust designs as a means to improve system flexibility. 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. In a later article, Rothwell and Gardiner[13] give several examples of robust designs and show how they "allow for change because essentially they contain the basis for not just a single product but rather a whole product family of uprated or derated variants".

Some Basic Elements of Open Engineering Systems Design

The basic premise in designing an open engineering system is to get a quality product to market quickly and then remain competitive in the marketplace through continuous development of the product line. This can be done by developing a common baseline model where continuous improvement of the product allows several generations, i.e., *families*, of systems to be developed around the baseline model. The IBM PC is an excellent example of this; however, the success of the IBM PC as an open engineering system was more serendipitous than planned. In order to reproduce this type of success for future open engineering systems, a foundation needs to be developed for designing, realizing, sustaining, and retiring a *family* of systems which satisfy the changing needs of customers.

We believe the design of open engineering systems relies heavily on three things: (1) increasing design knowledge in the early stages of design,[14] (2) maintaining design freedom in the early stages of design, and (3) increasing efficiency throughout the design process, Figure 2. Particular attention should be paid to the change in shape of the design knowledge and freedom curves in the figure. The design knowledge curve is compressed because we want to get the product to market more quickly. Notice however that we want to maintain design freedom longer; thus, the design freedom curve is drawn differently with only a gradual decrease at the beginning.

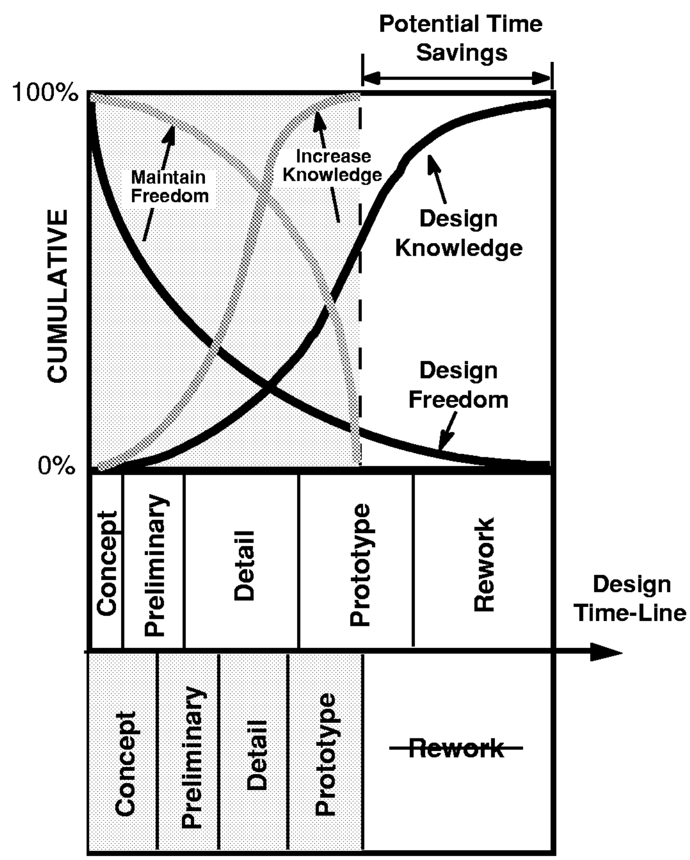


Figure 2. Reducing Time-to-Market by Increasing Design Knowledge and Maintaining Design Freedom

By spending a larger portion of time in conceptual design as shown in Figure 2 and by maintaining design freedom and increasing design knowledge, design changes (especially those which occur during later design stages) can be avoided, and a potential time savings and greater return on investment can be achieved. Moreover, *rework* can be eliminated from the design process because maintaining design freedom and increasing design knowledge helps prepare for unforeseen changes in the later stages of design and facilitates adaptation to these changes. By maintaining design freedom and increasing design knowledge, *system flexibility is enhanced.*

In our work, we have identified the following ways to increase design knowledge and maintain design freedom in the early stages of design. By spending a larger portion of time in the early design stages, design knowledge can be increased by:

- determining how the design variables affect the system performance by identifying key design drivers and the significance of the design variables,
- examining how the design variables change as a result of different design scenarios or trade-off studies,
- developing a better understanding of the design space through enhanced concept exploration, and
- posing and answering several "what-if" questions during the design process.

Similarly, by spending a larger portion of time in the early design stages, design freedom can be maintained by:

- searching for satisficing,[15] ranged sets of solutions rather than optimal or point solutions, and
- incorporating robustness into the design process to make the design insensitive to adjustments or changes.

If efficiency can also be increased during the design process, time-to-market can be decreased and design knowledge can also be increased by allowing more time to be spent on the detailed aspects of the design. In this manner, increasing efficiency in the design process increases effectiveness[16] and more importantly, improves the quality of a design.

Some Examples of Open Engineering Systems

There are several examples[17] of open engineering systems with which many of us are familiar, e.g., the IBM PC and the Boeing 747 series. Several generations of IBM PCs have been developed (built around the Intel 80286, 80386, and 80486 chips), and the modularity of the components allows many variations to occur within each generation. Similarly, the Boeing 747-200, 747-300, 747-400, and 747-SP share a strong technological family resemblance; few would argue with Boeing's view either of the family or the models within the family.[18]

Another example of an open engineering system is being developed at the University of Illinois at Urbana-Champaign (UIUC). They have established the Machine Tool Agile Manufacturing Research Institute (MT-AMRI)[19] which offers several software testbeds available over the Internet. The modular design of the testbeds allows industrial users running "in-house" software packages to augment their resources and capabilities using various computer resources from UIUC across the Internet. *Open engineering systems such as these are becoming more and more prevalent; they have only been made possible by the Information Revolution.*

Characteristics of Open Engineering Systems

We assert that open engineering systems can be readily adapted to changes in their comprehensive environment. Ideally, the system (which includes the product, process, and/or service as well as the producers and the customers) should be readily adaptable to any or all of the following changes.

