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THE CHARACTERISTICS OF INNOVATIVE, MECHANICAL PRODUCTS

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ABSTRACT

It is not easy to design an innovative product that delights customers. Current engineering design methods provide help in designing a good product, but the designer lacks tools that help him or her create a truly innovative, successful product. In this study, we analyzed 95 innovative, award-winning products against their competition to identify what made those products stand out from the competition. We focused on finding engineering-level characteristics that made the products successful. We developed a set of conditionally repeatable innovation categories that are used in the analysis. We found that the most innovative products were innovative in multiple categories. Overall, a vast majority (greater than 70%) of the award-winning products exhibited enhanced user interactions, with a similar percentage displaying enhanced environmental interactions, compared with approximately one-third of products offering an additional function and approximately half displaying innovative architectures. We conclude that breakthrough or innovative products are becoming increasingly centered on user interactions and that engineers need better methods to design these products.

1 INTRODUCTION

Making a successful product is difficult. In fact, a large number of products introduced to the market fail within the first few years. The failure rate of new products varies from about 30% to 90% depending on the novelty of the market, the product category, and the industry [3, 5, 35]. On average, a little over 50% of new product development projects are successful [11]. The rest of the products fail. A small fraction of the products are very successful and conquer the competition with significantly larger market shares, greater profit margins, or better brand recognition. But what makes a product a success? What can a design engineer do during the design process to help the product he or she is developing become successful? Are there some engineering metrics that could be used to design a more successful product?

Successful products are typically known as products that satisfy customer needs in particularly innovative or unexpected ways. From the perspective of the Kano diagram [24] in Figure 1, successful products *delight* customers. In a Kano diagram, standard "must-have" features are so common that customers are disappointed unless they are implemented expertly. Baseline features satisfy customers with their presence, and the level of satisfaction typically depends on the degree of functionality. The most successful products, on the other hand, tend to incorporate features that delight the customer, by performing beyond his or her expectations. Since the delightful features exceed the customer's expectations, it can be impossible for the customer to articulate these needs in an interview or survey.

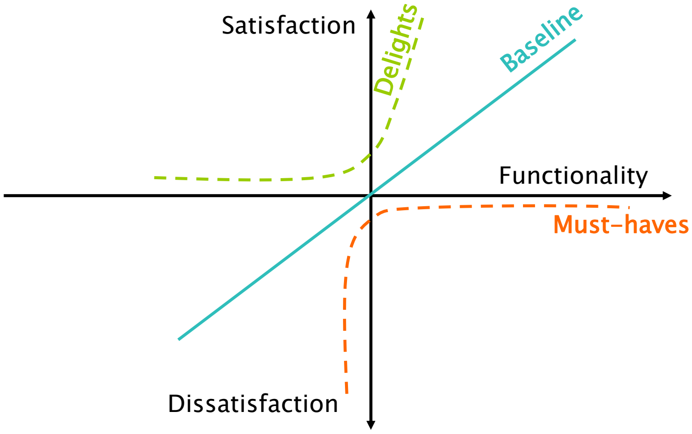

Figure 1. Kano diagram [24]

The development of a new product typically starts with identifying the customer needs. Unfortunately, the typical needs articulated by a customer fall under the "baseline" needs in the Kano diagram, and fulfilling these needs is not enough to create an innovative product. How could one create a "delight"? As discussed in the following sections, there are many tools in engineering design, but few that help the design engineer answer this question.

In this paper we take a set of innovative products and investigate the features that make them successful. We focus specifically on features that the designer can influence directly during the design process. The objective of this paper is to identify the types of engineering-level characteristics that make a product successful so that a designer can realize the next breakthrough innovation.

2 LITERATURE REVIEW

Numerous underlying factors can influence the success of a product. Cooper [10] classified these factors into the following categories: market, synergy of product and firm's skills, characteristics of the product venture, execution of development, the product itself, and information found during development. Within these categories, 18 dimensions of success were identified from related literature. The same list has been modified and supported by numerous studies [12, 27, 43, 53], and similar lists have been suggested by additional studies [1, 4, 20, 36]. Despite the abundance of supporting research, however, the categories may not be universally applicable to different markets and cultures. Mishra [37] found that the application of Cooper's dimensions, which had been studied in Canada [10] and China [53], did not correlate to similar results in a study of Korean innovation. Cooper and de Brentani [12] argued that success factors may be ranked differently for products outside of the manufacturing sector, such as financial service products.

