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THE CONSTRUCTION OF PREFERENCES FOR CRUX AND SENTINEL PRODUCT ATTRIBUTES

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ABSTRACT

Applying theory from behavioural psychology, we demonstrate that product preferences are not "found" in people, but rather constructed by people on an as-needed basis. The demonstration explores the relationship between *crux* product attributes, which are both important and difficult for people to assess, and *sentinel* attributes, which are easy for people to assess and have a perceived association with a crux attribute. A narrative of the relationship between crux and sentinel attributes is proposed and subsequently supported by the results of a discrete choice survey, analyzed using a new technique called the full factorial marketplace. We generalize our approach to a constructed preferences methodology that can be used to identify crux/sentinel relationships between product attributes.

Keywords: construction of preferences, context effects, discrete choice, conjoint analysis, stated-choice, preference model, inferences, paper towels

1 INTRODUCTION

Most design processes endorsed by the engineering design community include a stage of user need-finding. The term need-finding and many of the common practices associated with this term assume that customers have needs that can be *found*, and all a designer must do is effectively gather these needs. The term "need" has a loose definition in product design and typically refers to needs, wants, requirements, and preferences.

However, the most recent theory in behavioral psychology asserts that needs, specifically preferences, do not rest latent in the customer waiting to be found, but rather the customer *constructs* them on a case-by-case basis when making related decisions. Behavioural psychologists and economists have discovered many situations in which a person asserts they want one thing when asked in one manner, but want another when asked in a different manner [1]. This paper serves to demonstrate that even small modifications to a preference elicitation technique in a design process can cause large inconsistencies in customers' constructed preferences. We are able to elicit a variety of inconsistent constructed preferences by making small modifications to a customer survey, a discrete choice question framework.

Such preference construction sensitivity to the elicitation technique may initially cause trepidation in the designer; collecting preference information might appear ineffective. However, the fact that preferences are constructed widens, not narrows, the application of preference elicitation processes. Designers can study constructed preferences to understand relationships between customers, products, and product attributes. Subsequently, they can design products that enhance customer demand through controlling customer preference construction, or that ensure demand through robust design for varying preference constructions, or a combination of the two approaches.

In [2], a companion to this article, we introduce a new framework of different types of preference inconsistencies, including within-respondent inconsistencies, and three types of across-respondent inconsistencies: comparative, external, and internal. A summary of the research findings below is presented in [2] as an example of a *comparative preference inconsistency*. We define a comparative preference inconsistency as an inconsistency identified by comparing preference constructions of different groups of respondents in response to very similar preference elicitation procedures. Psychologists and marketers sometimes refer to this type of inconsistency as a context effect [3, 4].

This research in this paper utilizes a comparative preference inconsistency to develop a set of inequalities that define the customer's conceptualized relationship between *crux* attributes, i.e., product attributes that are important and complex, and *sentinel* attributes, i.e., product attributes that have a perceived association with crux attributes but are less complex and often easier to evaluate in product purchase decisions. First, we define the terms crux and sentinel attributes and then define the relationship between them using five hypothesized inequalities. We then explain the techniques we use to explore these hypotheses. Next, we apply these techniques to an example product, describe the survey methodology used with the example, and report the results of the survey and analysis of our hypotheses. In the discussion section, we offer an explanation for our findings, a generalized methodology for identifying crux/sentinel relationships in product attributes, and thoughts on the implications of constructed preferences in design methodology. We conclude with a summary of our findings and the identification of areas for future work.

2 CRUX ATTRIBUTES INFLUENCE PREFERENCE CONSTRUCTION

In early-stage preference elicitations, a finished product is unavailable, and so designers typically represent the product with attributes that customers can understand, discuss, and visualize. The exact nature of this representation affects the construction of preferences, especially for well-known products with identifiable crux attributes. Because crux attributes may be difficult or impossible for customers to evaluate and "trade-off" with other attributes in the preference elicitation process, they are frequently represented as combinations of easier-to-evaluate sentinel attributes. As an example, consider that airbags may appear very important to automobile customers, but, in fact, customers really care about crashworthiness. However, asking customers the question "How crashworthy would you like your car to be?" is pointless. Therefore, designers present crashworthiness as a bundle of attributes that customers can use to articulate their preferences for crashworthiness, and trade-off with things like stereo system power: thus the apparent importance of airbags.