- *Changes in the market* - includes any change in taste of the average consumer. For example, consumer taste changed from excess in the 80's to eco-consciousness in the 90's. In a highly commercialized culture such as ours, companies themselves are largely responsible for fueling this type of change.
- *Changes in customer needs/requirements* - includes any changes inflicted by the customer separate from those by the market. For example, a person owns a simple desktop copy

machine and then wants a copier which can sort and collate copies as well as have an automatic document feeder. In this case, customer requirements have changed and the original copier is no longer sufficient even though it still works.

- *Changes in technology* - include any advancements that can improve a system's function. In this way, a faster chip represents a change in a computer's technological environment, but at the same time CD innovations do not represent a change in a phonograph's technological environment. The advent of CD technology, in fact, forced a change in the phonograph's market environment.
- *Changes in resources* - includes those that affect the manufacture of a product and those that affect the performance of a product. Resource changes that affect manufacturability include changes in the availability of manufacturing materials, in the availability of manpower, etc. Resource changes that affect performance include changes in the availability of fuel (cells) needed to power a product, availability of mating products, etc.
- *Changes in the system environs* - includes all changes in the immediate physical environment of a system. Examples of such changes are the increased temperature on a machine shop floor during a hot day, the changing tides of a body of water on a dock, and an automobile which is driven from Death Valley to Alaska.
- *Changes in the government/legislation* - includes changes in state, and federal regulations, such as air quality standards, as well as changes in any laws that might restrict consumer use, e.g., changing FAA regulations which affects the aircraft industry or increased safety standards for the automotive industry.

Only some of these changes can be predicted; therefore, flexibility of options must be maintained to enable systems to be successfully adapted to change. There are several ways to realize this flexibility in an open engineering system, but remember, this *flexibility comes only when there is sufficient information to exploit*. We believe that this flexibility can be achieved through one of three characteristics -- modularity, mutability, and robustness -- as depicted in Figure 3. These three characteristics can be classified according to their influence on the system's form and function as illustrated by the two axes in the figure. The horizontal axis is ***change in function*** which ranges from 0% to 100% and indicates how much the function changes. The vertical axis is ***change in form*** which also ranges from 0% to 100%, indicating how much the form changes. The gray shading indicates the influence of each characteristic with regard to either a change in function or a change in form. We define each of these characteristics as follows.

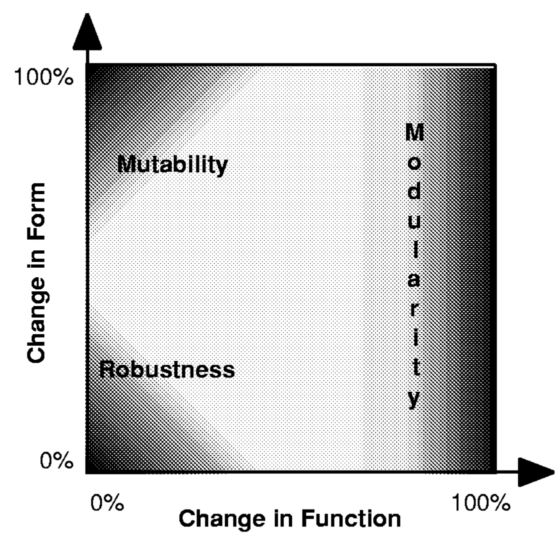


Figure 3. Relationship Diagram for Open Engineering System Characteristics

- *Robustness* is the capability of the system to function properly despite small environmental changes or noise. Robustness implies an insensitivity to small variations and does not dictate a change in form nor a change in function.
- *Modularity* is the relationship between a product's functional and physical structures such that there is (1) a one-to-one correspondence between the functional and physical structures, and (2) a minimization of unintended interactions between modules.[20] Modularity allows the product to be used in different ways, i.e., changing functions, and may facilitate the rearrangement/replacement of physical components, i.e., changing form.

- *Mutability* is the capability of the system to be contorted or reshaped in response to changing requirements or environmental conditions. Mutability implies a change in form but does not indicate a change in function.

Two Engineering Applications of Our Open Engineering Systems Philosophy

To better anchor our philosophy of open engineering systems, we present two engineering applications. We first discuss the implications of our open engineering systems philosophy on the field of structural design. Then we describe the use of the open engineering systems philosophy for designing families of products.

Creating Open Structural Design Models Using the Open Engineering Systems Philosophy

We use structural design examples to illustrate the aforementioned characteristics of open engineering systems in this area; structural design refers the process of geometric modeling, structural analysis, and design optimization. In a computer-aided design environment, solid modeling is often used to construct a precise mathematical description of the shape of the real object. Then, the finite element method is widely used for analysis, after loads, boundary conditions, material properties, etc. are modeled, and a mesh is generated. An important goal of engineering activities is to improve and to optimize technical designs, structural assemblies, or components. The task is to support the engineer in finding the best-possible design alternatives of specific structures, where the "best-possible" or "optimal" structure is the one that corresponds to the designer's desired concept, while meeting multidisciplinary requirements relating to manufacturing, operating, etc.[21] We focus on geometric modeling and optimization to highlight examples of flexibility in structural design. We call structural designs that have these analogies to open engineering systems *Open Structural Design Models*.