The majority of research suggests that innovation and competitive advantage are leading factors in product success [4, 10, 12, 27, 53, 55], but there may be too many market factors to draw a linear relationship between technical innovation and success. For example, the research of Kleinschmidt and Cooper [27] suggested that while highly innovative products and products with a relatively low level of innovation find commercial success, products of moderate levels of innovation are less likely to find success. A high level of technical innovation is encouraged, but innovation alone will not necessitate market success. Due to the multitude of determinants of success, an innovative product was defined, for the sake of this study, as a product that changes or has the potential to change the nature of the marketplace by satisfying a new (or latent) customer need or by satisfying customer needs in a significantly new way. In contrast, a breakthrough product was defined as an innovative product that had *already* experienced commercial success in the context of numerous market and business influences.

While numerous factors influence the success of a product, only a product's innovation is affected directly at the engineering level and the product design stage. Designers are currently told to innovate, but few tools are provided to help a designer maximize the likelihood of product success. Should the designer add an additional function, reduce product size, make the product easier to use, or pursue other options? What are the engineering-level characteristics of innovative products?

The dilemma begins with the difficulty of gathering customer needs to create innovative products. Several sources suggest that the creation of highly innovative or breakthrough products cannot be done with traditional customer needs analysis because the needs are latent, or not yet articulated [9, 13, 36, 54, 59]. Some customer analysis tools, such as voice of the customer (VOC) [22] and the lead user method [59], claim to result in more successful products than other methods; however, product success is far from guaranteed.

The difficulty of creating innovative products is further exacerbated by apparent differences in customer evaluation and acceptance of innovative products based on their similarity to related products [13, 39]. The more successful products seem to be difficult for customers to categorize because they do not fit neatly into preexisting product categories. Customers spend more time analyzing innovative products, and cannot make quick decisions based on previous experiences. Customers' evaluations of innovative products often demonstrate lack of familiarity, irrationality, user-product interaction problems, uncertainty, compatibility, aesthetics, and fixation on seemingly trivial details of the product [58]. These non-function related product components that also include the emotional design branch of industrial engineering are important to the customer's purchase decision, but are also difficult to evaluate at the engineering level early in development. To further increase the difficulty of developing innovative products, several studies support that the development and management of products differ greatly based on the level of innovation [29, 30, 38, 40, 50, 52, 55].

For an engineer tasked with designing an innovative product, it is not only difficult to extract useful information from customers, but it is also difficult to characterize the appropriate target level of innovation. In a comparison of innovation factors cited in the literature, Garcia and Calantone [19] identified more than 15 constructs of innovation with 51 attributes. They distinguished incremental, really new, and radical forms of innovation to clarify and unify the theories of innovation by merging existing terminology. Incremental innovation is the classical approach of utilizing customer needs analysis to create slight generational improvements to an existing product. Radical innovations cause disruption of the marketplace by introducing a breakthrough technology. Really new innovation can be any combination of factors between incremental and radical. These classifications are supported with s-curves [6, 17], in which products experience slow evolution in their initial development, followed by an accelerated series of improvements, only to level off into a final period of slow development. In this way, the evolution of a product follows an "S" shaped pattern of improvement on a plot of quality over time. Discontinuities in improvement, or jumps, create new curves of higher quality. It was suggested that the market of a product also follows an s-curve and that radical innovation is defined by causing jumps on both a product's technology and market curves. Really new innovation is characterized by a jump in either curve, but not both. Incremental innovation is classified as movement along existing curves. Innovation should therefore be viewed as a relative property as suggested by Dewar and Dutton [14] because it is inherently based on the degree to which one product distinguishes itself from preceding and competing products. Based on these classifications, the literature suggests that radical innovation is rare and occurs in less than 20% of innovations, while incremental innovation is much more widespread [19].