The terms crux and sentinel are intentionally new to designers. Since the relationship between crux and sentinel attributes is specific, measurable, and hypothesis-based, we sought to distance the terms from other more general terms such as "primary" and "secondary." Crux and sentinel were chosen because they are unique in the engineering lexicon and also descriptive of the attributes they represent. The word "crux" can be defined as both "the chief problem; the central or decisive point of interest" and "a difficulty which it torments or troubles one greatly to interpret or explain…" The word "sentinel" is defined as a sentry, one who "stands guard" [5]. As people perceive that a sentinel attribute "stands guard" for its crux attribute, which is a "chief problem" and "difficult to interpret," we found this terminology appropriate.

We hypothesize that, in some cases, apportioning a crux attribute into sentinel attributes is not accompanied by a representative apportioning of the product decision into the sentinel attributes. In the absence of mentioning a crux attribute, one representative sentinel attribute may take on a larger importance in the product decision than the crux attribute would have had if it had been mentioned. In order to explore this proposed relationship between crux and sentinel attributes, this paper investigates the preferences elicited from three related discrete choice question frameworks. The frameworks, described generally in Table 1, influence the customer's (survey respondent's) construction of preferences with respect to crux and sentinel attributes.

Table 1. Overview of Variation in Preference Elicitation Technique

Attribute	Scenario A	Scenario B	Scenario C
Crux	Not mentioned	Fixed	Configurable
Sentinel	Configurable	Configurable	Configurable

According to our proposed relationship between crux and sentinel attributes, one would expect the following hypothesized inequalities to be satisfied:

- The sentinel attribute acts as a stand-in when the crux attribute is not mentioned, and thus the importance *I* of sentinel attribute *Sentinel* in product choice scenario *A,* where the crux attribute is not mentioned, is greater than the importance of the sentinel attribute in product choice scenarios *B* and *C*, where the crux attribute is mentioned.

$$I_{Sentinel,A} > \max(I_{Sentinel,B}, I_{Sentinel,C}) \quad (1)$$

- The sentinel attribute does not act as a stand-in when the crux attribute is mentioned and configurable, and thus the importance of a sentinel attribute in product choice scenario *A* is greater than or equal to the importance of the associated crux attribute *Crux* in scenario *C*.

$$I_{Sentinel,A} \geq I_{Crux,C} \quad (2)$$

- The sentinel attribute importance has a larger range (varies more) across choice scenarios than that of the importance of non-sentinel attributes.

$$\max_{A,B,C}(I_{Sentinel}) - \min_{A,B,C}(I_{Sentinel}) > \max_{A,B,C}(I_{Non-sentinel}) - \min_{A,B,C}(I_{Non-sentinel}) \quad (3)$$

- The crux attribute is included and configurable in scenario C, thus the importance of the sentinel attribute in scenario *C* is less than the importance of the crux attribute in scenario *C*.

$$I_{Sentinel,C} < I_{Crux,C} \quad (4)$$

- The level of the sentinel attribute hypothesized as having association to the most-preferred level of the crux attribute must be the most-preferred level for the sentinel attribute in Scenario A.

$$\text{Preference}_{A,\textit{Sentinel level for more-preferred crux level}} > \text{Preference}_{A,\textit{ Sentinel level for less-preferred crux level}} \quad (5)$$

3 EVALUATING THE CONSTRUCTION OF PREFERENCES

3.1 Discrete Choice Analysis

We require a quantitative framework to evaluate the impact of preference construction on the importance of attributes in choice decision. We choose utility theory as a basis for evaluation because it is commonly used in preference estimation. Also, the assumptions underlying utility theory allowed behavioural psychologists and economists to conclude that preferences are constructed [1]. According to utility theory, when a person decides between two choices, it is assumed that the choice with the higher utility is the preferred decision outcome. There is no absolute scale of utility; it can only be measured relatively in the presence of choices (in this case, products) and at least one person (in this case, a potential customer for the product).

The so-called random utility of product *j* is conceptualized as the sum of two components: a portion that can be measured and is systematically related to the attributes of the items in the choice set, v_j, and a portion that cannot be measured and contributes to the modelling of the stochastic nature of observed choice data, the error term ε_j.

$$U_j = v_j + \varepsilon_j \quad (6)$$

In order to estimate v_j, we elect to use a discrete choice survey analyzed with a multinomial logit model. Louviere, Hensher and Swait provide an excellent, comprehensible explanation of the multinomial logit model [6]. The utilities of products are estimated by fitting a model to the choices customers make in a multiple choice survey about product scenarios. According to utility theory, the most preferred choice is modelled so that it receives the highest utility, described in Eq. (7) as the probability that product *j* has the highest utility U_j of all available products.