Parametric Models in Geometric Modeling

We ignore the possibility to model each new geometry from scratch, which is of course possible in a computer-aided environment, and believe that the minimum requirement for flexibility is equal to having a *parametric* model. The primary issue to do structural design effectively is to develop such a parametric structural analysis model. By modifying the model's design variables such as geometric dimensions, the structural model (geometry, finite element mesh, boundary conditions, etc.) has to have the ability to be changeable according to new variable values. Parameters, relations, or functions are introduced to fully specify the model's geometry, thereby enhancing the flexibility, the core characteristic of an open engineering system. In order to develop a parametric model, a larger portion of time has to be spent in the early design stages, i.e., geometric modeling. A considerable amount of time is needed to introduce and model all of the variables which may change quantitatively during the design process. However, a parametric model allows us to maintain design freedom because the computer easily performs the tasks required to update the model according to specified parameter values.

An example from the field of blow molding is given in Figure 4. It represents the geometric model of a thermoplastic bottle with handle. The purpose in the blow molding example is to analyze the behavior of the bottle under internal pressure, compression and impact. Only half of the bottle is modeled because of symmetry. The surface shape is highly complex because of all the curvature in the model, especially around the handle. The modeling process itself has been difficult and time-consuming; therefore, a parametric model has not been implemented. This means that this model represents one of a kind bottle and the only value that can be modified easily is the wall thickness. Another flexibility aspect exists through scaling, since the basic shape remains the same if the model is supposed to change in size only.

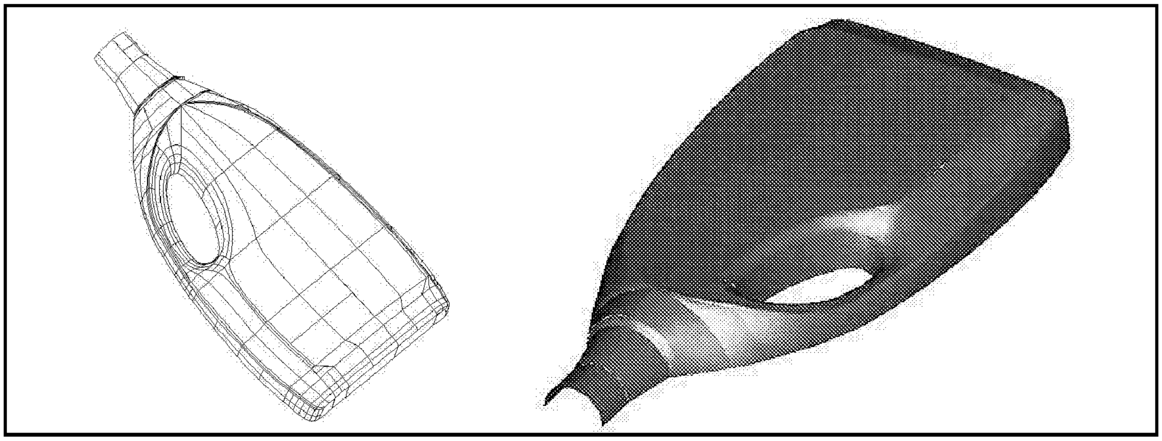


Figure 4. Geometric Model of Bottle with Handle

In order to represent system modularity, we could assume that each single surface in the model represents a module, but there is no real functional distinction as defined for modularity between adjacent surfaces. We could assign groups of surfaces being modules such as the lid area, the handle or the bottom, but this model is actually not developed to serve modularity, even though it is possible to do so. A change in geometry can only be done if surfaces are deleted, new ones are generated and connected to the remaining system/model. New surfaces can be treated as new modules which have to fit the interfaces of the remaining model. It is easy to see that this model is very inflexible and that the effort put into the modeling process does not provide a good "return on investment" if product changes are necessary. If flexibility can not be achieved, a designer is highly involved in time-consuming remodeling tasks and the investment becomes even larger.