Despite all of this research on innovation, the engineer is still left with very little guidance on the engineering-level characteristics of innovative products. The current product attribute checklists available to designers, including categories for decomposing product specifications and checklists for embodying concepts [18, 41, 42], do not directly encourage innovation for the sake of potential market success. These lists are normally used throughout the design process to ensure that all aspects of a product's development cycle are considered, but they do not provide guidance for competitive advantage or innovation. While the majority of the characteristics of innovation developed in this study correlate with items on these lists (e.g., function, layout, energy, ergonomics, and costs), their importance is lost with the inclusion of so many other engineering factors of product design (e.g., safety, production, quality control, assembly, transport, and scheduling). They do not help differentiate and distinguish one concept from another at the state of ideation, which according to Goldberg [20] is a promising time to evaluate concepts for potential innovation and success.

Some tools are available for this critical early stage of development. The creation of a project mission statement [41], for example, encourages designers to identify potential areas of innovation at the beginning of a design project, but no guidelines are provided to examine potential areas thoroughly. Also, there are many creativity and brainstorming tools that help the designer create as many ideas as possible. Examples include 6-3-5 [42,48], C-sketch [51], TRIZ [2], Design by Analogy [34], and Biomimetic Concept Generation [7]. Similarly, there are numerous tools for selecting the concept that best meets customer requirements (e.g., [25],[47],[49]). Interestingly however, Cooper finds that many concept selection methods are designed to select mediocre concepts, because the methods do not use "product superiority" as a criterion [11] and therefore do not lead to breakthrough products.

Additionally, benchmarking the competition [41] is an important part of the House of Quality [22] for comparing a product to leading competitors and connecting customer needs with engineering specifications; however, this tool may suffer from the challenges of extracting customer needs effectively and moving beyond incremental innovation.

The aforementioned tools, from customer needs analysis to the house of quality, are available to all designers, but somehow only a fraction of products can truly claim to be breakthrough products. What is it that makes a product stand out from the competition? It has been shown that factors such as having a good design process with reviews, clear strategy, and willingness to take risks and enter new markets [11] contribute to good business performance from the management point of view, but what can the design engineer do during the design process?

It would be helpful for the innovation-driven engineer to understand the types of engineering-level characteristics that typically characterize innovative products so that those criteria can be used to drive and evaluate the design process.

3 RESEARCH METHODOLOGY

A research methodology was developed to establish a set of engineering-level characteristics of innovative products and to use those characteristics for analyzing trends among award-winning, innovative products. The research proceeded in a series of three steps: (1) developing a comprehensive list of engineering-level characteristics of innovation, (2) selecting innovative products to be analyzed, and (3) analyzing the products with respect to the characteristics identified in the first step. A subsection is devoted to describing each of the steps.

3.1 Developing a Set of Engineering-Level Characteristics of Innovation

The goal of this step was to compile a set of engineering-level characteristics that describe innovative products. Engineering-level characteristics are those that describe observable features of the product itself, such as architecture or functionality, rather than enterprise- or market-level characteristics such as market share or profitability. The engineering-level characteristics are selected to be *domain-independent*, *comprehensive*, and *mutually independent*. A *domain-independent* characteristic can be used to describe various types of products, rather than a specific product (e.g., material flow versus gallons per mile). The characteristics in a *mutually independent* set should not overlap; in other words, it should be possible to identify a product that exhibits one specific characteristic without exhibiting the remaining characteristics. A *comprehensive* set of characteristics should be sufficient for describing any innovation in the domain of interest. The mechanical domain was the focus of this study;

innovations that are purely chemical, electrical, or materials-related, without a mechanical component, were not considered in the study.

With these features in mind, the characteristics of innovative products were compiled by reviewing a variety of innovative products. While reviewing each product, the researchers asked, "What features made the product more innovative than competing products at the time of its release?" The review was conducted from the perspective of the customer, rather than the manufacturer or the designer. For example, customers cite a product's compact size as innovative, rather than the advances in material processing and manufacturing that enabled it; therefore, improved size is a potential characteristic of innovative products. Characteristics were added to the set as necessary to accurately describe the differences between products. The set was refined for comprehensiveness, mutual independence, and domain-independence. For validation purposes, characteristics were developed independently by two of the authors and then critically evaluated and merged into a unified set. Also, the final set was compared with other lists of product criteria, such as the requirements list checklist provided by Pahl and Beitz [42] to verify its completeness.