$$P_j = \mathrm{P}\left[U_j > U_{j'} \text{for all } j' \neq j\right] \quad (7)$$

In the standard implementation of discrete choice analysis, U_j is calculated by assigning a portion of a product's measurable utility v_j to each *attribute/level* present in the product, Eq. (8) below. The attribute ζ is a product feature or characteristic and the levels ω of the attribute are the ways in which the attribute can be configured. Each product can have only one level included for any given attribute, and each attribute/level combination has its own discrete utility or "part-worth," signified as $\beta_{\zeta\omega}$. Summing the part-worths of a particular product *j* gives the measurable portion of utility. In Eq. (8), $x_{j\zeta\omega}$ is a dummy variable that takes a value of 1 for attributes/levels present in product *j* and a value of 0 for attributes/levels absent from product *j*. Under some assumptions about the distribution of the error term, P_j simplifies to Eq. (9), as proven in Chapter 3 of [6]. We estimate Eq. (9) using a hierarchical Bayesian analysis package [7].

$$v_j = \sum_{\zeta} \sum_{\omega} \beta_{\zeta\omega} x_{j\zeta\omega} \quad (8)$$

$$P_j = \frac{e^{v_j}}{\sum_{j'} e^{v_{j'}}} \quad (9)$$

3.2 A New Approach: Full Factorial Marketplace Analysis

In order to test our proposals about preference construction and subsequent changes in attribute importance, we must compare results across survey versions. Yet, it is not possible to directly compare part-worths across survey versions when the parameters are estimated separately because utility is not estimated on an absolute scale. However, it is possible to normalize utilities to the same scale in the form of choice share per product using Eq. (9). Typically, Eq. (9) is used to predict the choice share of several competing products; we diverge from the typical use of this equation by introducing the full factorial marketplace. The full factorial marketplace is a hypothetical marketplace populated with products that have all possible combinations of attributes and levels. A simple example of a full factorial marketplace for a ball with three possible sizes (small, medium, large) and three possible colours (red, blue, green) is described in Table 2.

Table 2. Products in example full factorial marketplace

Small Red	Medium Red	Large Red
Small Blue	Medium Blue	Large Blue
Small Green	Medium Green	Large Green

The definition of Eq. (9) in the full factorial marketplace becomes "the exponential of our product's utility over the sum of the exponential of every possible product's utility." The more an attribute/level is preferred *versus* other attribute/levels, the higher its part-worth utility, and the larger the choice share of the full factorial marketplace will have that attribute/level included. The choice shares for each product in the full factorial marketplace will always sum to 1 (100%). Therefore, a full factorial marketplace can be thought of a normalizing procedure for the part-worths, thus allowing separate multinomial logit estimates to be compared on the same scale. The percentage of the full factorial marketplace that has a particular attribute/level can be calculated by that attribute/level's *aggregate market share* in the full factorial marketplace, described in Eq. (10). Eq. (10) is a summation of the choice shares of all products in the full factorial marketplace that contain a particular attribute/level.

$$\hat{P}_{\zeta\omega} = \sum_{j} x_{j\zeta\omega} P_j \quad (10)$$

3.3 A New Metric: Full Factorial Importance of Attributes

We use full factorial aggregate market shares to investigate the effects of preference construction on the relative importance of attributes in product decisions. In order to do so, we must quantitatively define "Importance" in the realm of the full factorial marketplace. Importance can be defined as the percentage of a product choice that is determined by a specific attribute. A large percentage implies a higher importance in the decision. Quantitative measurements of importance have been suggested previously [8]. Preferences are directly related to the concept of importance: the stronger the preference is for one level of an attribute vs. the other(s), the larger the difference in part-worth utility between these two or more levels, and the greater the overall importance of the attribute in the product decision. For an attribute with two levels, *1* and *2*, aggregate market shares for the levels are determined using Eq. (11) and (12).