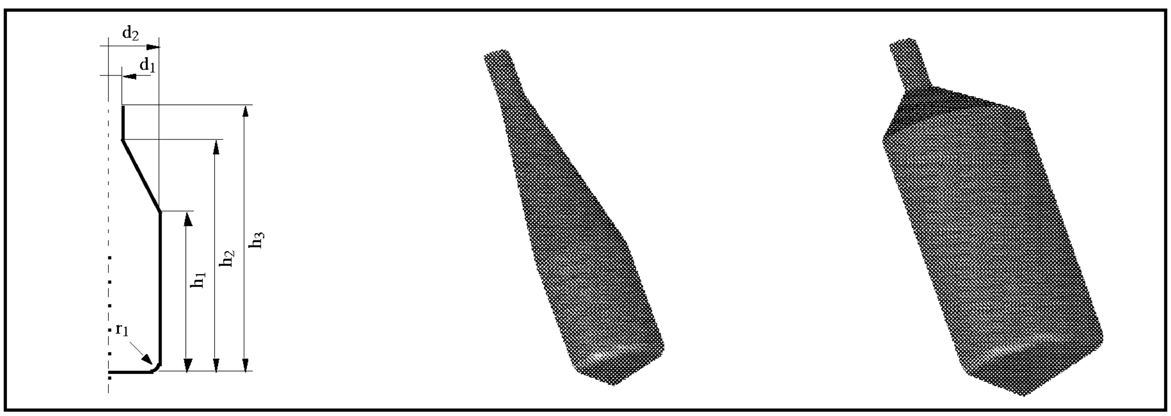


Figure 5. Parametric Flexibility in a Round Bottle

A step towards creating a more flexible model is shown in Figure 5. A round bottle is modeled as a 90° section. According to the technical draft, the geometry is perfectly symmetric and could therefore be modeled as a line model, but the blow molding process results in a wall thickness distribution of the actual product which varies extremely with the section angle. The geometric model can be easily created by specifying five vertex points, four connecting lines and rotation of the line section by a specified angle. The parametric model dimensions can be specified to improve model flexibility. We define three height dimensions h_1, h_2, h_3, two diameters d_1, d_2, and the radius r_1 to smooth the corner on the bottom of the bottle. Constraints can be put on the model to ensure parallel lines. The bottle model shown in Figure 5 consists of six parameters which can easily be modified to create a variety of new shapes and sizes. *Thus, when customer needs are specified, we can quickly generate the necessary shapes at very little cost to us.*

The parametric model representation enhances flexibility, but this is only a starting point since the model still has many limitations. A *change in form* is possible through a change in parameters. Changes in shape are achieved through modifying the corners into arcs or replacing the straight lines with more flexible splines. For modularity, each corner point could be identified as the interface between modules (e.g., lid and bottom). Additionally, a new module which is connected to the model via two new geometric points (module interfaces) is introduced, Figure 6. We further assume that the formulation of the new module enhances flexibility so that we can model many different shapes (e.g., use a B-spline as opposed to a straight line). *That way, if requirements change, we could easily use the capabilities of the new module to adapt to the new needs and adjust the shape of the bottle.* Thus, in this context, modularity provides model interfaces to account for changing requirements, enabling us to prepare a variety of models with little added effort. But how do we know where to put the interfaces and if it is worth the effort? Our current answer is to carefully evaluate each new design, estimating how much time and effort should be invested into the modeling process and what benefits would arise in the future. We believe that this example of designed-in modularity is a long-term investment necessary to maintain design freedom and achieve a flexible design.

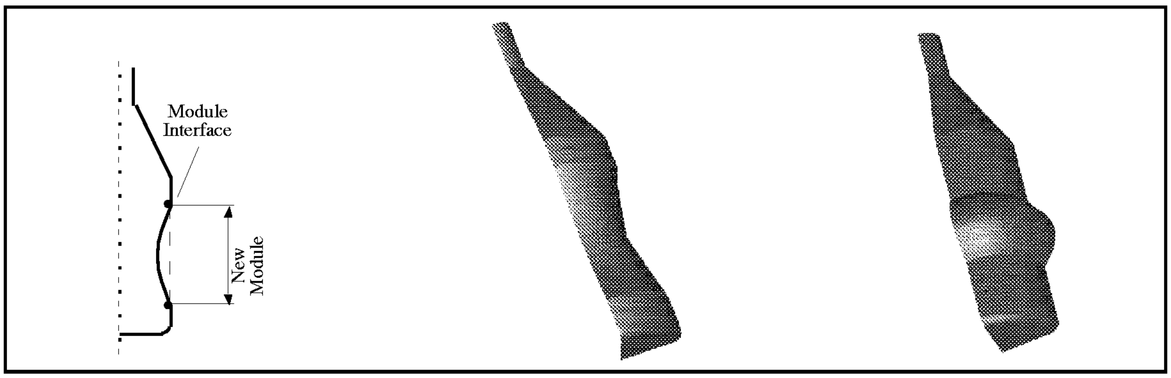


Figure 6. Designed-in Modularity and Mutability

Flexibility within Structural Optimization

Several analogies exist between structural optimization techniques and the characteristics of open engineering systems. The development of a parametric structural analysis model is a must before design optimization can be applied. This simplest form of flexibility can be referred to as *parameter optimization* where mathematical programming procedures are employed to find the "best" parameter values. Through employing other strategies such as shape, topology and stochastic optimization, or model decomposition a large amount of flexibility can be achieved.

<u>Shape and Topology Optimization</u>

As stated before, mutability is the capability of the system to be reshaped in response to changing requirements, Figure 3. A corresponding analogy can be identified in shape optimization. In contrast to parameter optimization problems where we search for optimal design variable values or parameter configurations, in solving shape optimization problems, we search for optimal functions that describe the shape of a structure.[22] For practical solutions to shape optimization problems, today the so-called *direct* methods are preferred, that transform the original shape optimization problem into a parameter optimization problem, usually through the introduction of special shape functions. For direct shape optimization, the choice of the shape functions is extremely important because the original solution space will be reduced and the optimization result will also be influenced. We want to have high flexibility with a small number of free parameters to describe surfaces or lines. *Flexibility is important when rendering a large variety of possible shapes during optimization according to customer specifications.*

Topology optimization deals with making decisions regarding the position and layout of structural elements. The objective of topology optimization is to substitute the existing intuitive design of variants by mathematical-mechanical strategies in the design phase and thus to make it more efficient. Topology optimization involves starting with little information, e.g., applied forces and feasible solution space (topology space), and finding solutions for structural designs, Figure 7.[23] Thus, since only little information is required for this technique, it is a valuable tool for use in the early stages of design. One of the applied topology optimization methods is the so-called "Homogenization Method" or "Bubble-Method" which simultaneously combines shape optimization and topology optimization.[24] The procedure is very flexible since it can be easily adapted to changing environmental conditions or design requirements. A change in form is obvious; a change in function is also possible since there are no initial limitations other than the initial definition of the topology space.

