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PRINCIPLES OF PRODUCT FLEXIBILITY

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ABSTRACT

Contemporary products need to evolve to accommodate competitive market pressures, rapid technological change and transient and multi-dimensional customer requirements. Product flexibility is defined as the adaptability of a system in response to these factors. Currently, flexible products are realized with *ad hoc* methods that rely on the experience and intuition of the designer. In this work, a set of formal principles is presented for guiding the design of flexible products. These principles are derived from the results of an empirical study of the United States patent repository. As part of the study, patents are analyzed with a dissection tool, and representative principles are derived from the data. The utility of these principles is demonstrated via the design of a flexible fuel cell system. The effectiveness of these principles is validated using a Change Modes and Effects Analysis (CMEA) tool to compare the resulting fuel cell concept to a typical device of similar functionality.

KEY WORDS:

Flexibility, Design flexibility, Methodology for flexibility, Flexibility principles, Design principles, Fuel cell, Principle driven concept generation.

1 INTRODUCTION

1.1 Motivation & Overview

Technological change is an ever-expanding aspect of our modern society, and the rate of this change is accelerating. Between the years of 1963 and 1991 the United States Patent and Trademark Office (USPTO) granted 1.9 million utility patents, and between 1991 and 2004 granted 1.8 million more [1]. This rate of intellectual property has a pervasive effect on the field of product development. Due to the nature of the competitive market, changes in available technology necessitate changes in the design of available products. Since revolutionary breakthroughs are relatively rare, and most technological advances occur as a series of evolutions, many companies are forced to constantly redesign and remanufacture their products in order to retain their market share.

Another factor which contributes to the need for product redesign is the transient and multi-dimensional nature of customer requirements. It is a rare occurrence for any product to meet every customer need identified by the marketing research. Unmet needs provide opportunities for redesign and evolution to occur.

Such redesign efforts can involve considerable costs, such as production costs of adding new inventory, the reorganization of manufacturing processes, and the loss of market share due to increased cycle time. Incorporating flexibility into the design of a product early in the development process would allow a company to greatly reduce such costs. Work has been carried out on determining the economic ramifications of product flexibility (or inflexibility), and the results show that these are readily

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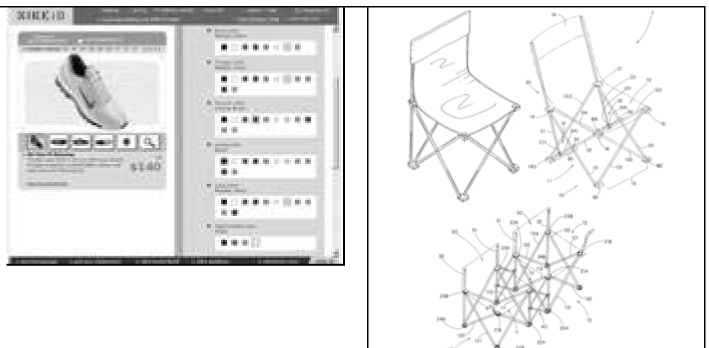
apparent and quite staggering [2-5]. What is needed now is a systematic method of incorporating flexibility into the product development process. This paper develops and presents such a method in the form of a set of flexibility principles, and then illustrates the application of these principles through the use of a case study involving the development of a portable fuel cell powered electric generator. This fuel cell generator is designed to maximize flexibility.

1.2 Background

Product flexibility is defined as the degree of responsiveness (or adaptability) of a system to the multi-dimensional needs of the customers and to any future change in a product. Figure 1 illustrates two different products which exemplify this definition of flexibility. Nike ID [6] shoes provide flexibility to the customer in terms of color choice, customized emblems (such as college names, symbols, and mascots), and choice of sole designs. The foldable chair products shown illustrate the direct evolution of a single chair, to a reclining and then to a dual chair product. These product evolutions include added features and functionality with little or no change to the original product architecture.



(a) Nike ID Shoes [6]

(b) Foldable Chair Products: Single, Reclining, and Dual [7-9]

Figure 1. Products Illustrating Flexibility

A number of methods have been proposed to incorporate flexibility into the design of a product. These methods generally concentrate on the creation of a common platform architecture [10-12] or the implementation of a modular product architecture [13, 14]. This method can be effective but tends to be highly subjective. What is needed is something more systematic and more repeatable. Martin and Ishii [14] have presented such a method in their general approach to reducing the effects of product variety on a design solution based on their Generational Variety Index (GVI) method of measuring the amount of redesign required for a component to meet future market needs. This method, however, was intended to deal mainly with parametric redesign of components rather than an adaptive redesign of systems. The principles of flexibility are intended to provide more system-level ways of guiding the design process to allow the creation of a design solution capable of adapting to the different types of changes resulting from product evolution.

Efforts have also been made to create metrics to measure product flexibility so that the success of such methods can be validated. The GVI method which is based on an estimate of required changes in a component due to external factors is one such metric [15]. Another method for measuring flexibility is the Change Modes and Effect Analysis (CMEA) tool which is analogous to the widely accepted Failure Modes and Effects Analysis (FMEA) [16]. This method outputs the Change Potential number (CPN) for a product which essentially describes how readily that product is able to absorb change. The CPN incorporates a measure of the inherent flexibility of a design, from one that requires a total redesign to respond to an evolution to a product which could respond without any changes whatsoever being made.

A number of methods have also been proposed for accommodating design changes caused by uncertainty in customer requirements and in manufacturing capability. Those methods which deal with uncertainty in customer requirements generally recommend the use of controllable tuning parameters [17 – 19], the use of reconfigurable modules [17, 20]. Parkinson and Chase [18] propose some 'principles' of adaptive robust design which suggest ways to make a system which can adapt to the variation introduced by the environment of use, manufacturing processes or by the requirements of the user. These principles are preliminary findings and demonstrate the need to develop a more comprehensive list. For dealing with uncertainty in manufacturing processes, Roser and Kazmer [21, 22] propose a method for optimizing the parameters of a design in order to make it more 'robust' to unpredictable changes.

One of the possible drawbacks of flexibility is that embedding it into a system can be costly. Suh et al. [23] propose a method to optimize the design variables of a flexible system in order to reach the best compromise between cost and performance. This method is designed to choose between a preexisting set of flexible concept variants and so adds to the utility of a list of flexibility principles by providing a way to develop the design solutions they produce to a high level of embodiment.

1.3 Objectives

The objectives of this paper are threefold: first, to present a research methodology by which principles of flexibility may be developed; second, to present the principles derived by this methodology; and third, to illustrate a method for applying these principles through the use of a product development case study.

2 RESEARCH METHODOLOGY: DEVELOPMENT OF THE PRINCIPLES OF FLEXIBLITY

The research strategy followed in the development of the principles of flexibility begins with the presumption that flexibility is an existing property of certain products which results from design choices made by their inventors, and that these choices can be discovered and expressed in the form of a set of principles. Based on this presumption, a research strategy may be expressed as a series of questions.

First, *if flexibility is to be found in existing products, where might one find such products*? Such a source must reference a wide variety of products and must provide as much information as possible regarding the basis of the design that led to their development. Potential data sources which satisfy these requirements include reverse engineering actual products, trade magazines and journals, Harvard business cases and the worldwide patent repositories. The USPTO now holds almost seven million patents and so offers an enormous quantity of data for search. Because of requirements of complete disclosure associated with the grant of a patent, it provides extensive information about the inventions it contains, and because it uses a common patent template, facilitates the comparison of a variety of different devices. For these reasons, this paper will focus on a research methodology which uses the USPTO patent repository as a source of information regarding the design choices made by inventors.

Once a data source has been chosen, the next relevant question becomes, *how does one choose, for further examination, those inventions which display flexibility in their design*? To this end, a patent search methodology has been developed and is presented here.

Once a sufficient quantity of promising product patents have been collected, it is time to ask, *what design choices were made by the inventors which led to the inclusion of flexibility in this product*? This data is extracted from a patent through the use of a dissection tool. Specific data from the various sections of a patent are extracted from which inferences can then be made regarding design flexibility.

Finally, one must answer the question, *how can these design choices best be expressed so that they can be used to guide the development of future products*? This issue is addressed by collecting all the inferences made using the data from the patent dissections and organizing them into a list of principles, which may then be used by designers to guide the concept generation process. In some ways, this process is similar to that employed by Dr. Genrich Altshuller in the development of his TRIZ (or TIPS, Theory of Inventive Problem Solving) principles, which are widely accepted and an often used a tool for problem solving [24]. This research methodology is illustrated in Figure 2, and each of its stages is detailed further in the following sections.

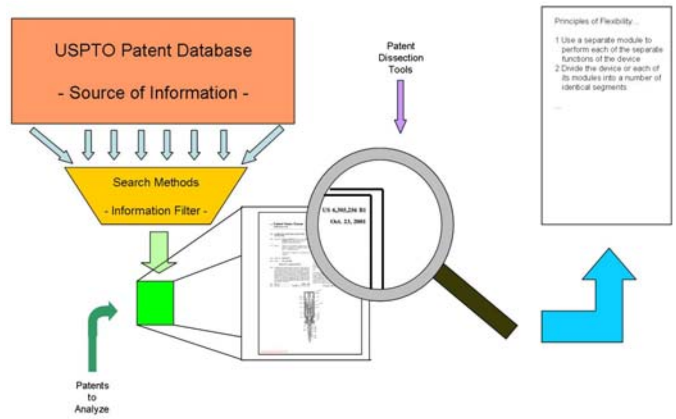


Figure 2. Research Approach

2.1 Patent Searches

2.1.1 Search Tools

A variety of tools are available for searching the many worldwide patent databases. Among these tools are the USPTO website, the European Patent Office (EPO) website, and Free Patents Online [25 - 27]. A number of software packages also exist for searching the various patent databases. These software packages provide an aid in understanding the complex relationships between patents. These include IPVision, founded at the Massachusetts Institute of Technology, Aureka and PatentWeb, both developed by MicroPatent, and the Public Web Examiner Search Tool (PubWEST) developed by the USPTO. All of these require expensive site licenses to operate.

The patent search methodology presented here focuses on the USPTO website, the Free Patents Online website and the PubWEST search tool. The USPTO website allows users to phrase their own search query using Boolean terms in any combination of 31 distinct indexes, such as assignee name, inventor, title, etc. It is also free and convenient to access, but has the disadvantage of only being able to display patent documents one page at a time. The Free Patents Online website allows users to view and download entire patents and includes the ability to link to any past and future references of a selected patent.

The PubWEST software package is capable of much more powerful searches than others as it allows for the use of proximity operators such as ADJ, NEAR, WITH and SAME. The ADJ operator allows for searching two words that are next to each other, or a specified number of words from each other. The NEAR operator finds adjacent words that are in the same sentence, regardless of what order they appear in. The WITH operator searches for any two words in the same sentence, in any order. The SAME operator is similar to the WITH operator, except that SAME searches within the same paragraph. PubWEST also utilizes a very useful user interface which allows numerous way of displaying or linking data.

2.1.2 Search Methods

Three different types of search methods were used to identify those patents which showed a potential for exposing principles of flexibility, and are illustrated in Figure 3. The first of these were *direct methods*, which seek direct references to flexibility in the text of a patent. These methods involved exploring keywords which describe the hypothetical characteristics of a flexible system, such as *adaptable*, *accommodating*, *modifiable*, etc. These searches were combined with limiting words in order to reduce the results returned to a manageable number of patents, to exclude any patents which would not be relevant to the problem at hand, e.g. process patents or design patents, and to limit the scope of the results to the mechanical domain, the focus of this study.

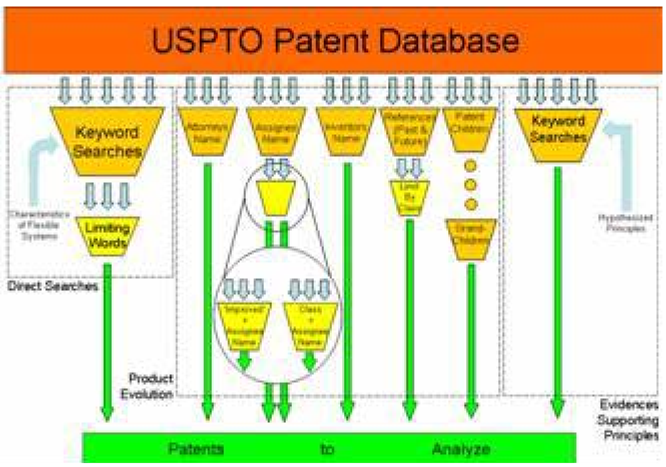


Figure 3. Patent Search Methods

The second type of search was *indirect methods*, or *product evolution* searches, intended to identify candidate patents as a starting point for discovering previous and future evolutions of an invention. The candidate patents were identified by searching for the keyword '*improved*' (or synonymous terms) in the title field and could be limited to patents assigned to a single company or entity in order to reduce the number of results returned. Additional candidates were discovered by searching for patents granted to the same inventor based on the assumption that certain inventors focus on product improvement. Also, the name of the attorney representing the inventor was used as a search term, since some attorneys or firms might specialize in product improvement patents. Further evolutions of the product were found by searching for patents issued to the same assignee listed under the same U.S. Classification by the USPTO. The classification is a means of separating patents into categories according to their context so that they can be more easily organized. Another way in which the patent classification was used is by browsing through the list of all past and future references and identifying those which share the same classification. These are most likely to yield other evolutions of the product. Examining patent continuity data can also be a potential source of product evolutions. Continuity data provides information about patent *parents* and *children*, where '*parents*' refers to those patents which the current one relies upon for priority in the application process and '*children*' are those patents which rely upon the current one for that same priority [28]. Both of these types must necessarily relate to the same invention, although they might be older or newer versions of it.

The third type of search method was *targeted methods*. These were used once a list of principles of flexibility had already been hypothesized in order to discover further examples to support those principles. This search was completed by generating a list of keywords based on design characteristics particular to products exemplifying each principle and then using these keywords as search terms. The results obtained in this way were also limited as before by eliminating certain types of patents and reducing the scope of the searches to the mechanical domain.

2.1.3 Search Results

The search methods yielded a wide variety of patents which showed potential to provide insights about flexibility, 295 distinct patents in total. An initial reading of these filtered out a short list of 90 patents for detailed study. These patents showed the highest likelihood of yielding flexibility principles, based on criteria such as references to other evolutions, multiple preferred embodiments, and direct references to design flexibility in their text. They are listed in Figure 4.