$$\hat{P}_{\zeta 1} = \sum_{j} x_{j\zeta 1} P_j \quad (11)$$

$$\hat{P}_{\zeta 2} = \sum_{j} x_{j\zeta 2} P_j \quad (12)$$

For an attribute with levels that are not very important in predicting product choice, estimated part-worths for these levels approach zero (when constraining degrees of freedom in the estimation by setting the sum of all part-worths associated with a particular attribute equal to zero). As the estimated part-worths of a two-level attribute approach zero, the aggregate full factorial market shares of the two levels approach equality at 50%. This intuitive principle applies to attributes with more levels: *as the overall importance of the attribute decreases, the aggregate shares of the marketplace amongst the attribute's levels will approach equality at* n^{-1} *where n equals the number of levels for the attribute.* Forthcoming work will include a rigorous proof of this principle, as well as a proof that aggregate market shares for attributes in the full factorial marketplace have the same values in certain fractionally-factorial marketplaces. If a no-choice option is included in the survey, note that this principle only applies if the no-choice option is not included in the full factorial marketplace or comprises an insignificant choice share in the marketplace. In this study, the no-choice option would have constituted a tiny choice share in the marketplaces, less than 0.1%, so it was excluded from the marketplace. Following from this principle, we present a new quantitative analytical tool for judging the importance of attributes: summing the squared deviations of the levels' aggregate full factorial market shares from their respective n^{-1} equality shares for each attribute, as in Eq. (13).

$$I_{\zeta} = \sum_{\omega} \left(\hat{P}_{\zeta\omega} - n^{-1} \right)^2 \qquad (13)$$

4 SURVEY INSTRUMENT DESIGN AND ADMINISTRATION

A discrete choice survey and analysis were conducted as a demonstration of both the new techniques above and a test of the hypothesized relationships between crux and sentinel attributes outlined in Eq. (1-5). The survey investigates preferences for paper towels. Paper industry and Consumer Reports information were used to identify the crux attributes for the paper towels: strength, softness, and absorbency [9, 10]. We investigate two potential sentinel attributes: quilting and recycled paper content. Because of the towel industry's strong advertising of the connection between quilted towels and improved absorbency, we concentrated on investigating the relationship between quilting and absorbency. Recycled paper content was included as a potential sentinel attribute because customers may perceive a link between high recycled paper content products and low quality [10]. We had no specific predictions as to particular links between the crux attributes and recycled paper content. Table 3 repeats Table 1 as applied to the towel study, in which three versions of a discrete choice survey with ten multiple choice tasks were constructed. The attribute/levels available for choice in the survey are presented in Table 4.

- In Version *A* of the survey, respondents were given no information on strength, softness and absorbency. The respondents made their choices based on quilting, pattern, packaging, and recycled paper content. Total Respondents: 70; Average Age: 48; Male Respondents: 40%
- In Version *B*, respondents were presented with paper towels that all had average "2 out of 3" ratings in strength, softness, and absorbency (ratings explained in detail below). The respondents made their choices based on quilting, pattern, packaging, and recycled paper content, as all choices had the same, average strength, softness, and absorbency. Total Respondents: 73; Average Age: 54; Male Respondents: 37%
- In Version *C*, respondents chose between paper towels with a variety of strength, softness, and absorbency ratings as *attributes*. The respondents made their choices based on strength, softness, absorbency, quilting, pattern, packaging, and recycled paper content. Total Respondents: 74; Average Age: 48; Male Respondents: 43%

Table 3. Detail of Variation in Preference Elicitation Technique

Attribute (identifier)	Version *A*	Version *B*	Version *C*
Strength (crux)	Not mentioned	Fixed configuration	3 configurations
Softness (crux)	Not mentioned	Fixed configuration	3 configurations
Absorbency (crux)	Not mentioned	Fixed configuration	3 configurations
Quilting (sentinel)	2 configurations	2 configurations	2 configurations
Recycled Paper Content (sentinel)	4 configurations	4 configurations	4 configurations

Table 4. Attribute/ Levels (Abbrev.) presented in combinations in discrete choice survey

Attribute	Levels
Pattern	Patterned (PY), Not Patterned (PN)
Quilting	Quilted (QY), Not Quilted (QN)
Recycled Paper Content	0% (RC0), 30% (RC3), 60% (RC60),100% (RC100)
Packaging	1 roll 150 sheets (N1), 2 rolls 75 sheets (N2), 3 rolls 50 sheets (N3)
Absorbency	1 out of 3 (AB1), 2 out of 3 (AB2), 3 out of 3 (AB3)
Softness	1 out of 3 (SO1), 2 out of 3 (SO2), 3 out of 3 (SO3)
Strength	1 out of 3 (SR1), 2 out of 3 (SR2), 3 out of 3 (SR3)