As shown in Table 1, five important categories of innovation were identified: Functionality, Architecture, Environmental Interactions, User Interactions, and Cost. The first category is used to evaluate whether the breakthrough product offers a significant new function, relative to competitive products. The second category is used to evaluate whether there are any architectural innovations (related to size, layout, or usage context) in the breakthrough products that are not generally found in competitive products. The environmental interactions category addresses modified flows of material, energy, or information into or out of a functional model [11] of the product. A modification includes a change in the type of flow (e.g., electrical energy replaced by solar energy in a solar-powered device) or in the magnitude of the flow (e.g., a more fuel-efficient vehicle). The environmental interactions category also includes product interactions with pre-existing infrastructure, such as data formats, standardized connectors, or other types of pre-existing hardware, software, services, or networks. The user interactions category is used to evaluate whether the innovative products are more user-friendly than competitive products. For example, the physical demands characteristic refers to innovations that make the product easier to use under various physical conditions, including permanent or temporary physical disabilities. The sensory demands characteristic includes innovations that enhance ease of use for sensory-impaired persons or persons with temporary sensory impairment (e.g., a cell phone user at a loud concert). The modified cognitive demand characteristic refers to innovations that make it easier to understand a product, including its assembly, operation, and/or inputs/outputs. Finally, cost is included as a secondary characteristic that sometimes accompanies other characteristics (e.g., a change in design enables both modified material flows and reduced operating costs).

Table 1. Characteristics of Innovation

Functionality
- *Additional Function*- Allows the user to solve a new problem or perform a new function while still performing the function of the comparison product.

Architecture
- *Modified Size*- The physical dimensions during operation or storage have changed in expansion or compaction beyond subtle or incremental differences.
- *Modified Physical Layout*- The same elements of the product are still present, but the physical architecture has changed.
- *Expanded Usage Physical Environment*- The product can now be used in more usage environments with different resource availability or different physical characteristics.

Environmental Interactions
- *Modified Material Flow*- Accepts or creates different materials or uses materials in new ways.
- *Modified Energy Flow*- Utilizes new sources of energy or converts to a different form of energy than previously used.
- *Modified Information Flow*- Different types or amounts of information are being gathered, processed, or output/displayed.
- *Interaction with Infrastructure*- The product interacts with previously owned infrastructure.

User Interactions
- *Modified Physical Demands*- The product is easier to use physically beyond subtle or incremental differences.
- *Modified Sensory Demands*- The product is easier to use from a sensory stand point beyond subtle or incremental differences.
- *Modified Mental Demands*- The product is easier to use mentally beyond subtle or incremental differences.

Cost (Secondary Characteristic)
- *Purchase Cost*- Purchase cost is **significantly** different.
- *Operating Cost* – Operating and/or maintenance costs are **significantly** different.

The sample products in Table 2 illustrate several of the innovation characteristics. The Vicks Forehead Thermometer, illustrated in Figure 2, is a thermometer designed to eliminate the difficulty of taking a child's temperature by accurately measuring temperature from the forehead rather than the standard mouth, ear, rectal, or armpit methods. It also displays a background color based on the grade of the fever, ranging from green for no fever to red for high fever. Relative to competing, home-use thermometers, the color-coded display increases the amount of information displayed, as recorded in the "Modified Information Flow" column of Table 2. It also makes it easier for the user to determine if a fever exists without having to memorize appropriate temperature ranges, as classified by the "Modified

Cognitive Demands" column in Table 2. The thermometer also embodies "Modified Physical Demands" because it is physically easier to measure a child's temperature on the forehead, relative to other locations.

Table 2. Sample products that illustrate characteristics of innovation

Product	Vicks Forehead Thermometer	Nike+	Oliso Frisper
Comparative Product	children digital thermometer	running pedometer	home vacuum sealer
Function			
Additional Function		x	
Architecture			
Modified Size		x	x
Modified Physical Layout		x	
Expanded Usage Environment	x		
Environmental Interactions			
Modified Material Flow			
Modified Energy Flow		x	x
Modified Information Flow	x	x	
Interaction with Infrastructure		x	x
User Interactions			
Modified Physical Demands	x		
Modified Sensory Demands		x	
Modified Cognitive Demands	x		
Cost			
Purchase			
Maintenance			x

Figure 2. Vicks Forehead Thermometer [23]

Figure 3. Nike+ Apple iPod pedometer attachment [44]