S.No.	Patent #	Patent Title	S.No.	Patent #	Patent Title
1	5255478	Modular institutional workstation	46	5367947	Coffee machine
2	6305041	Pocket tool with removable jaws	47	6122370	Telephone design for mass customization
3	6032386	Golf shoe with removable sole	48	6279836	Portable unit and wall dispensers and method for dispensing with timer
4	5819612	Multiple bit storing hand tool having minimized bulk volume and high storage capacity	49	6663937	Universal mat with removable strips
5	4705176	Article vendor with adjustable column transfer provision for accommodating locally-prevalent space-to-sales ratio	50	6598926	Transformable rear seat
6	6513863	Vehicle interior door apparatus and interlock system	51	5826301	Vacuum cleaner auxiliary brush
7	6265091	Modular electric storage battery	52	5234143	Multi-purpose travel bag
8	4421111	Low-voltage surgical cast cutter with vacuum exhaust of debris	53	5298821	Battery-powered tool
9	6649820	Double bass-drum pedal	54	4421111	Surgical cast cutter with vacuum exhaust
10	3973179	Modular cordless tools	55	6072940	Wallpaper remover with suction cups
11	5588696	Convertible chair with armrests which converts to a backpack	56	6848244	Rotating cutter head
12	5628715	Squat press exercise machine	57	6854350	Calibrated custom instrument gauge module and means for assembly
13	5933918	Handle with interchangeable kitchen implements	58	6179429	Illuminated instrument cluster dial for an automotive vehicle
14	5964065	Advanced surgical suite for trauma casualties	59	6839939	Hubless caster
15	6676179	Front structure of a vehicle body	60	6865821	Vacuum lumber drying kiln with collapsing cover and method of use
16	4238862	Pocket multiple tool	61	6871875	Supporting structure of a commercial vehicle
17	5234143	Multipurpose travel bag	62	6776600	Injection molding machine for producing injection-molded articles
18	5826301	Multipurpose auxilary brush for a vacuum cleaner	63	6540502	Mechanical drive assembly for a brick molding apparatus
19	6216301	Multipurpose folding tool with easily accessible outer blades	64	6446422	Chain drive cutting mechanism for combine
20	6286673	Convertible carrier for golf clubs	65	6299588	Quick release mechanism for orthopedic limb brace
21	6485076	Versatile attachment for a shovel	66	6758650	Bar guiding device in a feeder for feeding machine tools
22	6557871	Stroller with adjustable seat back arrangement	67	6732618	Machine tool
23	6578736	Carton with an improved dispensing feature	68	6871016	Recyclable camera and method for assembling same
24	6580606	Modular drive cage assembly	69	6870650	Illumination device and method for laser projector
25	6598926	Transformable rear seat for a vehicle	70	6869048	De-orbit instrument package
26	6609599	Extensible handle system for carrying containers	71	6865978	Well perforating gun
27	6629601	Multi-function travel golf bag	72	6862842	Modular green roof system, apparatus and methods, including pre-seeded modular panels
28	6634609	Universal accesory adapter for collapsible outdoor furniture	73	6863703	Compact footprint CFB with mechanical dust collector
29	6648372	Skateboard truck guard	74	6869372	Composite wrap bat
30	6659764	Palm actuation lighter	75	6872088	Connector structure and portable terminal device
31	6675413	Lightweight bottom wall structure for play yard, pen, and cot	76	6875945	Welding tongs
32	6708086	Vehicle computer	77	6874726	Corrugated-core flanges for spools and reels
33	6708205	E-mail messaging system	78	2928623	Metal reel and the like
34	4875736	Method for the production of motor vehicle seats an seats obtained	79	1911427	Reel
35	6095660	Equipment using mounting hole for ceiling as fixing elements	80	3108758	Cable reel having sheet metal cheeks
36	3982785	Chair	81	1675507	Reel
37	5451071	Bicycle frame	82	5474254	Spool and method of making same
38	5176645	Pneumatic, modular device for dispensing medication to animals	83	1448355	Wheel disk and the like
39	6293499	Modular, producible, testable and serviceable spacecraft design	84	6820341	Hacksaw having improved blade storage
40	6511263	System for spreading particulate material	85	4238884	Orbital jig saw
41	6142399	Seasoning container having modular components	86	6848985	Hand tool comprising a dust suction device
42	4849585	Modularly constructed vehicle control stalk with interchangeable parts	87	5772498	Electrical hand grinder
43	4050003	Modular Cordless Tool	88	5779195	Satellite assembly having modular common bus components
44	5105398	Three hands type clock with belt drive	89	5145130	Robot serviced space facility
45	6705774	Camera apparatus	90	4126850	Heat pump control having an electronic control module with a bypass system

Figure 4. List of Patents Analyzed for Flexibility

2.2 Patent Dissection

Once a list of patents has been collected for analysis, it is necessary to have a systematic method for extracting data from it and for organizing that data in a way that is convenient for comparison. For this purpose, a data sheet tool was created which provides a template for collecting the kind of data that will be helpful in understanding the facets of an invention's design which make it flexible, which can then be used for formulating a list of principles. This data sheet tool is structured as a series of questions which are designed to lead an examiner towards specific information which is relevant to flexibility. This approach is based on the Socratic Method, which suggests that using questions instead of directive statements helps to promote active participation and to stimulate thinking in focused areas [29]. These questions are further organized into categories phrased as more general questions which are meant to provide the examiner with a context for the information being extracted.

Another feature of this data sheet tool is that it includes an application of Dr. Altshuller's Laws of Development of Systems [30]. These laws allow an examiner to predict ways in which the product is likely to evolve. The data sheet tool includes a list of questions, based on these laws, which are meant to help the examiner predict the next step in the evolution of the device under examination. Once these evolutionary steps are hypothesized, an examiner can search through a patent for those aspects of the product which allow it to accommodate the changes associated with these evolutions, or those aspects which hinder this accommodation. This approach can lead to greater insights about flexibility than reading alone, as it allows an examiner to think about those aspects of the design which might not be explicitly stated in the text of the patent and thus possibly discover less obvious aspects of flexibility. The complete data sheet tool is presented in Figure 5, and an example dissection using this tool is included in Appendix A.

1. General Information		
Front Page		
Patent Number	Patent Title	
2. Reference Information for Product Evolution (Indirect) Searches		
Front Page		
Inventor(s)	Assignee	Attorney, Agent or Firm
References Cited	Referenced By	
U.S. Classification; Explanation of Classification		
Related U.S. Application Data; Patent Children and Grandchildren		
Background and Prior Art Section		
Q: Are Any Products Mentioned Which Might be Previous Evolutions of the Current One?		
3. Information Related to Product Novelty; What Makes it Distinctive?		
Background and Prior Art Section		
Q: Are There Any Unmet Customer Needs in the Previous Products?		
Summary of Invention Section		
Q: What is the Stated Purpose/Field of the Invention?		
Q: What is the Stated Functionality of the Product?		
Q: What is the Stated Novelty of the Product (Advances Over Prior Art)?		
Claims		
Q: Do Any of the Claims Relate to Flexibility?		
4. Product Dissection: How Does it Work?		
Drawings Section and Detailed Description Section		
Create a Drawing of the Preferred Embodiment Architecture; Identify the Modules		
Q: What Function Does Each Module/Component Perform?		
Q: How Difficult Would it be to Separate Each Module From the Rest of the Product, i.e. How Distinct is Each Module?		
Q: What Makes Each Module More/Less Distinct?		
Create Drawings of All Material, Signal and Energy Interfaces		
Q: Does This Patent Have Multiple Embodiments?		
Create a Drawing of the Second Preferred Embodiment Architecture; Identify the Modules		
Q: What Function Does Each Module/Component Perform?		
Q: How Difficult Would it be to Separate Each Module From the Rest of the Product, i.e. How Distinct is Each Module?		
Q: What Makes Each Module More/Less Distinct?		
Create Drawings of All Material, Signal and Energy Interfaces		
Describe How the Product is Configured While in Storage		
Describe How the Product is Configured While in Use		

5. Comparison of Various Embodiments; What Allows it to Change?
Q: What are the Differences Between the Various Embodiments?
Q: Are There any Differences in the Architecture/Layout of the Different Embodiments?
Q: Are There any Differences in Module/Component Sizing?
Q: Are There any Differences in Functionality?
Q: Are There any Differences Between the Storage Configuration and the Use Configuration?
Q: Is the Product Reconfigurable? In What Way?
6. Comparison with Previous Evolutions; How Has it Changed?
Create a Drawing of the Preferred Embodiment Architecture of the Previous Evolution; Identify the Modules
Q: Compare This with the Current Product; What Has Changed? What Has Been the Effect of These Changes on the Other Parts of the Product? What Has Stayed the Same? Why Has This Not Changed?
7. Information Helpful to Predicting Future Evolution; How Will it Change?
Summary of Invention Section
Q: What Type of Product is This?
Q: What is the Target Market of This Product?
Q: What are the Limitations of its Use (e.g. gender, size, weight, etc.)?
Detailed Description Section
Q: What Types of Energy are Used (e.g. human, mechanical, electrical, etc.)?
Q: What Materials is the Product Composed of?
Q: In What Way Does the Human Interact with the Product?
All Sections
Q: What changes would occur in the product as the next step in its evolution under the following laws of development of systems?
1. **The Law of Completeness of Parts of a System** (every technical system must eventually contain an engine, a working organ, a transmission and an organ of steering)
2. **The Law of 'Energy Conductivity' of a System** (energy should be able to pass unhindered through all parts of a system)
3. **The Law of Harmonizing the Rhythms of Parts of the System** (the frequencies of vibration, periodicity, etc. of all parts of the system should be in sync)
4. **The Law of Increasing the Degree of Idealness of the System** (a system strives towards zero weight, area and volume although its ability to carry on functioning remains undiminished)
5. **The Law of Uneven Development of Parts of a System** (the different parts of a system improve at different rates)
6. **The Law of Transition to a Super-System** (once all possibilities for development are exhausted a system is included into a super-system as one of its parts)
7. **The Law of the Transition from Macro to Micro Level** (the development of working organs proceeds at first on a macro level and then on a micro level)
8. **The Law of Increasing S-Field Development** (fields tend to replace substances in the performance of functions, in systems where substances and fields are already interacting the trend is a transition from mechanical to electromagnetic fields, and to greater dispersal of the substance(s) in the field(s))
Question: What alterations would be necessary to allow each of the new features/functionality to be included into the current design?
Question: For those cases where very little alteration is required, what aspect of the current design enables it to accommodate each of the evolutionary changes?
Question: For those cases where considerable alteration is required, what aspect of the current design makes this alteration necessary?

Figure 5. Data Sheet Tool

2.3 The Principles of Flexibility

Martin and Ishii [14, 15] have previously prescribed two broad approaches to achieving flexibility in design. The research presented here has uncovered a total of seventeen new principles of flexibility. Once these principles had been formulated, it was desirable to phrase them in a common lexicon in order to achieve a similar semantic level. This lexicon was derived from an analogy to Dr. Altshuller's TRIZ principles [17] and to the approaches to reducing GVI presented by Martin and Ishii [14, 15]. The principles are divided into four general approaches to achieving flexibility. Each of these approaches begins with a leading statement which is then completed by the principles themselves. The individual principle statements can be applied directly to drive concept generation, while the leading statements and the approaches provide instructions at progressively increasing levels of generalization. Organizing the list in this way fosters a greater depth of understanding in the designer which can lead to the creation of less obvious solutions which might not be directly prescribed by the principles themselves. The complete list of principles is presented in Figure 6.

Modularity Approach

Increase the degree of modularity of a device by…

1 Using a different module to carry out each different function.
2 Dividing each module into a number of smaller, identical modules.
3 Collecting parts which are not anticipated to change in time into separate modules.
4 Collecting parts which perform functions associated with the same energy domain into separate modules.

Spatial Approach

Facilitate the addition of new functionality by…

5 Creating room on the exterior surfaces of the device, in its interior, and around those components which are designed to interface with humans.
6 Extending the available area on the transmission components of the device.
7 Locating those parts which are anticipated to change near the exterior of the device and those which are not near its center.

Interface Decoupling Approach

Reduce the communications between modules and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules by…

8 Standardizing, or reducing the number of different connectors used between modules.
9 Reducing the number of fasteners used, or eliminating them entirely.
10 Reducing the number of contact points between modules.
11 Simplifying the geometry of modular interfaces.
12 Routing flows of energy, information and materials so that they are able to bypass each module at need.
13 Locating modular interfaces on exterior surfaces.
14 Increasing the number of support points present on the structure of the device.
15 Constructing modules from compliant materials.
16 Simplifying the geometry of each component.

Adjustability Approach

Enable the device to respond to minor changes by…

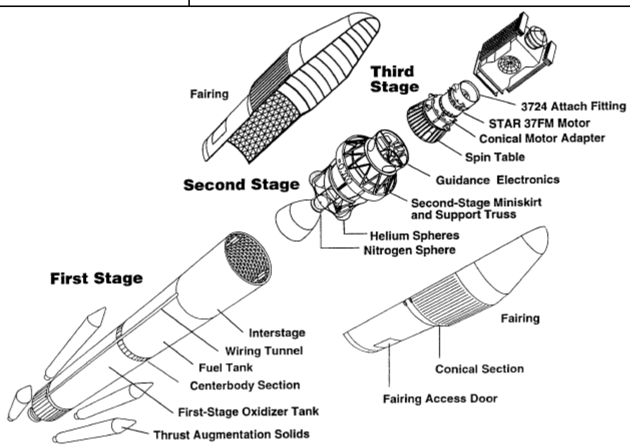
17 Controlling the tuning of design parameters.

Figure 6. The Principles of Flexibility

These principles are listed in Appendix B, along with brief explanations and examples of devices which show aspects of each principle. This should provide the reader with a context to help understand the principles and clarify how they are supposed to be used. Some excerpts from Appendix B are presented in Table 1.

Table 1. Explanation and Examples of the Principles

<table>
<tr><th colspan="2">MODULARITY APPROACH</th></tr>
<tr><th colspan="2">Increase the degree of modularity of a device by…</th></tr>
<tr><td>Principle 1</td><td>Explanation</td></tr>
<tr><td>Using a different module to carry out each different function.</td><td>This principle is exemplified by the method of functional modeling presented in Otto and Wood, 2001. It suggests grouping those functions together which are most closely related to each other and separating a device into modules based on those grouping. The ideal case of an application would be a device in which each function is performed by a distinct module.</td></tr>
<tr><td colspan="2">

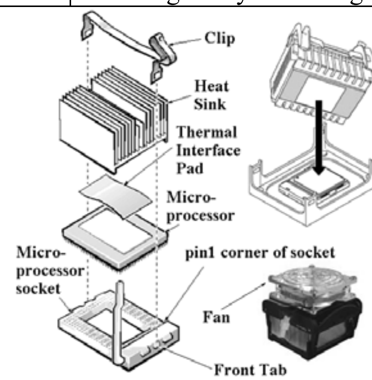


Multi-Stage Rocket [31]

The rocket consists of four highly distinct modules, or stages. The first stage performs the interrelated functions of propulsion and fuel storage, the second performs the function of maneuvering, the third performs the function of stabilization and the final stage is the payload which performs all functions related to scientific testing.</td></tr>
<tr><td colspan="2">

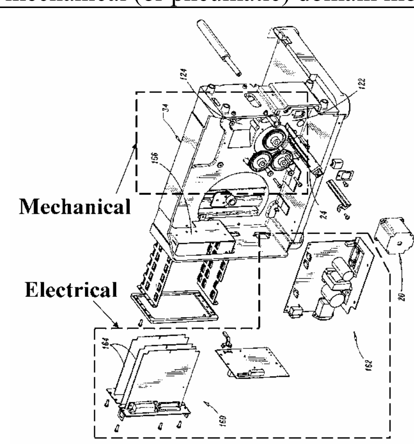
Creative ® MuVo Mp3 Player [32]

This Mp3 player consists of four distinct modules. The protective cover is the clear plastic piece to the far left and performs the function of protection and interfacing with the arm band and other attachments. The power module is the blue piece and contains the rechargeable battery. The black piece with the LCD display is the data module and is essentially a flash memory drive. Finally, the headphones are the output module and serve to export the music and interface with the human user.</td></tr>
<tr><td>Principle 4</td><td>Explanation</td></tr>
<tr><td>Collecting parts which perform functions associated with the same energy domain into separate modules</td><td>This principle is exemplified by the dominant flow modular heuristic method introduced in Otto and Wood, 2001. The idea is that fields of technology tend to advance at different rates and this principle seeks to be able to upgrade a module whose field has advanced without affecting the system design.</td></tr>
<tr><td colspan="2">



Computer Microprocessor Thermal Management System [33]

There are three distinct systems associated with the microprocessor chip which drives modern computing applications. There is the chip itself, i.e. the electrical domain module, the heat sink, i.e. the thermal domain module, and the fan, i.e. the mechanical (or pneumatic) domain module.</td></tr>
<tr><td colspan="2">



Modular Printer [34]

In this design the mechanical and electrical domains are assembled into separate modules. The electrical domain consists of the circuit board inserts and the mechanical domain consists of the force transmission components which drive the paper through the different sections of the printer.</td></tr>
</table>

To validate the completeness of this list of principles, data was collected for a subset of the total patents dissected regarding the number of principles found in each patent examined, and is shown in the graph in Figure 7. This graph shows that over 80% of found in this subset resulted from the dissection of the first half of patents examined. From this data, it can be assumed that the total set of 87 patents resulted in the discovery of a significant subset of all flexibility principles, for the mechanical domain focus of this study.