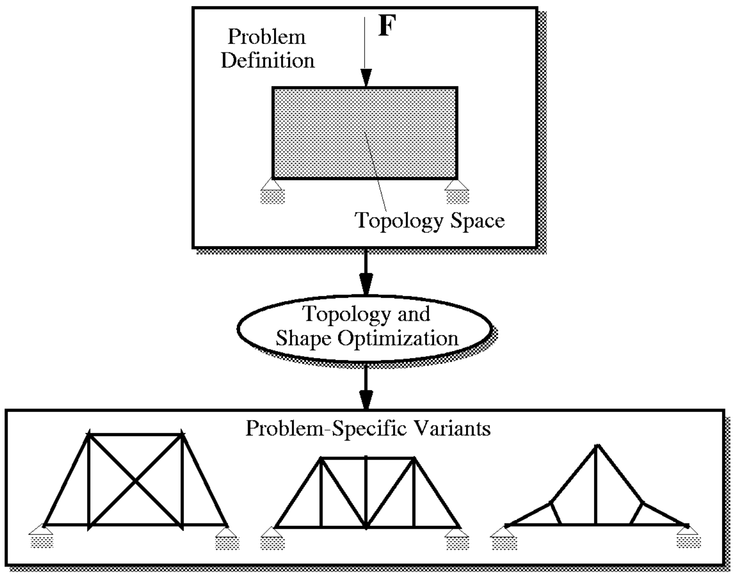


Figure 7. Topology Optimization in Structural Design

Model Decomposition

In the field of structural design, the structural model as well as the optimization model can often be decomposed. The phrase *decomposition strategy* describes what is decomposed for the solution of structural optimization problems.[25] The most important decomposition strategy is model decomposition since it involves the separation of the mathematical model into equations and/or variable vectors. The application of model decomposition leads to a reduction in simultaneously treated system variables.

Modularity can be achieved through decomposition of the original system into several smaller subsystems. By using this strategy, subsystems or modules can be replaced by other modules. The less coupling there is between the subsystems, the less effort there is to make changes; however, coordinating the interactions between modules always remains of utmost importance. A change in form is also possible when modularity exists, refer to Figure 3. The key for this concept is to develop the proper interfaces and coupling in the design model.

Stochastic Optimization

Robustness is the capability of a system to function properly despite small environmental changes or noise. Robustness implies an insensitivity to small variations and does not dictate a change in form nor a change in function, see Figure 3. Stochastic optimization can be applied under the consideration of stochastic variables and constraints, where (i) stochastic failure criteria have to be determined, e.g., ceramic materials, or where (ii) various stochastic variables and constraints of stochastic state variables have to be modeled, which are not stochastic failure criteria of the material. The first point is important when we consider "new" materials which replace previously used materials. New materials can be developed through new processes, design and optimization and can be used in new applications or improve current technology.[26] The second point covers robust design applications. In robust design, we deal with stochastic variables and noise factors and try to address quality issues in a design.

Designing a Family of Products Using the Open Engineering Systems Philosophy

Having anchored our open engineering systems philosophy in structural engineering, we now shift our focus to designing families of products. Specifically, we focus on the design of a family of General Aviation aircraft using the open engineering systems philosophy. The term General Aviation encompasses all flights except military operations and commercial carriers. General Aviation aircraft in the U.S. account for approximately 62% of all flight hours, 37% of all miles flown, and 78% of all departures. Its potential buyers form a diverse group that include weekend and recreational pilots, training pilots and instructors, traveling business executives and even small commercial operators.

Satisfying a group with such diverse needs and economic potential poses a constant challenge for the General Aviation industry since it is impossible to *satisfy all the market needs with a single aircraft*. The present financial and legal pressure endured by the General Aviation sector makes small production runs of specialized models unprofitable. As a result, many General Aviation aircraft are no longer being produced, and the few remaining models are beyond the financial capability of all but the wealthiest buyers. Combined with the harsh legal environment to which General Aviation airplanes and component producers have been subjected, the General Aviation sector is in a deep recession as shown in Figure 8.

In an effort to revitalize the General Aviation sector through the introduction of state-of-the-art design techniques and construction materials, the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) sponsored a General Aviation Design Competition.[27] A General Aviation aircraft (GAA):

- is a single-engine, single-pilot, fixed wing, propeller driven aircraft
- carries 2-6 passengers
- cruises at 150-300 kts
- range of 800-1000 n.mi.

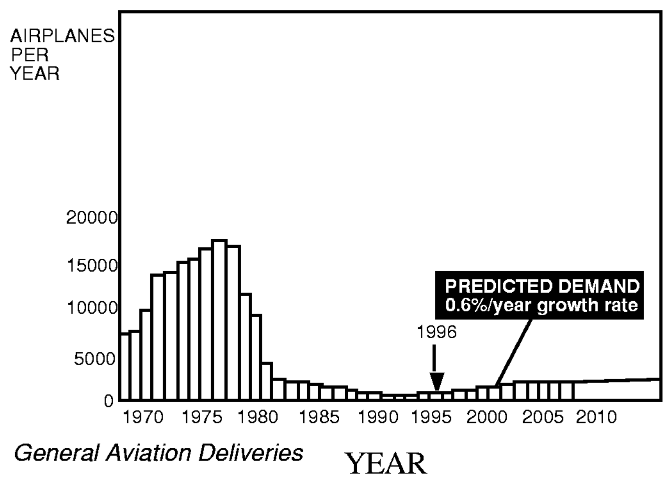


Figure 8. Airplanes Per Year

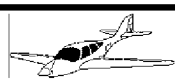
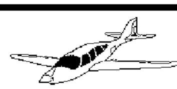
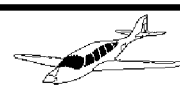
A reasonable solution to the GAA crisis is to develop an aircraft which can be easily adapted to satisfy distinct groups of customer demands. To do this, a *family* of General Aviation aircraft is designed around the 2, 4, and 6 seater aircraft configurations. The general dimensions of each aircraft are developed such that a significant number of top-level design specifications[28] can be shared by the different aircraft to facilitate the development of a common baseline model. If a common baseline model can be developed and maintained, *a family of aircraft which fulfills the market demands can easily be realized*, and as a result, the General Aviation industry can profit from its production. Consequently, the problem statement for the example problem is as follows.