The Nike+ is a jogging pedometer attachment for Apple iPod digital music players. A small piezoelectric measuring unit placed in or on a jogger's shoe collects pace data, and communicates it wirelessly to an iPod attachment, which broadcasts current and average workout pace through the iPod headphones. When connected to a computer, the device sends data from previous workouts to an online account that helps runners track their distance, pace, and running routes. These features justify marks in the "Additional Function" and "Modified Information Flow" columns in Table 2. The connection between the pedometer and an iPod and a computer is an advantageous "Interaction with Infrastructure." In this sense, the infrastructure interaction is manifested both geometrically, by attaching to the iPod, and digitally, by exchanging data between the shoe-based module and the iPod. Compared to competing, one-piece pedometers, the Nike+ is both smaller in size ("Modified Size") and modular ("Modified Physical Layout"). The use of a piezoelectric accelerometer in the foot unit is considered a "Modified Energy Flow" because competing products used springs and lever arms at the time of its release, which require more energy. The Nike+ also provides "Modified Sensory Demands" by allowing users to hear their data over the iPod headphones in addition to tracking it visually.

Figure 4. Oliso Frisper home vacuum sealer [45]

The Oliso Frisper is a home vacuum sealer that punctures a tiny hole in any closable plastic bag, removes the air, and then heat-seals the hole to ensure a vacuum. As opposed to traditional vacuum sealers that require specialized bags, this method of sealing allows a variety of bags to be continually reused, and it is not required to span the full length of the bag to operate properly. The puncturing and resealing mechanism is considered a "Modified Energy Flow," and it allows the Oliso Frisper to be considerably more compact than the competition, as recorded in the "Modified Size" column in Table 2. The Oliso Frisper also exhibits improved "Interaction with Infrastructure" because it can be used with existing household sealable bags. The product also earns a reduced

"Cost" designation because the customer can use any sealable plastic bag (rather than expensive, specialized bags) and reuse the original bag countless times without function loss.

3.2 Selecting Innovative Products for Analysis

Products were selected from three published lists of innovative products: Time magazine's Inventions of the Year, Popular Science's Best of What's New, and Industrial Designers Society of America's (IDSA) International Design Excellence Awards (IDEA). Products were selected from these lists, rather than personal research by the authors, to avoid any researcher bias in the selection of products. The lists also provided a wide assortment of products to support a relatively broad analysis of innovation, with Time's list oriented towards the general public, Popular Science towards scientific-minded readers, and IDEA towards industrial designers and other professionals.

As shown in Table 3, a set of criteria was developed for selecting products from the published lists. Since the purpose of this study was to investigate mechanical innovation, products with no significant mechanical component were eliminated (e.g., new software, materials, or chemicals). The innovation also needed to be function-related, rather than a purely cosmetic or aesthetic change. This criterion eliminated fashion and most clothing, except for a few that demonstrated mechanical innovation. Also, products were required to be commercially available; prototypes were eliminated to ensure design feasibility. Only end consumer products were considered, rather than components (e.g., engines, transmissions). Since products were evaluated from a consumer perspective, it was difficult to evaluate components that were isolated from a parent product. The ability of a product to change or potentially change a marketplace was a significant criterion. This criterion eliminated useless innovation or innovation for the sake of innovation (e.g., a combination pen/fingernail clipper/money clip). Finally, it was necessary for the product to be relevant to the United States market, rather than international markets, so that the U.S.-based researchers could evaluate the product relative to competing products.

Table 3. Product Selection Criteria

- The innovative product must be mechanical or hardware-related.
- The innovation must be related to the functionality of the product, rather than its aesthetics alone.
- The product must be successful or potentially successful in the marketplace.
- The product must be available in the marketplace (i.e., no prototypes).
- The product must be an end consumer product, rather than a component.
- The product must have changed or have the potential to change the marketplace.
- The product must be relevant to the US market.

The selection criteria were used to extract products from the published parent lists. After analyzing the 2006, 2007, and 2008 editions of each parent list, 95 products were obtained. Although additional products could be obtained from earlier editions of the lists, the product count was hypothesized to be large enough to provide significant insights on innovation. (This hypothesis is revisited in Section 4.) Overall 20, 50, and 40 products were extracted from the Time, Popular Science, and IDSA lists, respectively, with 13 of those products receiving awards from multiple lists.