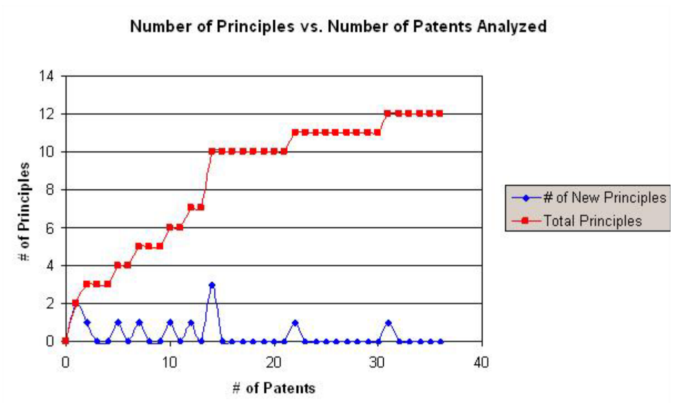


Figure 7. Principles Found vs. Patents Examined

3 APPLICATION OF THE PRINCIPLES: THE FLEXIBLE FUEL CELL GENERATOR

3.1 Motivation & Overview

Fuel cell technology is rapidly emerging as a viable alternative to fossil fuel based power generation systems. Fuel cells have the advantage of utilizing hydrogen as a fuel source, which is in plentiful supply, and producing water vapor as their sole exhaust product, thereby minimizing negative effects on the environment. Cropper et al. [35] states that although the potential environmental and economic benefits of fuel cells are most often cited as the driving forces for further fuel cell development, it is the fuel cell's inherent flexibility that is the most important justification for technology development. Even though fuel cells are intrinsically flexible due to the modular nature of the system, the design and embodiment of fuel cells has traditionally been very application specific. Therefore, as a case study in Design for Flexibility, we will develop a conceptual systems design for a portable fuel cell generator which can quickly and easily accommodate new technological advancements. From a commercial production viewpoint, this would lead to reduced redesign and remanufacturing costs for new product evolutions as well as greatly reduced time-to-market [36, 37].

A complete systems level design solution was created for the flexible fuel cell generator using the principles of flexibility to drive concept generation. This was done using a combination mind map and adapted 6-3-5 method, which is explained further in Section 3.3. The final design solution obtained was then evaluated using an adapted version of the CMEA tool developed by Palani [16]. This tool was used to compare the design of the flexible fuel cell generator to a design for a fuel cell generator produced by the Paul Scherrer Institute (PSI).

3.2 Background: How does a Fuel Cell Generator Work?

A proton exchange membrane (PEM) fuel cell system consists of a fuel cell stack assembly, hydrogen and oxygen supplies, gas supply piping and manifolds, humidity and pressure regulators, and electrical interconnects as well as various structural components. The PEM fuel cell stack itself consists of a bipolar plate, a gas diffusion layer, a catalyst layer and the proton exchange membrane as shown in Figure 8. Electricity is generated when electrons are stripped from the hydrogen at the catalyst layer. The membrane allows the hydrogen protons to pass through, but the electrons are forced to travel through an external circuit generating the current. On the other side of the membrane the hydrogen protons combine with oxygen to from water vapor. The gas diffusion layers and the flow field function to evenly disperse the gas over the membrane.

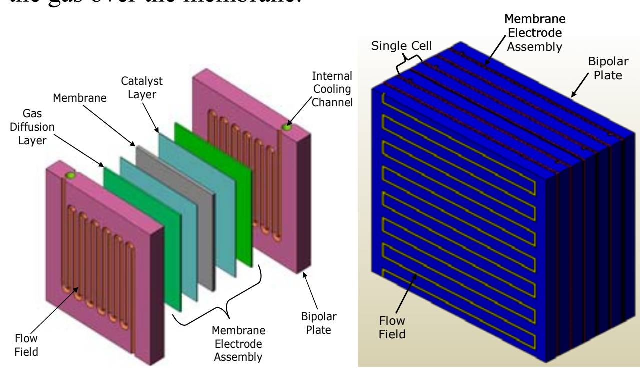


Figure 8. (a) Single cell of a fuel cell stack assembly; (b) Fuel cell stack

The bipolar plates function as current collectors and heat sinks to conduct the current and dissipate the heat of the chemical reaction. Although the fuel cell stack dictates the overall power capacity of the generator, the systems design of the supporting components is critical for maximizing overall system efficiency and ensuring advancements in stack performance have minimal impact on system redesign and remanufacturing costs. The redesign process incorporating the design flexibility principles discussed in the following sections addresses the latter systems design requirement.

3.3 Concept Generation Driven by Flexibility Principles

Concept generation for the flexible fuel cell generator was carried out using a combination mind map and adapted 6-3-5 methodology. The 6-3-5 method generally involves 6 people drawing 3 concepts each and then passing them on to the next person, who may develop these concepts further or add more of his/her own, with this process being repeated for 5 rounds [38]. This adapted method involves laying out a mind map which uses the principles of flexibility as its primary spokes, on the drawing sheet and then generating concepts related to each of the principles or spokes. Thus each person has to generate a number of concepts equal to the number of flexibility principles applied. This method is meant to produce a variety of concepts for each of the sub-systems of a product, which can then be combined into a complete super-system design. This direct application allows the principles to affect every individual part of the super-system and thus produces a more flexible overall solution. This organization also helps to arrange the individual sub-system concepts in a way that makes it easier to combine them into the final design solution. The concepts produced for the flexible fuel cell generator using this method, are presented in Appendix C, and summarized in the form of text in Figure 9.

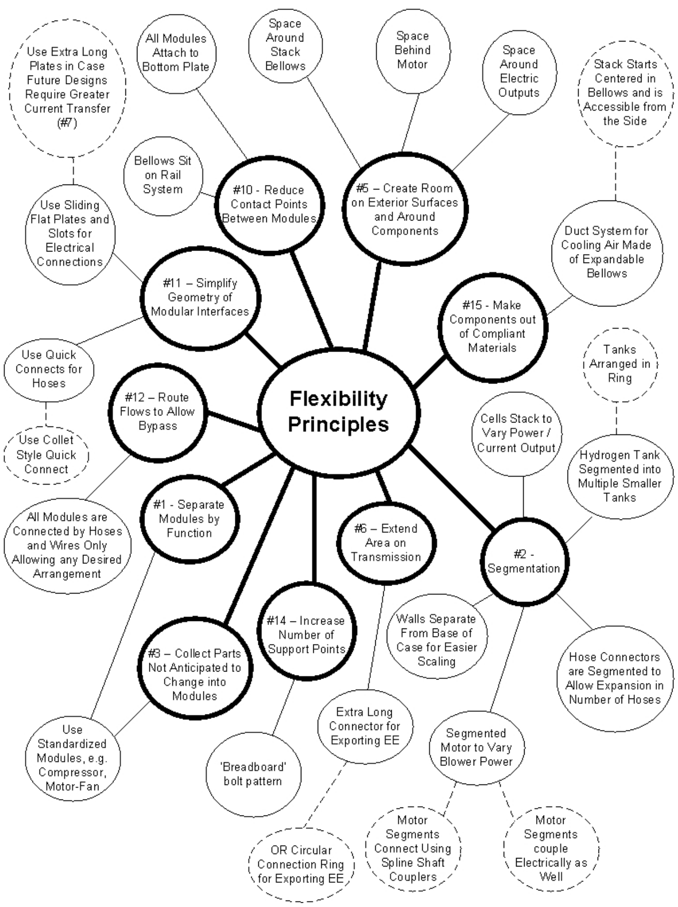


Figure 9. Mind Map of Flexibility Concepts

The systems design concept generated using this method is shown in Figure 10. All of the individual concepts are briefly described in Appendix D, along with the principles which drove their development. Several examples are given in Table 2.

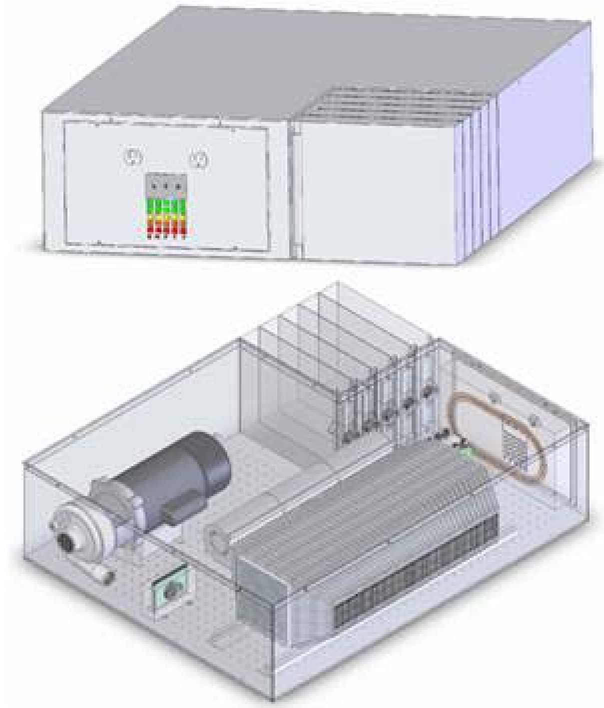
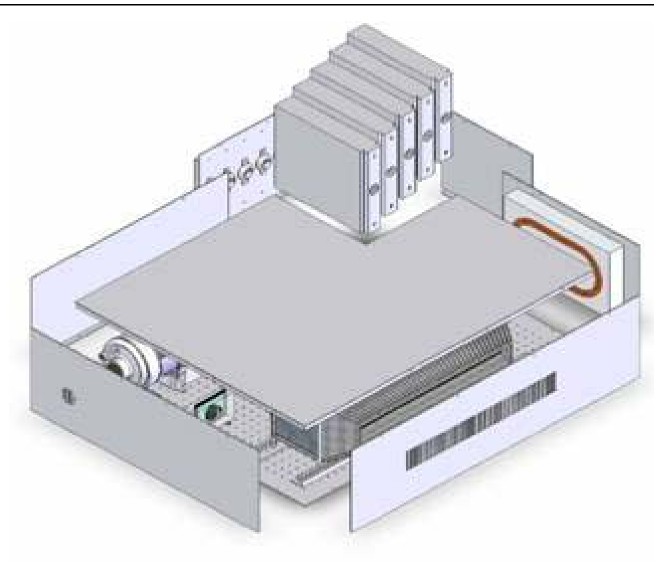
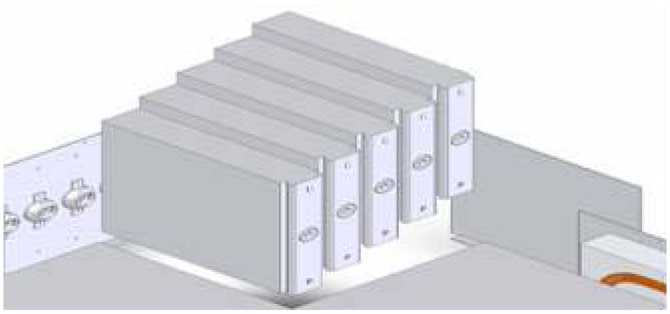
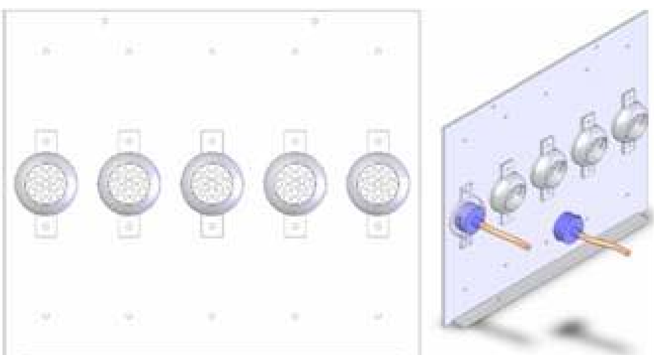
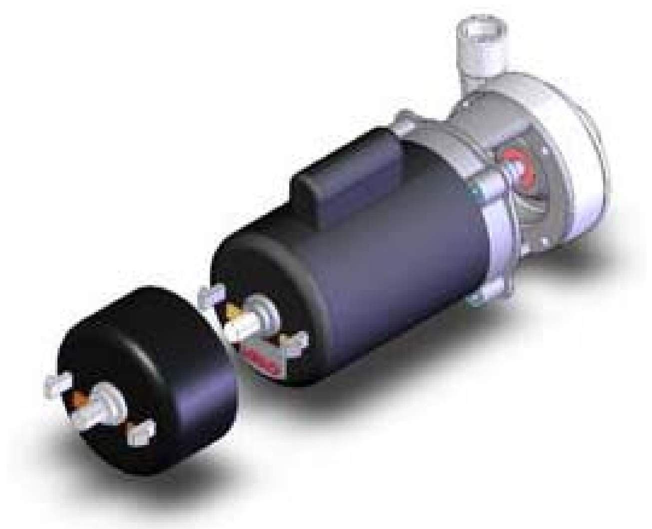
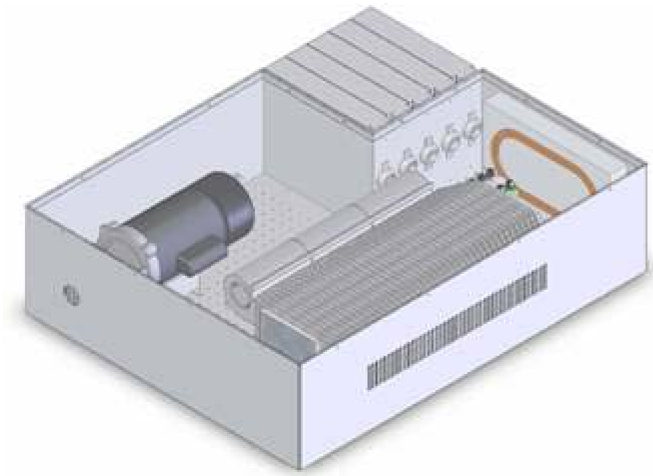
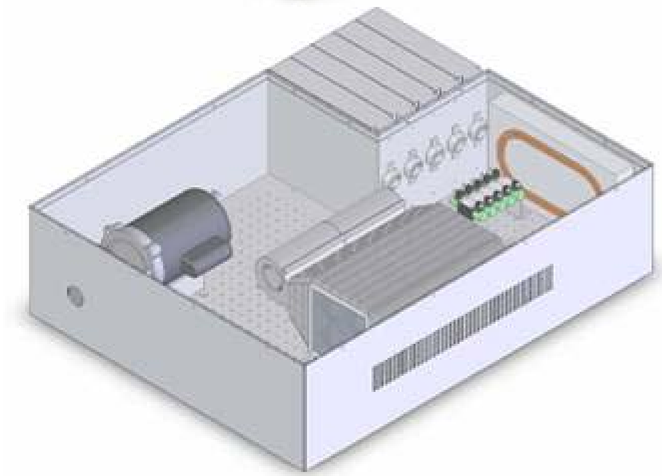


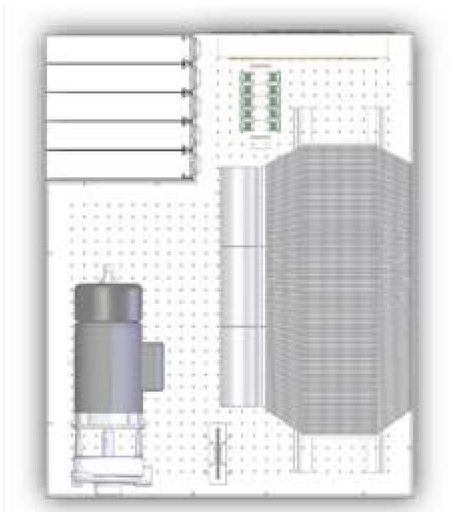
Figure 10. The Flexible Fuel Cell Generator

Table 2. Concepts Resulting from Application of Flexibility Principles

Principle 1: Use a different module to carry out each different function.
 The walls and ceiling of the product casing are made separate from the base plate so that changes to one would not affect the others. For example, re-sizing of inlet or exhaust ducts might require redesign of one or more side walls but would not affect the base plate.
This principle also contributed to the choice to use a standardized motor and pump as stated under principle 3.