Given the GAA competition guidelines and relevant GAA data, it is required to develop a ***ranged*** *set of top-level design specifications for a* ***family*** *of General Aviation aircraft capable of satisfying the diverse demands of the General Aviation public at an affordable price and operating cost while meeting desired performance, technical, and economic considerations.*

We have utilized two different approaches to design this family of three aircraft. First, we designed each aircraft individually and looked for commonalties between the top-level design specifications for each aircraft. These aircraft serve as the benchmark aircraft, and the top-level design specifications -- cruise speed, aspect ratio, sweep angle, wing loading, seat width, engine activity factor, tail length to diameter ratio and propeller diameter -- for each aircraft are shown in the top half of Table 1. For example, the desired aspect ratio is 7.56 for the 2 seater aircraft, 7.1 for the 4 seater and 7.7 for the 6 seater. The corresponding ranges of the system performance variables of interest are also given in Table 1, e.g., the maximum cruise range varies from 2360 to 2496 n.mi. for the three aircraft based on the given top-level design specifications.

For our second approach, we employed the Robust Concept Exploration Method[29] to design all three aircraft simultaneously rather than individually. The final configurations for these aircraft are given in the lower half of Table 1 along with the corresponding ranges of the system performance variables. Notice that we specify a range for each top-level design specification for all three aircraft rather than individual values for each aircraft. This is because these values are "common and good" for all three aircraft as determined by using the Robust Concept Exploration Method. It is encouraging that there is considerable overlap between the top-level design specifications and system performance ranges for these aircraft and the benchmark aircraft.

Table 1. The 2, 4 and 6 Seater Family of Aircraft

Top-Level Design Specification	 **2 Seater**	 **4 Seater**	 **6 Seater**	**Corresponding System Performance Range**	
		Benchmark Aircraft			
Cruise Speed	Mach 0.242	Mach 0.24	Mach 0.24		
Aspect Ratio	7.56	7.1	7.7	Fuel Weight	350-450 lbs
Prop Diameter	5.72 ft	5.86 ft	5.76 ft	Empty Weight	1895-1983 lbs
Wing Loading	22.1 lb/ft^2	20.9 lb/ft^2	21.1 lb/ft^2	Operating Cost	\$60/hr-\$62/hr
Sweep Angle	5.75°	5.95°	6.0°	Max. Lift/Drag	15.2-16.0
Engine Activity Factor	86.2	88.5	87.5	Purchase Price (1970's Dollars)	\$42310-\$43956
Seat Width	18.2 in	18.5 in	19.2 in	Max. Speed	190-198 kts
Tail Length/Diam	3.7	3.75	3.75	Max. Range	2360-2496 n.mi.
		Simultaneously Designed Aircraft			
Cruise Speed	⇦	Mach 0.24-0.34	⇦		
Aspect Ratio	⇦	7-8.8	⇦	Fuel Weight	435-487 lbs
Prop Diameter	⇦	5.5-5.96 ft	⇦	Empty Weight	1845-1896 lbs
Wing Loading	⇦	20-25 lb/ft^2	⇦	Operating Cost	\$59/hr-\$60/hr
Sweep Angle	⇦	6.0°	⇦	Max. Lift/Drag	15.2-15.5
Engine Activity Factor	⇦	85-92	⇦	Purchase Price (1970's Dollars)	\$41665-\$42556
Seat Width	⇦	14-20 in	⇦	Max. Speed	197-199 kts
Tail Length/Diam	⇦	3.75	⇦	Max. Range	2261-2341 n.mi.

The specific details regarding how these solutions were obtained are given elsewhere[30] as is a lengthy comparison of the robustness of the solutions, individual performance of each aircraft, and variation between design variables. Suffice it to say that while we increase our efficiency by designing all three aircraft simultaneously and make our designs more "robust", we lose some individual system performance for each aircraft, i.e., the individually benchmarked aircraft can fly further with less fuel but have a much wider spread in terms of price. The question that remains to be addressed is, when is this tradeoff worthwhile and when it is not? The answer can only be found through knowledge of customer wishes and demands.

In both cases, we sought to find a ranged set of top-level design specifications (design variables) which was "common and good" for all three aircraft which comprise the family By finding a ranged set of specifications rather than a point set of specifications, we have more design freedom which allows us to readily adapt our baseline design to meet a variety of customer demands.[31] In essence, we have created a "robust design" (using Rothwell and Gardiner's terminology) which is flexible and adaptable with respect to external changes in the market and customer demand. Once additional customer information is known, we can tailor our baseline model to better suit those needs.