3.3 Analyzing Innovative Products

Each of the 95 products was analyzed with respect to the innovation characteristics in Table 1. A sample analysis is illustrated in Table 2. Analysis was based on the description of the product in the award list. Each product was analyzed with respect to a comparative product. The comparative product was selected by identifying the product class likely to be most competitive with the innovative product at the point of purchase. The comparative product should be the product class that a customer would most likely consider purchasing, instead of the innovative product. For example, an iPod® would be compared to other digital music players, rather than a compact disc player.

As the products were analyzed, the repeatability of the study was investigated. Repeatability was assessed with inter-rater agreement, which measures the degree to which two judges assign the same ratings to each alternative [57]. Specifically, Cohen's [8] kappa coefficient, K, was used to calculate inter-rater agreement. Coefficient values can range from 0, which represents agreement equivalent to expected chance agreement, to 1, which represents perfect agreement. Generally, inter-rater agreement of 0.40 or less is considered "poor" agreement; 0.4 to 0.75 is considered "fair to good" agreement; and 0.75 and above is considered "excellent" [15, 28]. Lists of approximately 10 sample products were evaluated by two of the authors independently. Then, differences were discussed, and the procedure was repeated, as a means of training the judges, until an acceptable level of inter-rater agreement was achieved for the sample products. In this evaluation, judges were considered to agree if both indicated that a product satisfied (or did not satisfy) an innovation characteristic. Initial inter-rater agreement fell in the 0.45 range between authors, but discussion and modification of the innovation characteristics and their definitions raised the level to 0.75 for new samples of independently analyzed products.

4 Results

After all of the products were evaluated, the results were analyzed by characteristics and overarching categories as shown in Table 4. The first column lists all of the characteristics of innovation identified in Section 3, with category headings highlighted in bold. The second column indicates the percentage of products that displayed each characteristic. The third column indicates the percentage of products with at least one characteristic in each category. For example, 58.9% of the products exhibited at least one characteristic in the architecture category.

Table 4. Product analysis by innovation characteristics and categories

	Percent of products with each criteria (%)	Percent of products with at least 1 criterion for each category (%)
Function	-	35.8
Additional Function	35.8	
Architecture	-	58.9
Modified Size	23.2	
Modified Physical Layout	29.5	
Expanded Usage Environment	30.5	
Environmental Interactions	-	78.9
Modified Material Flow	8.4	
Modified Energy Flow	41.1	
Modified Information Flow	29.5	
Interaction with Infrastructure	15.8	
User Interactions	-	72.6
Modified Physical Demands	51.6	
Modified Sensory Demands	18.9	
Modified Cognitive Demands	15.8	
Cost	-	5.3
Purchase	1.1	
Maintenance	5.3	

Modified Physical Demands and Modified Energy Flow were the most frequently displayed characteristics, with 51.6 and 41.1% of products surveyed, respectively. Similarly, their parent categories, User Interactions and Environmental Interactions, were the most frequently cited categories, with 72.6% and 78.9% of products, respectively, exhibiting at least one characteristic in each category. In contrast, the percentage of products that granted the user an additional function was much lower at 35.8%. Since mechanical designers often associate innovation with functionality and technical superiority, this result is somewhat surprising. There are at least two different explanations for this difference. First, the results suggest that mechanical innovation may be more closely associated with a product's environmental and user interactions than with additional functionality alone, at least from the customer's perspective. Second, the environmental and user interaction categories are quite broad, as indicated by the number of characteristics associated with them. The breakdown in characteristics may also encourage the researcher to think more carefully about these categories and thereby identify more products that exhibit them.

Overall, neither the average number of characteristics per product nor the distribution of characteristics across categories differed substantially when compared across award lists or award list years. For example, the IDEA products were expected to display more User Interaction characteristics than the other award lists based on IDSA's origins in industrial engineering, but this hypothesis proved not to be the case. The consistency of the data across award years and lists suggests that the sample size is sufficiently large to accurately represent trends in innovation characteristics.

Table 5. Product analysis by number and type of awards

	# of Products	Average # of categories	Standard Deviation
Overall	95	3.06	1.24
Multiple Awards			
Single	82	2.95	1.12
Two	11	3.36	1.29
Three	2	6.00	2.83
Level of IDEA Award			
Finalist	9	3.44	1.68
Bronze	13	1.92	1.54
Silver	10	3.10	0.57
Gold	8	5.00	2.62
Level of Popular Science Award			
Regular	40	3.03	1.25
Grand	10	3.90	1.79

As shown in Table 5, products were also analyzed by the type and quantity of awards received. As recorded in the first row of the table, the 95 products in the study averaged approximately three innovation characteristics per product. This result suggests that innovative products often exhibit numerous innovative advantages over comparative products. The relatively substantial standard deviation of this statistic suggests that many products are viewed as innovative with only one or two innovative characteristics, but there are just as many with four or more criteria.