Principle 2: Divide each module into a number of smaller, identical modules.
 The hydrogen tanks are segmented into multiple smaller tanks for easy scaling in case of changes in customer requirements.
 The hose connection points are also segmented into a type of honeycomb pattern. Because if this changes in flow requirement need not affect the hose connection points although the hoses will still need to be scaled accordingly.
 The motor may also be segmented into a number of smaller stacks which can connect to each other at the shaft and also electrically so that the pump power may be scaled according to need.

Principle 15: Construct modules from compliant materials.
  The 'Bellows Manifold System' is meant to be used as a form of ducting for the fuel cell cooling system. The most common change expected in the fuel cell generator is the length of the cell stack due either to changing customer needs or to a variety of possible technological advances. Such technological advances might lead to a more efficient cell which would therefore require smaller stacks (in terms of length) or to cheaper manufacturing techniques which might increase the smallest achievable thickness of the cell layers thus causing the stack to get longer. The Bellows Manifold System is designed to expand or contract as the stack length changes or as cooling requirements change, and is mounted on a rail system which allows it to be anchored at any point along their length.

Principle 10: Reduce the number of contact points between modules. Principle 12: Route flows of energy, information and materials so that they are able to bypass each module at need. Principle 14: Increase the number of support points present on the structure of the device.
 Most of the components are fixed to the base plate only. They are connected to each other only by hoses or wires for the different flows and therefore are very easily reconfigurable. The 'Breadboard Bolt Pattern' advocates the use of an evenly distributed matrix of bolt holes instead of a specific pattern in order to provide more freedom in the way that components can be arranged inside the housing.

3.4 Evaluating the Design: CMEA

As a form of validation the complete system design concept was compared to a standard generator design by the Paul Scherrer Institute (PSI) using an adaptation of the CMEA methodology described in Palani et al. [16]. This adaptation involved using only the 'Design Flexibility' column of the CMEA table and brainstorming of the possible changes which might be made to the product, and what the effects (or ripple) of these changes would be to the rest of the product (what kind of redesign, new manufacturing would be needed). Once this information was defined numbers could be assigned for the degree of flexibility of the design to each particular change mode. These numbers were assigned on a scale of 1-10, where a rating of 1 for flexibility defines a system which would require a total change to each of its parts and a rating of 10 describes a system where no change whatsoever would be required to adapt to the new situation. For example, our analysis showed that changes in the customers' requirement of power output, alterations to current plate manufacturing technologies which allow bipolar plates to be produced more cheaply but cause them to be thicker, and the use of a cheaper catalyst which requires thicker catalyst plates, would necessitate a greater stack length. Such a change would impact every system of the PSI fuel cell and require major redesign of most, earning the design a flexibility rating of 2. The flexible Fuel Cell generator would require only an expansion of its 'Bellows Manifold System' and the connection of an additional motor segment, earning it a flexibility rating of 9. Finally, an average value was calculated for the entire system using the flexibility ratings of each individual component and this average used as a basis for comparison. The results of this comparison are presented in Table 3 and the CMEA analysis which produced them is included in Appendix E.

Table 3. Comparison of Flexibility Ratings

PSI Fuel Cell Generator	**5.14**
Flexible Fuel Cell Generator	**9.21**

4 CONCLUSIONS

The application of flexibility to engineering design certainly has important implications in terms of designing products which can adapt to technological change. While the previous work focuses on understanding the benefits of flexibility, finding ways to measure it, and employing it to achieve variety in a single product family, little has been accomplished in terms of assimilating changes wrought by advances in technology. This paper attempts to further our understanding and ability to make use of this very important idea through the creation of a set of flexibility principles.

The process of generating this set of principles comprised three distinct phases, i.e. a patent search, patent dissection and principle formulation. A list of 17 distinct principles is obtained in this way which can offer designers insights into the roots of flexibility. The principles were validated, in part, by their application to a design problem, resulting in the Flexible Fuel Cell Generator. This example shows the utility of using the principles to drive concept generation and collect the individual concepts together into an overall system design. The adapted CMEA results show a significant improvement in flexibility. Intuitive understanding of the product and its possible evolutions reaches the same conclusion. The case study also shows how the principles can be used for guidance during the design embodiment phase. During the embodiment of the stack design, we observed that the only metric changing was the length of the stack and that the design solution generated was capable of handling such a change. If there had been other changes, however, we might have referred back to the principles to evolve the design.

5 FUTURE WORK

Although much progress has been made towards the goal of defining and applying flexibility to engineering design, some areas still remain. The study and analysis of patents should be continued. Although Figure 7 in Section 2.3 suggests that a large percentage of flexibility principles have been found for the mechanical domain, it does not mean that there are no more to uncover. Dr. Altshuller, in his search for the 40 TRIZ principles performed an examination of 200,000 patents [39], and so it can be inferred that continued investigation into patents may revel additional flexibility principles.

Other sources of data should also be examined to determine if they yield any new insights. So far the focus has been on patents, but a thorough analysis of physical products would also be interesting and most useful. Once a comparable list has been obtained from that information domain then a comparison can be made with those principles derived from patents and the search can move on to yet other sources of information.

Further research is also needed to develop a more analytical approach to patent dissection. The approach followed thus far is more experimental and depends, to a great extent, on the expertise and subjectivity of the examiner. This would provide a more consistent data set from which to extract principles and would make great strides in the area of validation.

Acknowledgements

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APPENDIX A: AN EXAMPLE APPLICATION OF THE DATA SHEET DISSECTION TOOL

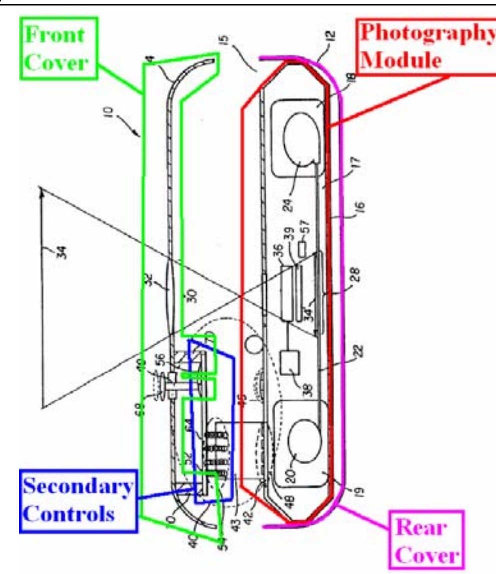
1. General Information	
Front Page	
Patent Number	Patent Title
6871016	Recyclable camera and method for assembling same

2. Reference Information for Product Evolution (Indirect) Searches		
Front Page		
Inventor(s)	Assignee	Attorney, Agent or Firm
Douglas W. Constable	Eastman Kodak Co.	Roland R. Schindler, II

References Cited	Referenced By
3517255, 3519879, 3864600, 4001640, 4082983, 4084167, 4184729, 4196458, 4322143, 4348087, 4438561, 4924149, 5060370, 5329330, 5574337, 5708878, 5717962, 5721986, 5814948, 6434342, 6462780, 6466744, 6473570	None

U.S. Classification; Explanation of Classification
396/6… Photography/Disposable or Recyclable Camera 396/206… Photography/Object Illumination for Exposure/Power Supply Detail/DC to DC Converter 396/542… Photography/Camera Detail/Having Printed Circuit Board
References with Matching U.S. Classification
5329330 (396/6)
Related U.S. Application Data; Patent Children and Grandchildren
Cross reference to related application SER 10/033482 filed December 27, 2001
Background and Prior Art Section
Q: Are Any Products Mentioned Which Might be Previous Evolutions of the Current One?
A previous design for a recyclable camera created by Sakai, et al., US Patent # 5329330

3. Information Related to Product Novelty; What Makes it Distinctive?
Background and Prior Art Section
Q: Are There Any Unmet Customer Needs in the Previous Products?
It is currently difficult to alter the functionality of the camera during the recycling process in order to meet the various customer demands faced by the supplier.
Summary of Invention Section
Q: What is the Stated Purpose/Field of the Invention?
A camera which is able to be easily configured to perform different sets of functions.
Q: What is the Stated Functionality of the Product?
It has to be able to take pictures in various lighting conditions, be easy to assemble and disassemble, and be reconfigurable between various different sets of functions, e.g. 'one touch' flash charging vs. 'press and hold' flash charging.
Q: What is the Stated Novelty of the Product (Advances Over Prior Art)?
The novelty of this product comes from the way in which the circuit board is embodied. The circuit board is split into two separate and distinct modules, the first of which can function independently or be combined with a second to alter the functionality of the overall board.
Claims
Q: Do Any of the Claims Relate to Flexibility?
17. The camera of claim **10**, wherein the second circuit board comprises more than one separate module.

4. Product Dissection; How Does it Work?
Drawings Section and Detailed Description Section
Create a Drawing of the Preferred Embodiment Architecture; Identify the Modules

Q: What Function Does Each Module/Component Perform?
Front Cover… support structure, light guidance (lens), human interface Rear Cover… support structure Photography Module… light guidance, basic controls, data

collection, data storage

Secondary Controls… advanced camera functions, e.g. 'one touch' flash charging

Q: How Difficult Would it be to Separate Each Module From the Rest of the Product, i.e. How Distinct is Each Module?

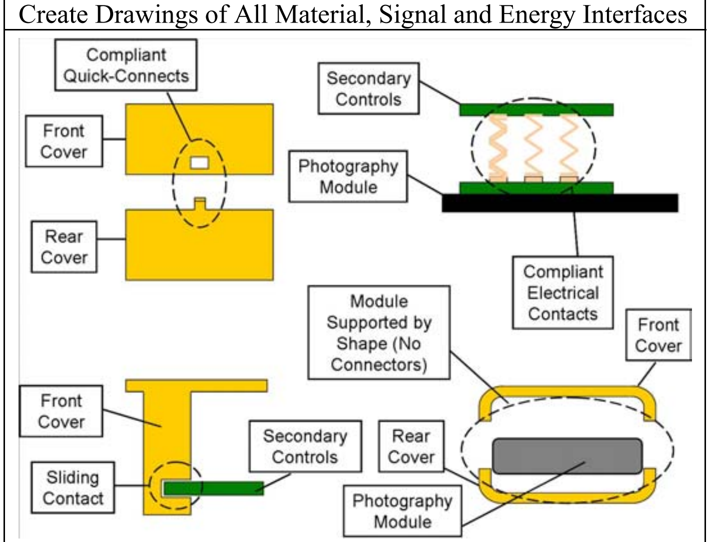
All modules are connected to each other using compliant quick-connects and so are very easy to separate from each other. The secondary controls module and photography modules cannot be separated from the device, however, unless the front cover is first separated from the rear cover.

Q: What Makes Each Module More/Less Distinct?

The secondary controls module is internal and therefore cannot be removed without first being accessed, which requires separating the front and rear covers. It connects to the front cover module by sliding into a slot which makes it very easy to remove, and interfaces to the photography module via compliant contacts, and is held in place by pressure exerted by the front cover and so separates very easily from the photography module.

Another factor contributing to the distinctness of each module is the separation of functionality. Most of the photography functions are contained in the photography module. Only the guidance of light is shared with the front cover and this function does not require any material interface to be shared. Also, the controls function is shared between the photography module and the secondary controls module but the design of the interface between these two modules allows them to be distinct. The compliant connectors allow freedom of placement of the secondary controls module relative to the photography module, and the contact of spring on flat conducting plate is very simple in terms of geometry and does not impose any additional constraints on the design.

Create Drawings of All Material, Signal and Energy Interfaces



Q: Does This Patent Have Multiple Embodiments?	Yes

Create a Drawing of the Second Preferred Embodiment Architecture; Identify the Modules

The various embodiments are different only in the way they connect the secondary control module to the front cover module. They each present different forms of quick-connect methods which do not involve the use of fasteners.

Q: What Function Does Each Module/Component Perform?

Same as primary embodiment.

Q: How Difficult Would it be to Separate Each Module From the Rest of the Product, i.e. How Distinct is Each Module?

Same as primary embodiment.

Q: What Makes Each Module More/Less Distinct?

Same as primary embodiment.

Create Drawings of All Material, Signal and Energy Interfaces

Same as primary embodiment.

Describe How the Product is Configured While in Storage

There is no change in configuration between storage and use.

Describe How the Product is Configured While in Use

See previous.

5. Comparison of Various Embodiments; What Allows it to Change?

Q: What are the Differences Between the Various Embodiments?

The only difference is the way in which the secondary controls module is interfaced with the front cover module as mentioned previously.

Q: Are There any Differences in the Architecture/Layout of the Different Embodiments?

See above.

Q: Are There any Differences in Module/Component Sizing?

See above.

Q: Are There any Differences in Functionality?

No.

Q: Are There any Differences Between the Storage Configuration and the Use Configuration?

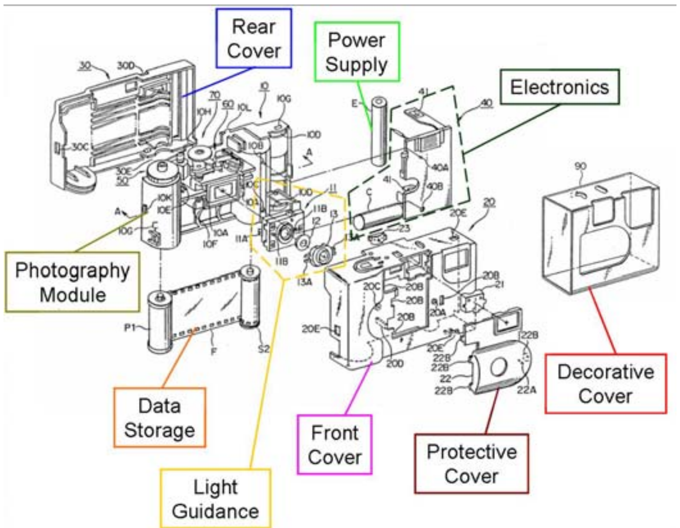
No.