Summary and Closing Remarks

Before wrapping up, let us first return to the question we posed at the start of this chapter, namely, *how can product realization teams provide increased product variety at less cost in a highly competitive, rapidly changing marketplace?* Clearly, the answer lies in how we deal with information and how we use it and manipulate it to achieve our objectives. A new form of competitive advantage lies in harnessing the nearly limitless information which now exists and being able to adapt quickly to changing customer demands. Embracing our open engineering systems philosophy and the ideas of modularity, robustness and mutability will enhance system flexibility and help maintain flexibility of options to accommodate the multitude of changes which occur in both design and the market.

Our intent is to introduce the notion of open engineering systems and describe key characteristics for both the design process and the product sides of open engineering systems. On the design process side, our primary concern for designing open engineering systems is to maintain design freedom, increase design knowledge and increase (computational) efficiency during the early stages of design. *This enables better decisions to be made before the freedom to make these decisions is eliminated.* On the product side, we have described several characteristics for open engineering systems including modularity, robustness and mutability. These characteristics are selected as descriptors for open engineering systems because they *promote flexibility and facilitate continuous growth and improvement in the face of change.*

Having identified core characteristics of open engineering systems, our next step is to develop *metrics* to assess the extent to which a system is modular, robust or mutable, i.e., the extent to which a system is open. Our initial efforts are aimed at measuring the design freedom and information certainty of a system,[32] but several questions remain unanswered.

- *On openness:* How should we measure openness? Do we either have it or not have it? Is there a relationship between design freedom and openness and if so what? Can we increase openness or just maintain openness of a system? If we can increase it, how? If not, why?
- *On later design stages:* How do we maintain design freedom in the later design stages? Do we want to? How (and when) do we narrow our ranged sets of specifications? When do we go for point solutions?
- *Design freedom:* How can we measure design freedom? Can we increase our design freedom or just maintain it? Does a larger performance/variable range mean more freedom than a smaller one and if so, how much more?
- *On small vs. large, complex systems:* The examples we have had are for large, complex systems such as aircraft and ships...what about smaller, less complex products like disposable cameras, copiers, stereos, a chair, a pencil, a tractor? How will our open engineering systems philosophy apply to these? Is it readily applicable or must it change? If so, how?
- *On Metrics:* What are metrics for modularity, mutability, robustness and flexibility?

More generally, we should contemplate:

- What are the consequences of this limitless information on the physical products (systems), the associated product realization processes and the organization of the company?
- What are some examples of open systems that support our principal theses? How has the Information Revolution affected their development and implementation?
- Are Open Systems worth pursuing? or are there alternate approaches which we should consider in face of the Information Revolution?
- What further impact does the Information Revolution have on realizing open engineering systems? How does it affect their design and management as well as their support and retirement?

Now that we have identified some of the "whats" and "whys" for open engineering systems, we need to look more at the "hows". In particular, we can begin developing design methods and tools for realizing open engineering systems, and this task has already begun.[33] The proposed design process, rooted in Decision-Based Design,[34] employs several mathematical tools and constructs which are part of the Robust Concept Exploration Method.[35] The Robust Concept Exploration Method helps maintain flexibility of options to facilitate continuous improvement and technological growth of a common baseline model and increases knowledge about a system. In a world where customer needs are constantly changing, flexibility can only be achieved when information is available, and designers and managers are willing (and able) to adapt. With the advent of the Information Revolution, implications such as these can no longer go unheeded.

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Notes and References

1. L. Dobbins & C. Crawford-Mason, 1991, *Quality or Else*, Houghton Mifflin, New York.
2. T.A. Stewart, 1992, "Brace for Japan's Hot New Strategy," *Fortune,* Vol. 126, No. 6 (September 21), pp. 62-74.
3. Stewart, *op. cit.,* Ref. 2.
4. For examples from (a) operations research see N. Gaithen, 1980, *Production and Operations Management: A Problem-Solving and Decision-Making Approach*, The Dryden Press, New York; (b) computer science see G.J. Nutt, 1992, *Open Systems*, Prentice Hall, Englewood Cliffs, NJ; and (c) marketing and management see P. Kotler, 1989, "From Mass Marketing to Mass Customization," *Planning Review,* Vol. 17, No. 5 (September/October), pp. 10(5); M.H. Meyer & J.M. Utterback, 1993, "The Product Family and the Dynamics of Core Capability," *Sloan Management Review,* Vol. 34 (Spring), pp. 29-47; and B.J. Pine II, 1993, *Mass Customization: The New Frontier in Business Competition*, Harvard Business School Press, Boston, MA.
5. S.C. Wheelwright & K.B. Clark, 1992, "Creating Project Plans to Focus Product Development," *Harvard Business Review,* Vol. 70 (March-April), pp. 70-82.
6. M. Uzumeri & S. Sanderson, 1995, "A Framework for Model and Product Family Competition," *Research Policy,* Vol. 24, pp. 583-607.
7. G.T. DiCamillo, 1988, "Winning Turnaround Strategies at Black & Decker," *Journal of Business Strategy,* Vol. 9, No. 2 (March/April), pp. 30-33.
8. R. Rothwell & P. Gardiner, 1988, "Re-Innovation and Robust Designs: Producer and User Benefits," *Journal of Marketing Management,* Vol. 3, No. 3, pp. 372-387.
9. K. Ishii, C. Juengel, & C.F. Eubanks, 1995, "Design for Product Variety: Key to Product Line Structuring," *9th International ASME Design Theory and Methodology Conference (A.C. Ward ed.),* Boston, MA, ASME, DE-Vol. 83 No. 2, pp. 499-506.