The remaining rows of Table 5 display the average number of characteristics per product as a function of the type or number of awards. Substantial differences were observed in the average number of characteristics per product, when compared across award levels. For example, IDEA offers bronze, silver, and gold awards, while Popular Science offers regular and grand awards. As shown in Table 5, the average number of characteristics more than doubles for gold IDEA award winners versus bronze level award winners. Similarly, Popular Science grand award winners display, on average, approximately one more characteristic than the regular award winners.

The results also suggest that products that win more awards exhibit a higher average number of innovation characteristics. As shown in Table 5, eleven products appeared on two award lists, and two products appeared on all three of the lists (the One Laptop Per Child XO laptop and the Apple iPhone). The triple award-winning products displayed approximately twice as many characteristics as the single award-winning products. These results have some interesting implications. First, they appear to validate the hypothesis that the innovation characteristics accurately describe product innovation, because products with higher level awards exhibit more characteristics on average. Second, the trend suggests that innovators may be wise to focus on *multiple* innovation characteristics, when attempting to design breakthrough products. Although trends are clearly visible in the data in Table 5, it should be noted that increasing the sample size of multiple award-winning products in future work would enhance the statistical significance of the data.

5 Closure

The empirical product study identified the types of engineering-level characteristics that describe a set of award-winning, innovative products. One of the most interesting outcomes of the study was the frequency with which different types of innovations were exhibited. Of the products analyzed in the study, 72.6% and 78.9% had an increase in user and environment interactions, respectively, compared to 35.8% with additional functions and 58.9% with innovative architectures. Based on these results, it appears that a customer may choose one product over another based on its environmental and user interactions more than any other trait. These modified or additional interactions seem to act as the delighters in the KANO diagram. They typically do not involve high functionality, but result in great satisfaction. This finding stresses the need for engineering design methodologies that help designers improve product interactions. Tools are available for considering function, architecture, and environmental interactions during the design process. These tools include an abundance of recent research on functional modeling, product architecture, and green design. While more research and industrial applications are certainly needed in those areas, there appears to be a significant gap between current design methodology and the need to incorporate innovative user interaction features as part of many successful products.

There are several emerging engineering design techniques that focus on customer interactions with a product, as a source of innovations. For example, Von Hippel and coauthors [32, 59, 60] conduct customer interviews with *lead users*—customers who push a product to its limits, experience needs prior to the general population, and benefit significantly from having those needs fulfilled. In related work, the authors have developed techniques for helping ordinary customers serve as lead users by interacting with a product under extreme conditions [21, 33]. Other techniques, such as empathic design [31], articulated use [41], and bodystorming [26], are also aimed at helping designers better understand, or even experience, how customers interact with products. For example, Ford engineers developed a simulation suit with goggles, ear plugs, thick gloves, and arm and leg weights and motion restrictors to help their young engineers understand the challenges faced by older drivers [16]. These principles have also been reflected in universal design studies that encourage designers to target broader sections of the population [46, 56]. Based on the results of this study, it appears that these types of techniques may become increasingly important.

In addition to the broad research opportunities motivated by this study, there are several opportunities for expanding and refining the study itself. For example, it would be helpful to expand the set of products to enhance the statistical significance of the results in Table 5. It would also be helpful to define the innovation characteristics more carefully so that repeatable results can be obtained by new researchers with limited training. Also, some of the innovation characteristics could be broken down further, for example, to differentiate between changes in type and changes in magnitude of energy, material, and information flows. It would be interesting to investigate the impact of these fidelity changes on the results of the study. A comparison of the followed methodology could also be done with customer interviews concerning their reasons for purchasing one product over the competition. Finally, the innovation characteristics developed in this study could be adapted as evaluation tools for analyzing the results of innovation studies. If the characteristics reflect the features of innovative products, then they should be useful as tools for predicting whether a product has the potential for innovative success.

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