Q: Is the Product Reconfigurable? In What Way?

It is possible to replace the secondary control module in order to perform any desired functions, or this module can be removed entirely and the camera can function with only the primary control system, which is integrated into the photography module.

6. Comparison with Previous Evolutions; How Has it Changed?

Create a Drawing of the Preferred Embodiment Architecture of the Previous Evolution; Identify the Modules



Q: Compare This with the Current Product; What Has Changed? What Has Been the Effect of These Changes on the Other Parts of the Product? What Has Stayed the Same? Why Has This Not Changed?

The `330 patent (5329330) was published in 1994 and the `019 patent (6871016) was published in 2005 so there has been considerable change in the technology involved between evolutions. The most striking change is that while the camera of the `330 patent (previous evolution) carries out most of its photographic functions, i.e. shutter action, film progression, etc., using mechanical means the camera of the `016 patent (current design) performs these functions using electronic means. Because of this the synchronization of the processes involved with photography has been automated whereas before it had to be performed manually by the user, and controls had to be provided for this purpose. This change from the mechanical to the electrical domain has also made miniaturization more feasible and so the interior volume of the current design is limited more by the focal length of the lens used than by the size of its components, as was that of the previous evolution.

Another change between evolutions is that the front cover of the current design integrates the protective and decorative covers of the previous evolution. This has the apparent effect of reducing the flexibility of the design between evolutions, but before such a determination can be made it will be necessary to have more information related to manufacturing of these components, as it is possible that advances in this area have made it cheap enough to vary the look of the front cover that it is not necessary to separate that function into a different module, as done in the previous evolution. It is also possible that advances in lens technology have made the protective cover unnecessary and it has therefore been removed rather than integrated or that it has been integrated, in a sense, into the lens itself to which its functionality is inherently tied.

One thing which has remained constant across evolutions is the functions performed by the photography module, although the manner in which they are performed has changed. This suggests that these functions are intimately associated with each other and probably constitute a standard module.

7. Information Helpful to Predicting Future Evolution; How Will it Change?

Summary of Invention Section

Q: What Type of Product is This?

Single use camera

Q: What is the Target Market of This Product?

Tourists/vacationers, special occasions.

Q: What are the Limitations of its Use (e.g. gender, size, weight, etc.)?

It is oriented for right-handed operation, is capable of a single focus only and can only be used until the included film is used up.

Detailed Description Section

Q: What Types of Energy are Used (e.g. human, mechanical, electrical, etc.)?

Mainly electrical, though some small amount of human energy is needed for control input.

Q: What Materials is the Product Composed of?

Plastics, trace metals in the circuitry.

Q: In What Way Does the Human Interact with the Product?

The human has to aim it and manipulate the buttons.

All Sections

Q: What changes would occur in the product as the next step in its evolution under the following laws of development of systems?

1. **The Law of Completeness of Parts of a System** (every technical system must eventually contain an engine, a working organ, a transmission and an organ of steering)

The camera system of the current design already contains an engine, in the form of the battery, a working organ, in the form of the shutter, a transmission, in the form of the circuit paths and wiring, and an organ of steering, in the form of the user interface. The greatest potential for change exists in the organ of steering. Currently this allows the user to choose to charge the flash or not and to snap pictures. No means for adjusting focus is available and that would be the most likely next evolutionary step. This might be accomplished by manual means using user input or automatically by the camera controls circuit. Further evolution beyond this might involve the inclusion of a steady shot feature or image targeting like the kind which exists in digital cameras currently.

2. **The Law of 'Energy Conductivity' of a System** (energy should be able to pass unhindered through all parts of a system)

N/A

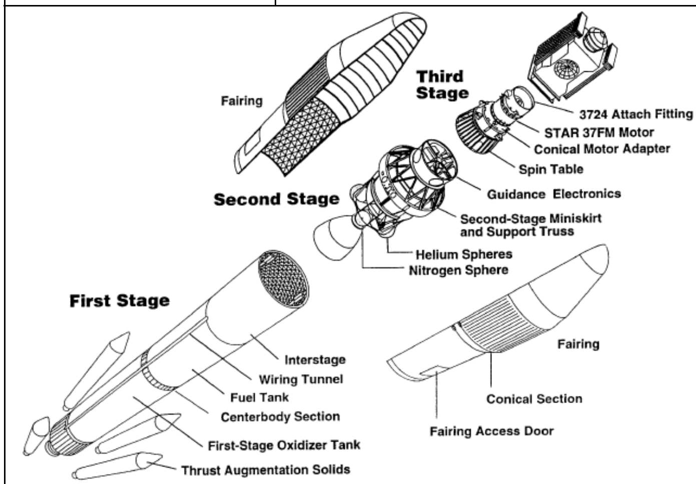
3. **The Law of Harmonizing the Rhythms of Parts of the System** (the frequencies of vibration, periodicity, etc. of all parts of the system should be in sync)
Currently the camera controls circuit synchronizes all the camera functions, i.e. flash, shutter, and film progression. The only evolutionary change envisioned here is that if any new functionality, e.g. auto-focus, is added to the camera the controls circuit would have to adapt its synchronization function to include this new functionality.
4. **The Law of Increasing the Degree of Idealness of the System** (a system strives towards zero weight, area and volume although its ability to carry on functioning remains undiminished)
Instead of storing the image information captured by the camera on a photographic film, a digital sensor and flash memory card could be used. Another, more unlikely possibility, is to replace the shutter mechanism with a lens capable of changing its transparency to block or allow light through.
5. **The Law of Uneven Development of Parts of a System** (the different parts of a system improve at different rates)
This law also lends support to the idea of moving from a film storage medium to flash memory.
6. **The Law of Transition to a Super-System** (once all possibilities for development are exhausted a system is included into a super-system as one of its parts)
N/A
7. **The Law of the Transition from Macro to Micro Level** (the development of working organs proceeds at first on a macro level and then on a micro level)
This law lends some support to the idea of a variable transparency lens, and also suggests the possibility of a compliant lens which can alter its focal length upon application of an electric potential or some other stimulus.
8. **The Law of Increasing S-Field Development** (fields tend to replace substances in the performance of functions, in systems where substances and fields are already interacting the trend is a transition from mechanical to electromagnetic fields, and to greater dispersal of the substance(s) in the field(s))
This law lends support to the idea of the variable transparency and variable focus lenses and to the transition form film media to flash memory. It also suggests the possibility of connecting circuits through wireless means rather than physical interfaces.
Question: What alterations would be necessary to allow each of the new features/functionality to be included into the current design?
Manual/Auto Focus… the current lens would likely have to be changed and a new movable lens added to the camera so that focus could be controlled. In order to implement auto focus, alterations to the control circuit would also be necessary. Steady Shot or Image Targeting… this would only be possible after a switch from film to digital media for image storing. Once this change was accomplished, the addition of steady shot or image targeting functionality would only require alterations to the control circuitry. It might also possibly involve a change in the image capture surface (steady shot requires an area slightly greater than the actual image captured) but this would depend on the embodiment of the image capture surface, as this extra area would be useful for other features as well, e.g. widescreen/panoramic view. Flash Memory… this evolution would likely involve major change to the photography module and some additional change to the control circuit of the camera. Variable Transparency/Focal Length Lens… this would involve a change in the lens integrated into the front cover module and an addition of functionality to the control circuit of the camera. Wireless Circuit Connections… this would only require a change in the camera circuits to include the receiving/transmitting functionality and would of course involve the removal of the current interfaces between circuits.
Question: For those cases where very little alteration is required, what aspect of the current design enables it to accommodate each of the evolutionary changes?
The empty space present between the front cover and the photography module allows for the inclusion of the second, movable lens. This space was probably included because of the focal length of the current lens, but could certainly be used to accommodate a focusing mechanism, especially if the current lens were changed to accommodate this mechanism. The modular circuit architecture and, with compliant interface and quick-connectors allows for quick and easy alterations to the functionality of the control system of the camera.
Question: For those cases where considerable alteration is required, what aspect of the current design makes this alteration necessary?
The integration of the image capture and data storage functions into the photography module requires changes in the whole module to accommodate the shift from film media to flash memory. If these functions were separated into a distinct module, it might be easier to adapt the current design to this change.

APPENDIX B: THE PRINCIPLES OF FLEXIBILITY

MODULARITY APPROACH

Increase the degree of modularity of a device by…

Principle 1	*Explanation*
Using a different module to carry out each different function.	This principle is exemplified by the method of functional modeling presented by Otto and Wood [52]. It suggests grouping those functions together which are most closely related to each other and separating a device into modules based on those grouping. The ideal case of an application would be a device in which each function is performed by a distinct module.



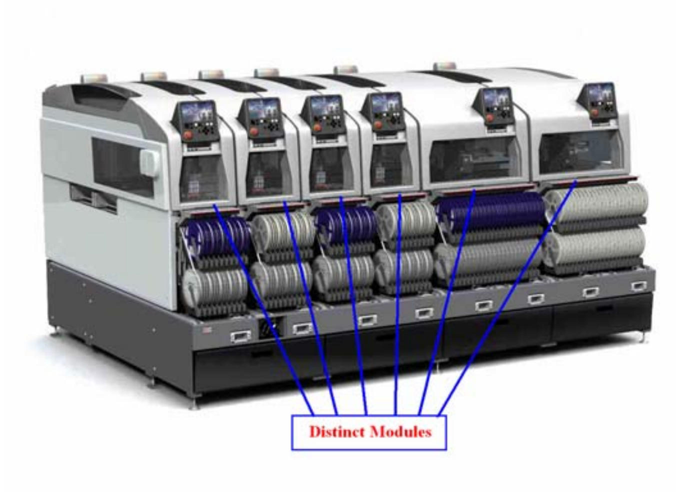
Multi-Stage Rocket [31]

The rocket consists of four highly distinct modules, or stages. The first stage performs the interrelated functions of propulsion and fuel storage, the second performs the function of maneuvering, the third performs the function of stabilization and the final stage is the payload which performs all functions related to scientific testing.

Creative ® MuVo Mp3 Player [32]

This Mp3 player consists of four distinct modules. The protective cover is the clear plastic piece to the far left and performs the function of protection and interfacing with the arm band and other attachments. The power module is the blue piece and contains the rechargeable battery. The black piece with the LCD display is the data module and is essentially a flash memory drive. Finally, the headphones are the output module and serve to export the music and interface with the human user.

Principle 2	*Explanation*
Dividing each module into a number of smaller, identical modules.	This is mainly to facilitate scaling and parametric redesign, and also to allow relative motion between the newly created segments thus enabling designers (or the user) to reconfigure the product in order to create empty space or otherwise facilitate the addition of new functionality.



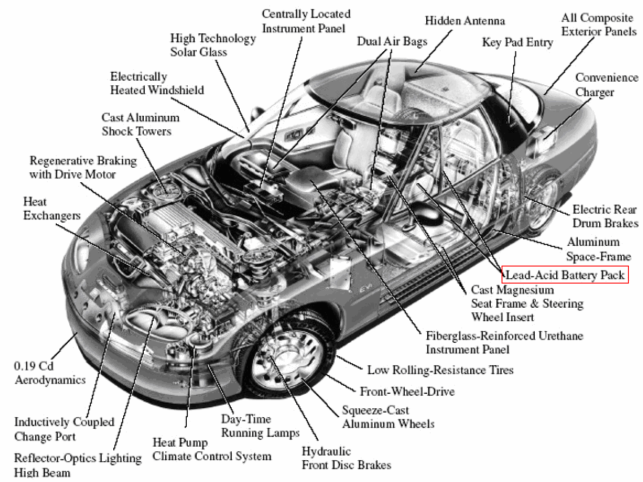
Chip Placement Platform [40]

The picture shows a machine which is used during the manufacture of circuit boards and is used to attach the silicon chips to the incoming wafers. Each of the modules shown are distinct and autonomous and so the device can easily be scaled to respond to technological improvements in other parts of the production line which might lead to increased production volume.

Dell ® Blade Server [41]

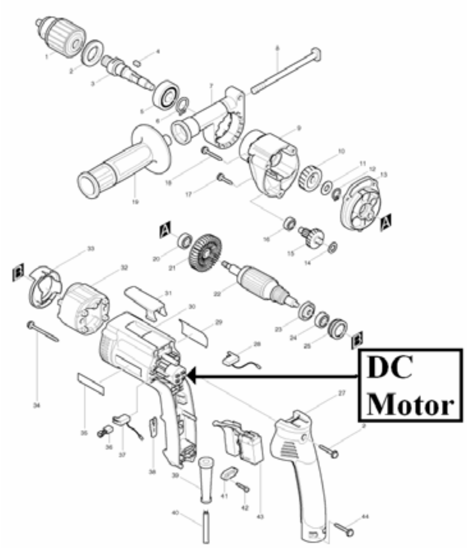
Blade servers are commonly used in high power computing applications. Each 'blade' is a separate and autonomous processor and thus processor capability may be scaled by the addition or removal of the required number of blades.

Principle 3	*Explanation*
Collecting parts which are not anticipated to change in time into separate modules.	Over time some technologies become commonplace and standardized. This principle suggests collecting these technologies into separate modules and using them in cases where a certain technical requirement is not predicted to change.



General Motor's EV-1 [38]

This was a concept car developed by GM intended to be powered by a hydrogen fuel cell and contain a number of other highly advanced technological systems, but the function of providing start up power was still performed by a simple lead-acid battery.

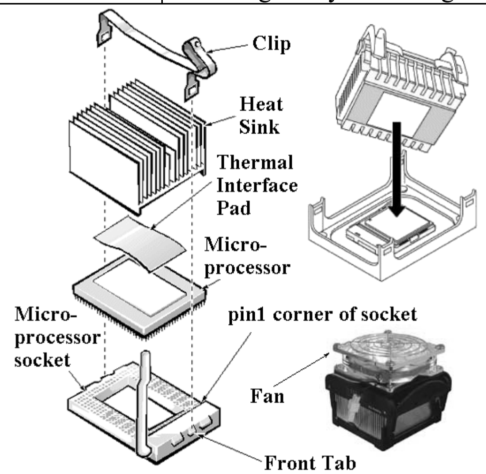


Makita ® Power Drill [42]

This Makita ® power drill and most other portable power tools make use of a standardized DC motor as their prime mover, regardless of their overall function.

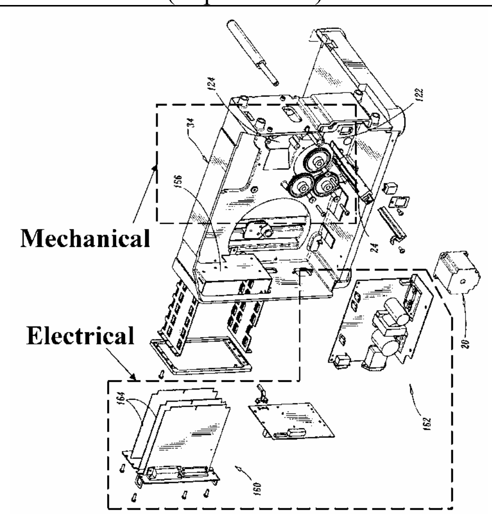
Principle 4	*Explanation*
Collecting parts which perform functions associated with the same energy domain into separate modules	This principle is exemplified by the dominant flow modular heuristic method introduced in Otto and Wood, 2001. The idea is that fields of technology tend to advance at different rates and this principle seeks to be able to upgrade a module whose field has advanced without

	affecting the system design.