[10]. M. Martin & K. Ishii, 1996, August 18-22, "Design for Variety: A Methodology for Understanding the Costs of Product Proliferation," *10th International ASME Design Theory and Methodology Conference,* Irvine, CA, ASME, Paper No. 96-DETC/DTM-1610.

[11]. W. Chen, D. Rosen, J.K. Allen, & F. Mistree, 1994, "Modularity and the Independence of Functional Requirements in Designing Complex Systems," *Concurrent Product Design (R. Gadh ed.),* ASME, DE-Vol. 74, p. 31-38.

[12]. Rothwell and Gardiner, *op. cit.*, Ref. 7.

[13]. R. Rothwell & P. Gardiner, 1990, "Robustness and Product Design Families," *Design Management: A Handbook of Issues and Methods (M. Oakley ed.),* Basil Blackwell Inc., Cambridge, MA, pp. 279-292.

[14]. The early stages of design are characterized by *uncertain* or *ambiguous* information which is "soft" compared to information in the later design stages.

[15]. Satisficing solutions are solutions which are "good enough" but not necessarily the "best", from H.A. Simon, 1981, *The Sciences of the Artificial*, Second, The MIT Press, Cambridge, Mass.

[16]. Efficiency is a measure of the swiftness with which information, that can be used by a designer to make a decision, is generated. Effectiveness is a measure of the quality of a decision (correctness, completeness, comprehensiveness) that is made by a designer.

[17]. Additional examples can be found in (a) Rothwell and Gardiner, *op. cit.*, Ref. 12, (b) S. Kotha, 1995, "Mass Customization: Implementing the Emerging Paradigm for Competitive Advantage," *Strategic Management Journal,* Vol. 16 (Summer), pp. 21-42; and (c) S. Maital, 1991, "The Profits of Infinite Variety," *Across the Board,* Vol. 28 (October), pp. 7-10.

[18]. Rothwell and Gardiner, *op. cit.*, Ref. 7.

[19]. MT-AMRI can be found on the World Wide Web at http://mtamri.me.uiuc.edu/mtamri.html.

[20]. K.T. Ulrich & K. Tung, 1991, "Fundamentals of Product Modularity," *ASME Winter Annual Meeting,* Atlanta, GA, ASME, pp. 73-80.

[21]. H.A. Eschenauer, 1995, "Multicriteria Structural Optimization as a Technique for Quality Improvement in the Design Process," *Microcomputers in Civil Engineering,* Blackwell Science Inc., Cambridge, MA, pp. 257-267.

[22]. H.A. Eschenauer, J. Geilen, & H.J. Wahl, 1993, "SAPOP - An Optimization Procedure for Multicriteria Structural Design," *Software Systems for Structural Optimization (H.R.E.M. Hörnlein and K. Schittkowski eds.),* Birkhäuser Verlag, Basel.

[23]. Figure 7 is from A. Schumacher, 1996, "Topologieoptimierung von Bauteilstrukturen unter Verwendung von Lochpositionierungskriterien.," Ph.D. Dissertation, University of Siegen, Siegen, Germany.

[24]. *Ibid.*

[25]. M. Weinert, 1994, "Sequentielle und parallele Strategien zur optimalen Auslegung komplexer Rotationsschalen.," Ph.D. Dissertation, University of Siegen, Siegen, Germany.

[26]. T. Vietor, 1994, "Optimale Auslegung von Strukturen aus sprden Werkstoffen.," Ph.D. Dissertation, University of Siegen, Siegen, Germany.

[27]. NASA and FAA, 1994, "General Aviation Design Competition Guidelines," Hampton, VA, Virginia Space Grant Consortium.

[28]. Top-level design specifications are used to define the overall system configuration, e.g., wing area, aspect ratio, sweep angle, etc., and subsystems at an abstract level. They can be either continuous, e.g., aspect ratio = [7 - 11], sweep angle = [0° - 6°], etc., or they can be discrete, e.g., single- or twin-engine, high or low wing, etc.

[29]. W. Chen, J.K. Allen, D. Mavris, & F. Mistree, 1996, "A Concept Exploration Method for Determining Robust Top-Level Specifications," *Engineering Optimization,* Vol. 26, pp. 137-158.

[30]. T.W. Simpson, W. Chen, J.K. Allen, & F. Mistree, 1996, September 4-6, "Conceptual Design of a Family of Products Through the use of the Robust Concept Exploration Method," *6th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization,* Bellevue, WA, AIAA, Inc., pp. 1535-1545.

[31]. Developing this ranged set of top-level design specifications and a lengthy comparison of the baseline models against the individual benchmark aircraft is also presented in Simpson, et al., *op. cit.*, Ref. 29.

[32]. T.W. Simpson, D. Rosen, J.K. Allen, & F. Mistree, 1996, August 18-22, "Metrics for Assessing Design Freedom and Information Certainty in the Early Stages of Design," *10th International ASME Design Theory and Methodology Conference,* Irvine, CA, ASME, Paper No. 96-DETC/DTM-1521.

[33]. T.W. Simpson, 1995, "Development of a Design Process for Realizing Open Engineering Systems," MS Thesis, Georgia Institute of Technology, Atlanta, GA.

[34]. F. Mistree, W.F. Smith, B. Bras, J.K. Allen, & D. Muster, 1990, "Decision-Based Design: A Contemporary Paradigm for Ship Design," *Transactions, Society of Naval Architects and Marine Engineers (H.R. Paresai and W. Sullivan eds.),* Jersey City, New Jersey, pp. 565-597.

[35]. Chen, et al., *op. cit.*, Ref. 28.