Respondents answered one of the three versions as the first part of a five-part survey about paper towels, which took a total of 30 minutes to complete. The survey was designed using Sawtooth Software, and Luth Research administered the survey via the Internet to participants from their survey research panel. Luth recruited participants by sending members of their research panel a generic e-mail message that invited them to take a survey and earn a one dollar incentive for completing the survey. It did not mention the nature or subject of the survey. It included a link to the starting webpage of the survey, an unsubscribe option, and the contact information for Luth Research. Upon entering the survey, respondents answered a screening question that selected only people who were over the age of 18 and had purchased paper towels in the past six months for participation. We believed respondents would answer the survey differently if they knew its academic origins, so the first webpage of the survey told respondents that a large consumer goods company wanted their input. The last page of the survey informed respondents of the true purpose of the survey and requested their participation in the research project. Regardless of their decision to participate, respondents were paid $1 for their efforts. A sample question from survey version *A* is presented in Figure 1.

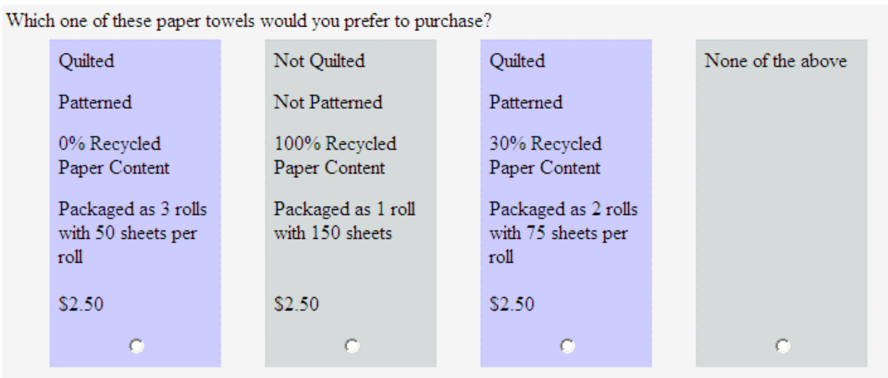

Figure 1. Sample discrete choice question from survey version A

Price was not included as an attribute in any version, and respondents were told that all paper towels described cost $2.50 for the 150 sheets. As customers can be price-sensitive to paper towels, we set the price fixed across conditions to allow respondents to focus on the other attributes of the scenarios. The strength, softness, and absorbency ratings mentioned in Table 4 were described to survey respondents as:

Softness:
A rating of 1 out of 3 is as soft as the store-label economy brand. It is the lowest rating.
A rating of 2 out of 3 represents average softness.
A rating of 3 out of 3 means the towel is among the softest towels that you can buy.

Absorbency:
A rating of 1 out of 3 can absorb a 2.5 inch water spill (About the same size around as a tomato slice).
A rating of 2 out of 3 can absorb a 4 inch water spill (About the same size around as a donut).
A rating of 3 out of 3 can absorb a 5 inch water spill (About the same size around as a small plate or saucer).

Strength:
A rating of 1 out of 3 is given to paper towels that can do a minor amount of scrubbing while wet without tearing.
A rating of 2 out of 3 is given to paper towels that can do an average amount of scrubbing while wet without tearing.
A rating of 3 out of 3 is given to paper towels that can do a large amount of scrubbing while wet without tearing.

The administration procedure for all survey versions and all respondents was identical. First, the respondents read descriptions and saw pictures (when relevant) of the attributes that were included in the survey. Respondents were given an example question. Then the survey began, showing respondents ten multiple choice questions and asking for their choices between products. Eight of the ten multiple choice questions were varied across respondents. That is, Sawtooth's web interface varied attribute/level combinations presented in the surveys in a random, orthogonal manner across the respondent population [11].

Two of the ten questions were identical across all respondents. In Fixed Question One, all attributes were held constant across the three product choices (quilted, not patterned, 2 rolls, and average strength, softness, and absorbency (in Version *B* and *C*)) except for recycled paper content, which varied as 0%, 30%, and 100%. Fixed Question Two was similar to Question One, but all three towels were patterned and recycled paper content varied by 30%, 60%, 100%. The responses to these fixed questions were not included in the preference estimation.

5 RESULTS AND ANALYSIS

The results of the survey were analyzed as described in Section 3. Three hierarchical Bayesian (HB) estimations of the multinomial logit models were performed using Sawtooth Software's CBCHB program [7]. The HB estimations used 100,000 draws and 100,000 estimation iterations each, and the resulting part-worth estimates were graphed over the 100,000 iterations to visually confirm convergence of the results. The results are presented in Table 5.