Computer Microprocessor Thermal Management System [33]

There are three distinct systems associated with the microprocessor chip which drives modern computing applications. There is the chip itself, i.e. the electrical domain module, the heat sink, i.e. the thermal domain module, and the fan, i.e. the mechanical (or pneumatic) domain module.



Modular Printer [34]

In this design the mechanical and electrical domains are assembled into separate modules. The electrical domain consists of the circuit board inserts and the mechanical domain consists of the force transmission components which drive the paper through the different sections of the printer.

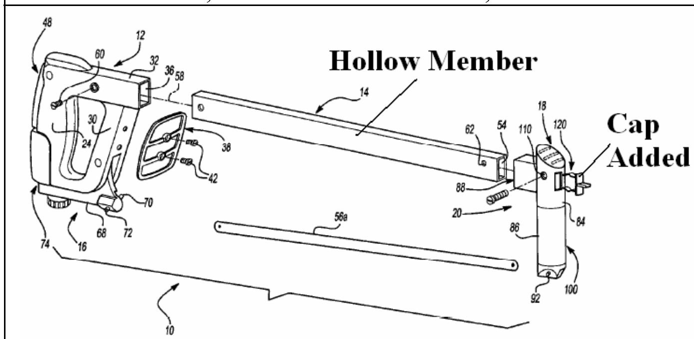
SPATIAL APPROACH

Facilitate the addition of new functionality by…

Principle 5	*Explanation*
Creating room on the exterior surfaces of the device, in its interior, and around those components which are designed to interface with humans	The idea behind this principle is to have space available for the future addition of components or modules related to new functionality or for expansion of existing components or modules.

Computer Case [43]

Computer cases generally contain empty space on the front section where additional components which require an external interface, such as DVD-RW drives, can be inserted.



Hacksaw with Improved Blade Storage [44]

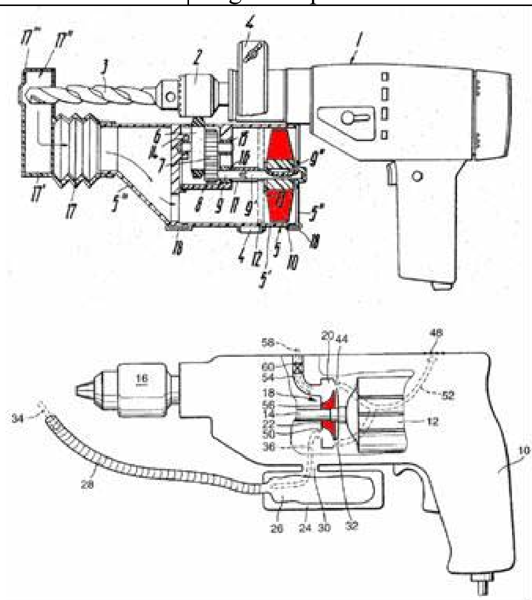
The structural member of the hacksaw shown above was hollow in its previous evolution as well. In this version of the device, a cap was added to the front end to allow this cavity to be accessed and thus used as storage for spare blades.

Pot with Extended Handle [45]

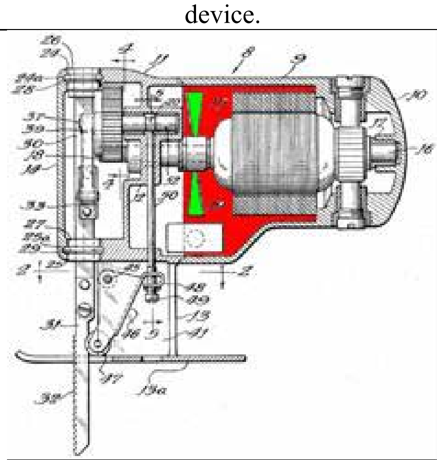
Then handle of this pot extends out in space so that there is ample clearance all around it, which would facilitate possible changes associated with ergonomic redesign, e.g. the addition of a wrap or rubber grip.

Principle 6	*Explanation*
Extending the available area on the transmission components of the	The idea behind this principle is to make it possible for components or modules added in a future evolution of the product should be able to

device.	receive energy from the existing engine or prime mover.

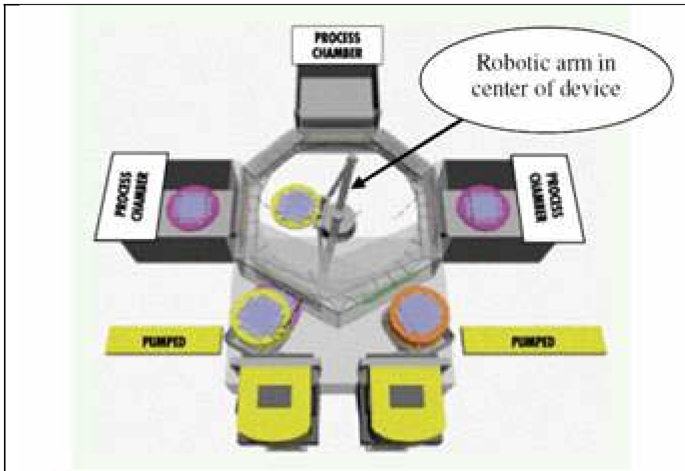


Drill Tool with Dust Suction Device [46, 47]
The design on top shows the need for a suction module to draw debris away from the drill bit and the bottom one shows how empty space around the transmission shaft could have facilitated the addition of that functionality to the original device.

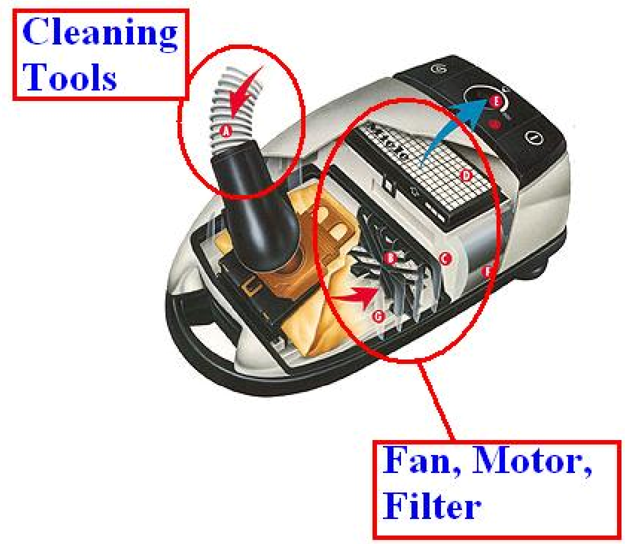


Portable Power Driven Reciprocable Cutting Tool [48]
In this design the cooling fan, shown in green, has been added onto the motor shaft. The empty space, shown in red, would have facilitated this addition.

Principle 7	*Explanation*
Locating those parts which are anticipated to change near the exterior of the device and those which are not near its center	The idea behind this principle is to allow changes to be made to the device without having a great effect on the manufacturing or assembly process.



Applied Materials Centura Wafer Machine [49]
The robotic arm can be used for a variety of different tests and so s placed in the center of the system, while the testing chambers, placed at the periphery may be altered at need.



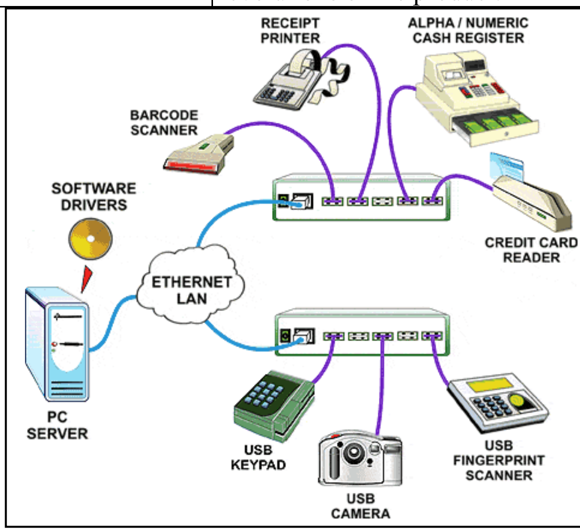
Vacuum Cleaner [50]
The motor, fan and filter components are placed closer to the center, while components such as the human interface, electrical connectors, and cleaning tools are placed closer to the exterior of the device.

INTERFACE DECOUPLING APPROACH

Reduce the communications between modules and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules by…

Principle 8	*Explanation*
Standardizing, or reducing the number of different connectors used between modules.	If fasteners are custom made, then it is best to use the same ones throughout the device to avoid the necessity of manufacturing multiple kinds. If that is not possible,

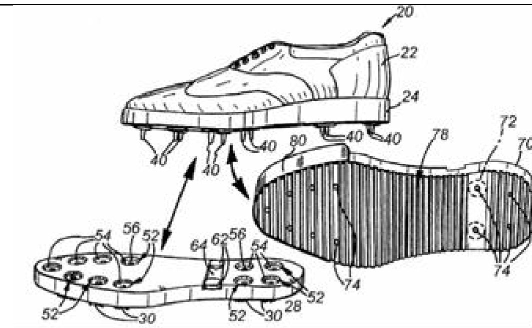
	commercially available fasteners should be used, so that compatibility issues may be avoided with future evolutions of the product.



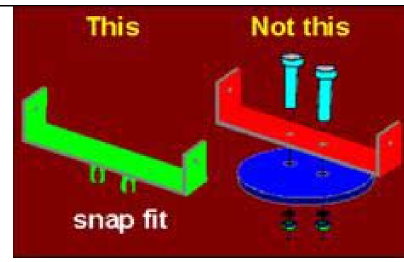
USB Connectors [51]
Many electronic devices use the common USB interface to link to a computer or to each other.

Audio Mixer Showing RCA Connectors [52]
Audio mixers are able to connect to their various input and output components using standard RCA audio connectors.

Principle 9	*Explanation*
Reducing the number of fasteners used, or eliminating them entirely.	The idea behind reducing the number of fasteners is to make the connections between modules less obtrusive and to reduce the effect of redesign on assembly procedures.

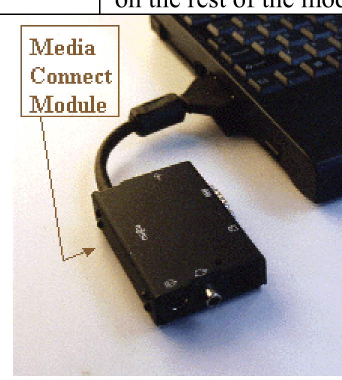


Golf Shoes with Interchangeable Soles [49]
The soles of the shoe connect using magnets and so there is no need for fasteners.



Compliant Quick-Connectors [49]
The use of compliant quick-connectors reduces the number of parts which have to be redesigned or remanufactured when a component changes.

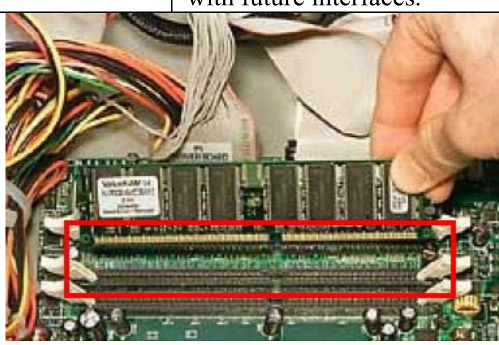
Principle 10	*Explanation*
Reducing the number of contact points between modules.	The idea behind this principle is to reduce the communication between modules allowing changes to be made to the interfaces between modules while minimizing the effect on the rest of the module.



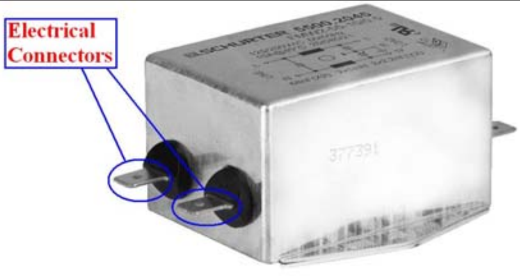
Media Connect Module [53]
This connects to the laptop only through its USB wire, and so there are no constraints in terms of what size or shape it has to be in order to interface and no such changes are necessary to the laptop either.

Camera with Flash [54]
The camera attaches to the flash at only a single point and so is able to accommodate a variety of different flash designs.

Principle 11	*Explanation*
Simplifying the geometry of modular interfaces.	This principle is also intended to reduce communication between modules, based on the idea that if modular interfaces are simpler, this reduces the chance of incompatibility with future interfaces.

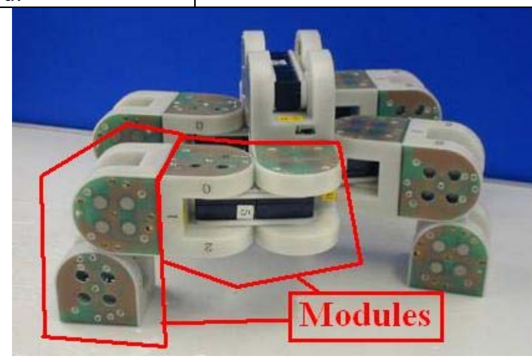


Computer RAM Memory Chip [49]
The electrical interface between the chip and the motherboard is accomplished by simple flat conducting plates mounted on a straight flat surface.

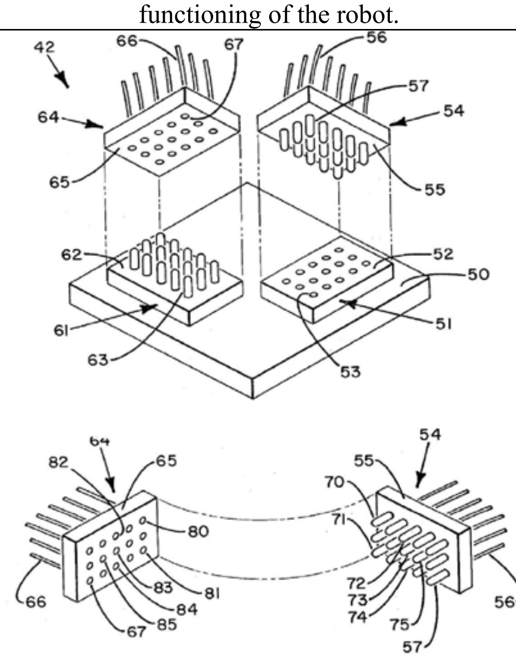


Single-Phase EMI/RFI Block Filters [55]
These filters make their electrical connections by means of simple flat conducting plates.

Principle 12	*Explanation*
Routing flows of energy, information and materials so that they are able to bypass each module at need.	The idea behind this principle is to enable a device to perform all its vital functions despite the replacement or removal of one of its modules, or in the case of reconfiguration.



M-Tran Self Reconfigurable Modular Robot [56]
The flow of power and information from any given point to another point in this device is independent of the arrangement or even number of modules used. Therefore, any module can be moved or removed entirely without affecting the functioning of the robot.



Electronic Circuit with Bypass [57]
The electrical connectors, 54 and 64 in the figure above, are designed to interface with each other in the absence of the control circuit and thus functionality can be maintained regardless or whether or not the control module is connected.

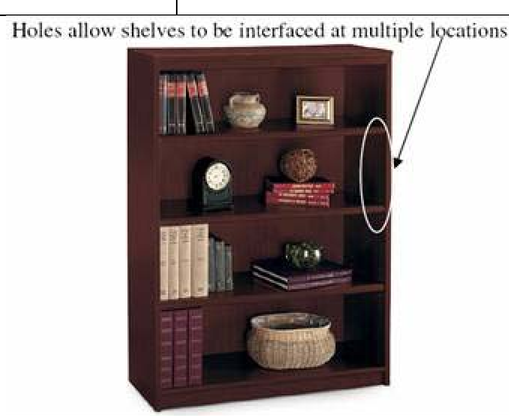
Principle 13	*Explanation*
Locating modular interfaces on exterior surfaces.	The idea behind this principle is to simplify the replacement of modules and also to minimize the effect of redesign on the assembly or

	manufacturing process.

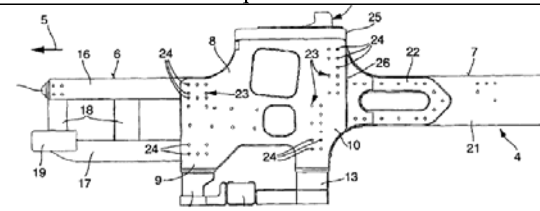
Black & Decker Fire Storm Multi Tool [49]
All the tooling modules attach to the exterior of the motor and battery core thus requiring no change to the core if a new tooling module is designed and added to the capabilities of the product.

Fighter Jet [49]
The weapon and fuel tank modules attach externally to the wings and so any alterations in these have only a minimal effect on the design of the rest of the jet.

Principle 14	*Explanation*
Increasing the number of support points present on the structure of the device.	The idea behind this principle is to allow the device layout to be easily changed thus allowing more options in terms of redesign.

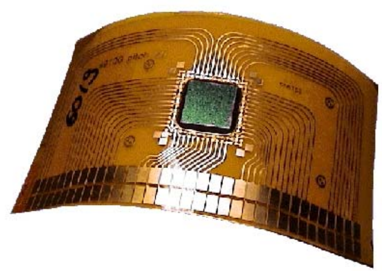


Bookcase [49]
Fastener holes to support shelves are located all along the insides of the vertical side walls. This allows the shelves to be resized at need and so adapt to changing customer requirements.

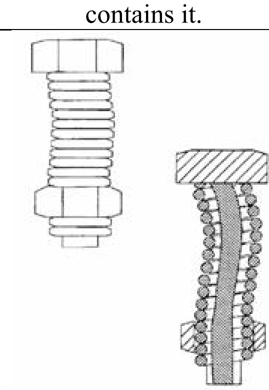


Support Structure of a Commercial Vehicle [58]
Extra fastener holes, 23 and 24 in the figure above, are included in this design to allow the components of the vehicle to be arranged in a variety of ways in order to achieve a variety of road clearances.

Principle 15	*Explanation*
Constructing modules from compliant materials.	The idea behind this principle is that compliant components can be deformed and so it is possible to open up new usable space and also provides more freedom in terms of the design layout.

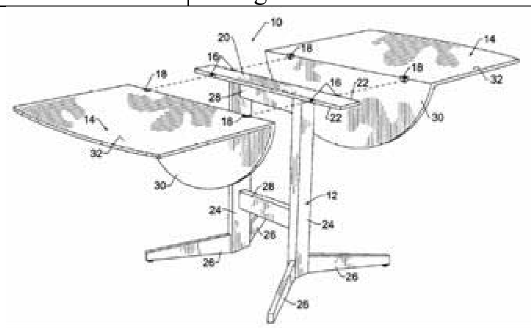


Flexible Circuit Board [59]
This circuit is printed on a compliant material and therefore is better able to adapt to possible changes in the housing which contains it.

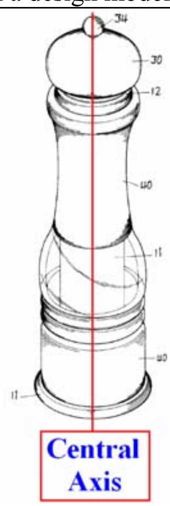


Flexible Fastener [60]
This nut and bolt set is comprised of spiral teeth wound round a compliant core and thus is able to accommodate a variety of

changes in the components it interfaces with.	
Principle 16	*Explanation*
Simplifying the geometry of each component.	The idea behind this principle is that the redesign effort will be sped up because such parts can be easily changed.

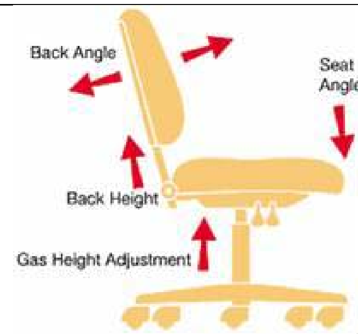


Convertible Table [49]
The components of this table are composed of regular shapes, i.e. straight rectangles and circles. Such components would be easier to represent in a design model and to manufacture.

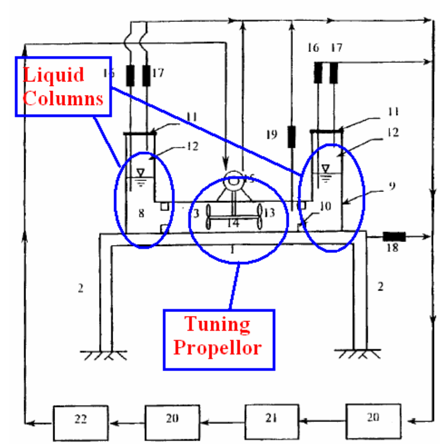


Seasoning Container [49]
All the components of this device are rounded and symmetrical around the central axis. This regularity simplifies redesign and also manufacturing as off-center features are generally more difficult to produce on rounded parts.

ADJUSTABILITY APPROACH	
Enable the device to respond to minor changes by…	
Principle 17	*Explanation*
Controlling the tuning of design parameters.	The idea behind this principle is to avoid minor redesign by introducing tuning parameters.

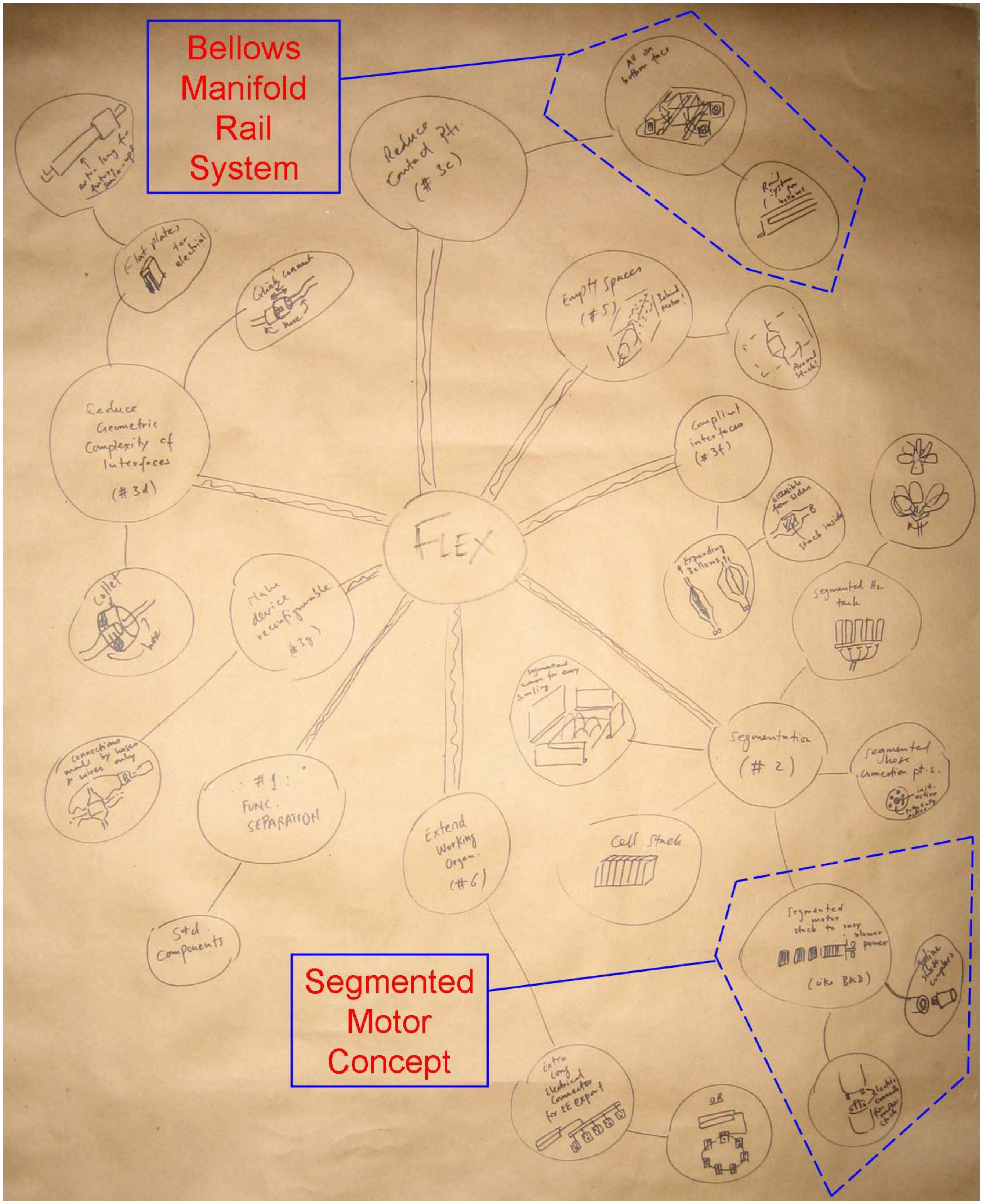


Adjustable Office Chair [49]
The chair is able to fine tune such aspects as seat eight, seat angle and back angle in order to accommodate a variety of customer body types.



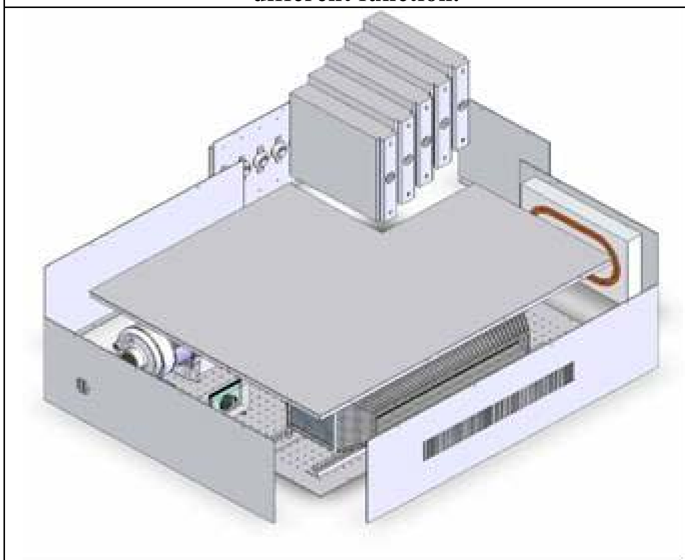
Propeller-Controlled Active Tuned-Liquid-Column Damper [61]
This is a vibration dampener system for a building that is used to counter the effects of an earthquake. This device can be actively tuned in order to respond to vibrations greater than could be handled by a passive system.

APPENDIX C: COMBINATION MIND MAP AND 6-3-5 CONCEPT GENERATION METHOD



APPENDIX D: CONCEPTS RESULTING FROM FLEXIBILITY MINDMAP

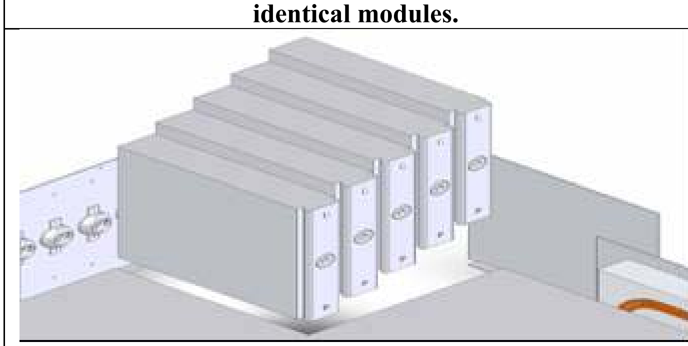
Principle 1: Use a different module to carry out each different function.



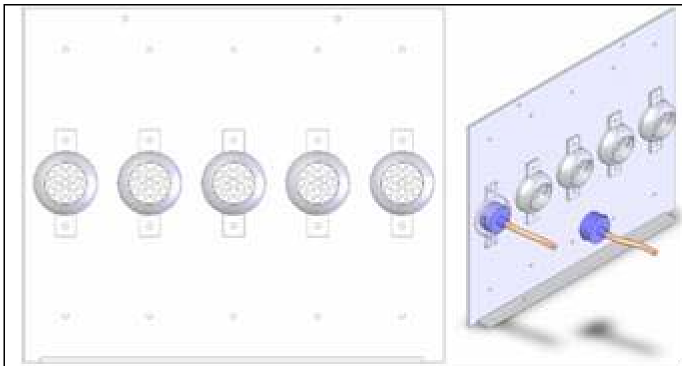
The walls and ceiling of the product casing are made separate from the base plate so that changes to one would not affect the others. For example, re-sizing of inlet or exhaust ducts might require redesign of one or more side walls but would not affect the base plate.

This principle also contributed to the choice to use a standardized motor and pump as stated under principle 3.

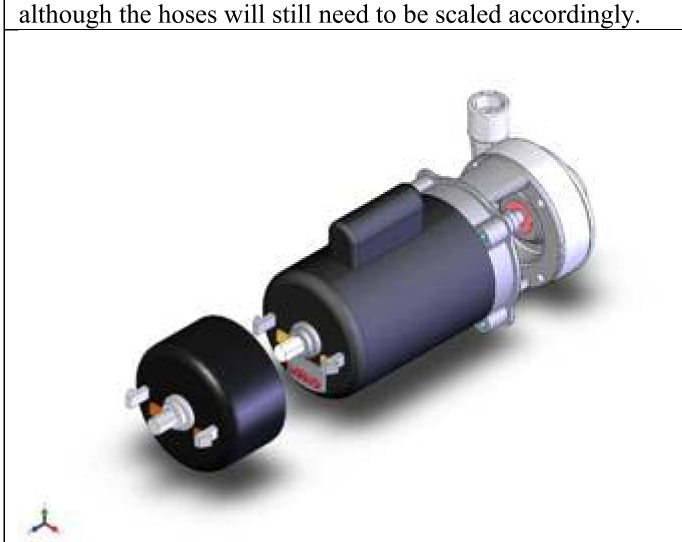
Principle 2: Divide each module into a number of smaller, identical modules.



The hydrogen tanks are segmented into multiple smaller tanks for easy scaling in case of changes in customer requirements.



The hose connection points are also segmented into a type of honeycomb pattern. Because if this changes in flow requirement need not affect the hose connection points although the hoses will still need to be scaled accordingly.



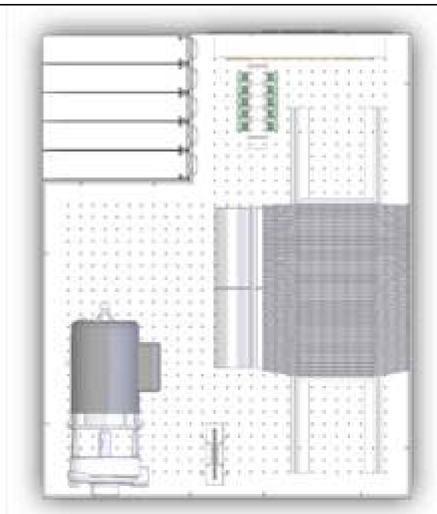
The motor may also be segmented into a number of smaller stacks which can connect to each other at the shaft and also electrically so that the pump power may be scaled according to need.

Principle 3: Collect parts which are not anticipated to change in time into separate modules.

The new design uses a standardized motor and pump to drive the reactant air, and standardized blower fans for the cooling system.

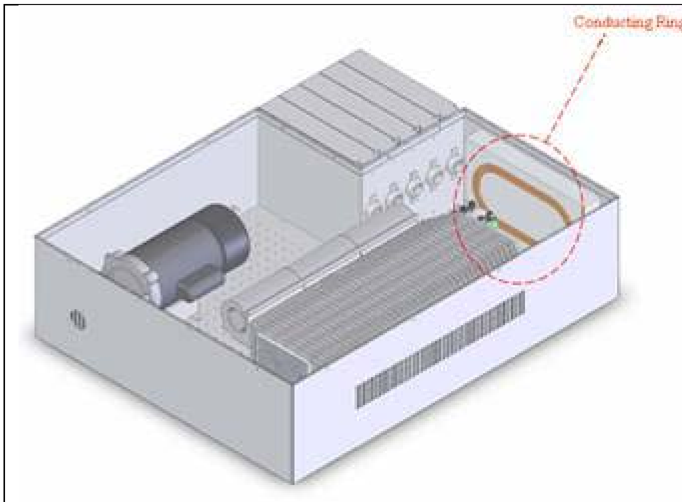
Principle 5: Create room on exterior surfaces of the device, in its interior, and around those components which are designed to interface with humans.

Empty space is left on the external surface containing the power outlets and other user interfaces. This is there in case future additions in functionality allow the inclusion of more outlets or additional sensor readouts.



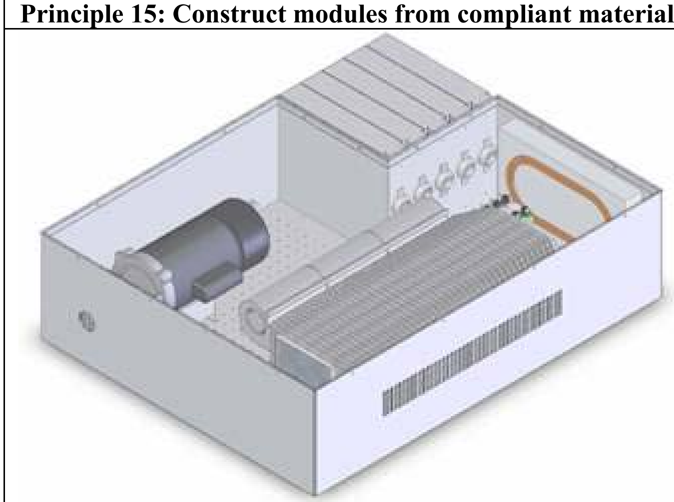
Empty space is left throughout the device, and behind the motor and around the stack in particular.

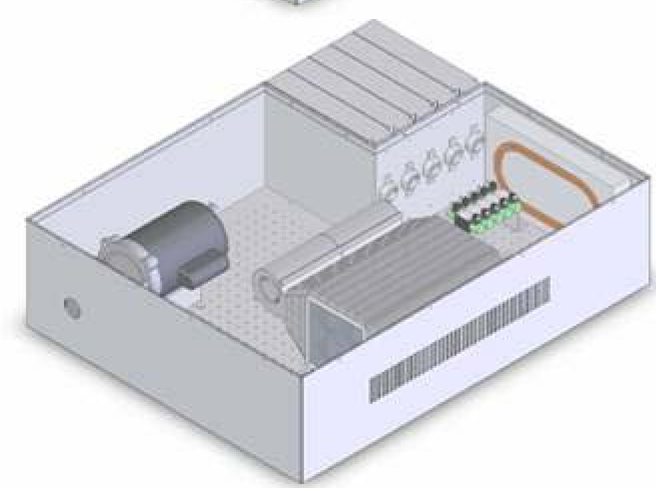
Principle 6: Extend the available area on the transmission components of the device.



In this application the type of energy being transmitted is electrical and so the electrical connector to which the external socket ports connect is made into a long ring structure to minimize the area taken up while maximizing the empty space available on it.

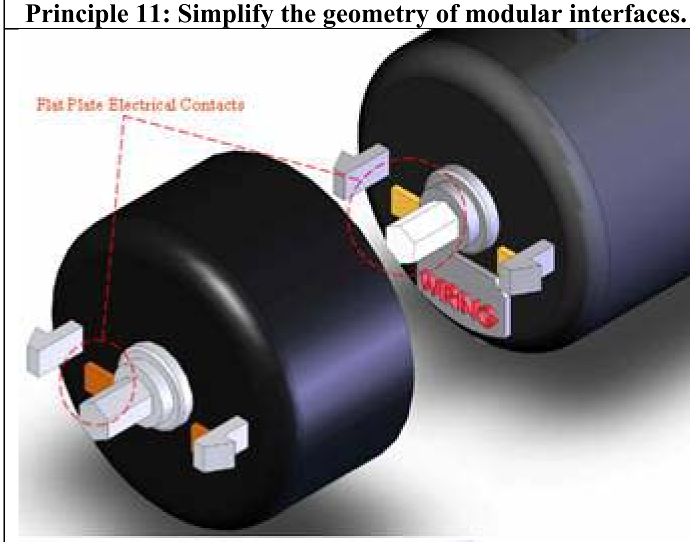
Principle 15: Construct modules from compliant materials.





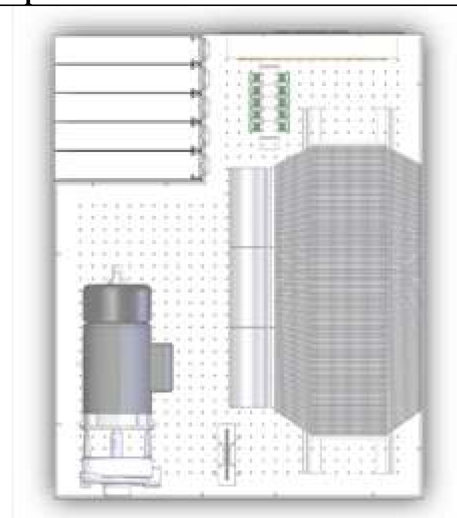
The 'Bellows Manifold System' is meant to be used as a form of ducting for the fuel cell cooling system. The most common change expected in the fuel cell generator is the length of the cell stack due either to changing customer needs or to a variety of possible technological advances. Such technological advances might lead to a more efficient cell which would therefore require smaller stacks (in terms of length) or to cheaper manufacturing techniques which might increase the smallest achievable thickness of the cell layers thus causing the stack to get longer. The Bellows Manifold System is designed to expand or contract as the stack length changes or as cooling requirements change, and is mounted on a rail system which allows it to be anchored at any point along their length.

Principle 9: Reduce the number of fasteners used, or eliminate them entirely.
Principle 11: Simplify the geometry of modular interfaces.



All electrical connections are made by simple flat plates and all hose connections are made by collet type quick connectors.

Principle 10: Reduce the number of contact points between modules.
Principle 12: Route flows of energy, information and materials so that they are able to bypass each module at need.
Principle 14: Increase the number of support points present on the structure of the device.



Most of the components are fixed to the base plate only. They are connected to each other only by hoses or wires for the different flows and therefore are very easily reconfigurable. The 'Breadboard Bolt Pattern' advocates the use of an evenly distributed matrix of bolt holes instead of a specific pattern in order to provide more freedom in the way that components can be arranged inside the housing.

APPENDIX E: ADAPTED CMEA ANALYSIS

Change Mode and Effects Analysis for Potential Changes in Product Design (PSI Fuel Cell)

Modules / Components	Potential Change Mode	Potential Effects of Change	Design Flexibility	Potential Causes of Change
Cooling System				
Blower	Increased Air Flow Required	Larger fan Increased duct size Alteration to mounting bolt pattern Possible change in wiring (to heavy duty) Possible change to product casing to accommodate larger fan	3	Improvements in power generation capabilities also effect heat produced and so require better cooling Increases in stack length due to greater power generation will require greater flow for cooling
	Decrease in Air Flow Requirement	Smaller fan Decreased duct size Alteration to mouting bolt pattern	7	New plate materials dissipate heat better and therefore require less cooling Decreased stack size requires less cooling
		Run fan at lower speed	9	New plate materials dissipate heat better and therefore require less cooling Decreased stack size requires less cooling
Ducting	Decreased Stack Size	Less space required in ducting Connection points need to be moved	6	Increases in achievable current density due to developments in plate material allow smaller stacks to produce the same amount of current Customer needs call for less power
	Increased Stack Size	More space required in ducting More space required in product casing to accommodate increased stack size	3	Alternate plate manufacturing techniques produce plates cheaper but thicker User requires more power from the product Cheaper, less efficient catalyst requires thicker catalyst layer and thus increases stack size
Reactant Air Circulatory System				
Pump	Higher Flow Rate Required	Larger pump required Larger, thicker hoses possibly required Larger hose connection points required on humidifier Larger air inlet required Alteration to mounting bolt pattern Possible change to product casing to accommodate larger pump	3	Cheaper, less efficient catalyst requires greater air flow to extract sufficient oxygen to sustain reaction Longer cell stack requires higher flow rate in to overcome losses More reactive catalyst able to use greater amounts of oxygen and can thus produce more power when provided with increased air flow
	Lower Flow Rate Required	Smaller pump required Possible change to hose sizes Smaller hose connection points required on humidifier Possible change to air inlet Alteration to mounting bolt pattern	6	More effective catalyst removes more oxygen per unit volume air and thus requires less flow to Smaller stack size requires a lower flow rate due to reduced losses
Humidifier	Lower or Possibly No Humidity Requirement	Reduced water level in humidifier Lower duty cycle of heating element to reduce operating temperature	9	Changes in membrane technology reduce or eliminate humidity level requirements
Hydrogen Circulation System				
Valve	Lower Flow Rate Required	Different valve required Possible alteration to mounting bolt pattern Possible change to hose sizes and hose connection points	6	Cheaper, less effective catalyst requires less hydrogen due to slowed reaction rate Smaller stack size requires a lower flow rate due to reduced losses
	Higher Flow Rate Required	Different valve required Possible alteration to mounting bolt pattern Possible change to hose sizes and hose connection points	6	More effective catalyst is able to make use of more hydrogen and thus requires greater flow rate Larger stack size requires greater flow rate in order to overcome losses
Storage	Greater Storage Capacity Required	Larger tank required Possible alteration to product casing required to accommodate larger hydrogen tank Possible alteration to mounting bolt pattern	4	Customer requires longer running time
	Less Storage Capacity Required	Smaller Tank Required Possible alteration to mounting bolt pattern	5	More efficient fuel cell is able to extract sufficient power to serve customer's needs with a smaller supply of hydrogen
Cell Stack				
	Stack Gets Larger	Larger ducting required Larger or more powerful cooling fan required Greater reactant flows required to overcome losses in stack More space required in product casing to accommodate increased stack size Alteration to mounting bolt pattern Possible changes to hose sizes and thicknesses to accommodate increased flow rates	2	Customer requires greater power output Alternate plate manufacturing techniques produce plates cheaper but thicker Cheaper, less efficient catalyst requires thicker catalyst layer and thus increases stack size
	Stack Gets Smaller	Smaller ducting required Running time or duty cycle of cooling fan must be reduced Alteration to mounting bolt pattern Possible changes to hose sizes and thicknesses to accommodate increased flow rates	3	Customer requires less power output Increases in achievable current density due to developments in plate material allow smaller stacks to produce the same New catalyst materials allow thinning of catalyst layer
Electrical Output Interface				
	Number of Connectors Increases	Alteration to internal electrical connections required Additional connectors required Alteration to mounting bolt pattern Alteration to product casing	3	Power generation improvements allow support for greater loads
Average Design Flexibility			5.14	

Change Mode and Effects Analysis for Potential Changes in Product Design (Flexible Fuel Cell)

Modules / Components	Potential Change Mode	Potential Effects of Change	Design Flexibility	Potential Causes of Change
Cooling System				
Blower	Increased Air Flow Required	Increase number of fan segments in use	9	Improvements in power generation capabilities also effect heat produced and so require Increases in stack length due to greater power generation will
	Decrease in Air Flow Requirement	Decrease number of fan segments or run fan at a lower speed	9	New plate materials dissipate heat better and therefore require less cooling Decreased stack size requires less cooling New plate materials dissipate heat better and therefore require less cooling Decreased stack size requires less cooling
Ducting	Decreased Stack Size	Contract Bellows Manifold System	10	Increases in achievable current density due to developments in plate material allow smaller stacks to produce the same amount of current Customer needs call for less power
	Increased Stack Size	Expand Bellows Manifold System	10	Alternate plate manufacturing techniques produce plates cheaper but thicker User requires more power from the product Cheaper, less efficient catalyst requires thicker catalyst layer and thus increases stack size
Reactant Air Circulatory System				
Pump	Higher Flow Rate Required	Increase the number of pump motor segments in use Use larger hoses, no change required to hose connection points Possible change to back wall segment (which containts the pump inlet) required	8	Cheaper, less efficient catalyst requires greater air flow to extract sufficient oxygen to sustain Longer cell stack requires higher flow rate in to overcome losses More reactive catalyst able to use greater amounts of oxygen and can thus produce more power when provided with increased air flow
	Lower Flow Rate Required	Decrease the number of pump motor segments in use Use smaller hoses Possible change to back wall segment	10	More effective catalyst removes more oxygen per unit volume air and thus requires less flow to Smaller stack size requires a lower flow rate due to reduced losses
Humidifier	Lower or Possibly No Humidity Required	Reduced water level in humidifier Lower duty cycle of heating element to reduce operating temperature	9	Changes in membrane technology reduce or eliminate humidity level requirements
Hydrogen Circulation System				
Valve	Lower Flow Rate Required	Different valve required Possible change to hose sizes, no change to hose connection points required	9	Cheaper, less effective catalyst requires less hydrogen due to slowed reaction rate Smaller stack size requires a lower flow rate due to reduced losses
	Higher Flow Rate Required	Different valve required Possible change to hose sizes, no change to hose connection points required	8	More effective catalyst is able to make use of more hydrogen and thus requires greater flow rate Larger stack size requires greater flow rate in order to overcome losses
Storage	Greater Storage Capacity Required	Connect additional tank segments	9	Customer requires longer running time
	Less Storage Capacity Required	Disconnect tank segments	10	More efficient fuel cell is able to extract sufficient power to serve customer's needs with a smaller supply of hydrogen
Cell Stack				
	Stack Gets Larger	Expand Bellows Manifold System Connect Additional Motor Segments	9	Customer requires greater power output Alternate plate manufacturing techniques produce plates Cheaper, less efficient catalyst requires thicker catalyst layer and thus increases stack size
	Stack Gets Smaller	Contract Bellows Manifold System	10	Customer requires less power output Increases in achievable current density due to developments in plate material allow smaller stacks to produce the same amount of current New catalyst materials allow thinning of catalyst layer
Electrical Output Interface				
	Number of Connectors Increases	Connect more sockets to the electrical export ring on the front wall segment	9	Power generation improvements allow support for greater loads
Average Design Flexibility			9.21	