Table 5. Part-worths estimated in HB Multinomial Logit Model

Attribute	Level	Version *A*	Version *B*	Version *C*
Packaging	1 Roll 150 sheets	0.26	0.33	0.54
	2 Rolls 75 sheets	0.07	0.16	-0.09
	3 Rolls 50 sheets	-0.34	-0.49	-0.46
Quilting	Quilted	1.36	0.65	0.46
	Not Quilted	-1.36	-0.65	-0.46
Pattern	Patterned	-0.11	0.33	-0.12
	Not Patterned	0.11	-0.33	0.12
Recycled Paper Content	0% RPC	-1.85	-1.65	-1.85
	30% RPC	-0.65	0.04	-0.39
	60% RPC	0.76	0.44	0.99
	100% RPC	1.74	1.16	1.25
Strength	1 out of 3	N/A	N/A	-2.75
	2 out of 3	N/A	N/A	0.88
	3 out of 3	N/A	N/A	1.87
Softness	1 out of 3	N/A	N/A	-1.10
	2 out of 3	N/A	N/A	0.05
	3 out of 3	N/A	N/A	1.05
Absorbency	1 out of 3	N/A	N/A	-3.79
	2 out of 3	N/A	N/A	1.23
	3 out of 3	N/A	N/A	2.56
None of the Above		-1.54	-4.48	-1.07

Table 6. Importances of Aggregate Full Factorial Market Shares

I_ζ	Version *A*	Version *B*	Version *C*	Range
Quilting	0.38	0.16	0.09	0.29
Pattern	0.01	0.05	0.01	0.05
Packaging	0.02	0.03	0.06	0.04
Recycled Paper Content	0.26	0.13	0.15	0.13
Strength	N/A	N/A	0.26	N/A
Softness	N/A	N/A	0.19	N/A
Absorbency	N/A	N/A	0.34	N/A

Full factorial aggregate market shares for each attribute in each of the three estimated models were calculated according to Eq. (10). Table 6 reports importances as calculated according to Eq. (13). Higher numbers indicate higher importance in the respondent choice decision. The hypothesized sentinel attribute of quilting in version *A* received the maximum importance value of 0.38. The calculated importances support our initial proposals, Eq. (1-5), on the relationship between the sentinel attribute of *quilting* and the crux attribute of *absorbency*:

- $I_{Sentinel,A} = 0.38 > 0.16 = \max(I_{Sentinel,B}, I_{Sentinel,C})$
- $I_{Sentinel,A} = 0.38 \geq 0.34 = I_{Crux,C}$
- $\max_{A,B,C}(I_{Sentinel}) - \min_{A,B,C}(I_{Sentinel}) = 0.29 > 0.13 = \max_{A,B,C}(I_{Non-sent.}) - \min_{A,B,C}(I_{Non-sent.})$
- $I_{Sentinel,C} = 0.09 < 0.34 = I_{Crux,C}$
- $\text{Preference}_{A,\text{Sentinel level for more-preferred crux level}} = 1.36 > -1.36 = \text{Preference}_{A,\text{ Sentinel level for less-preferred crux level}}$

The results are consistent with our ordinal predictions. A future step in validating these relationships is to compute the variance for all terms and give statistical merit to our conclusions. No such strong conclusions can be made for the hypothesized sentinel attribute of recycled paper content, as it does not conform to Eq. (5). The level (0% RPC) hypothesized to be associated with the more-preferred levels of the crux attributes (3 out of 3) was in fact less-preferred as compared to other levels (30, 60, 100%). We will now examine the aggregate full factorial market shares for this and all other attributes graphically in Figure 2. Compare quilting to pattern in Figure 2: Figure 2.A shows the aggregate full factorial market shares of quilted towels (QY) and not quilted towels (QN) across the three survey versions (*A,B,C*); Figure 2.B shows the same for pattern. The graphs indicate the equal market share of n^{-1} (50%) with a dotted line. The closer the predicted market shares for an attribute are to this dotted line, the less importance the available levels of that attribute has in the product decision. As shown in Figure 2.A, respondents that saw no information on the absorbency of the towel (version *A*) placed a high importance on the attribute quilting. Respondents that saw product choices with all equal absorbency (version *B*) placed less importance on quilting, but still prefer quilted to not-quilted. Respondents with the option to choose strength, softness, and absorbency (version *C*) placed even less of an emphasis on quilting; it approaches the importance of pattern in version *B*. Comparatively, in Figure 2.B, pattern was unimportant in versions *A* and *C*, and somewhat more important in version B, with no clear trend in either importance or preference.

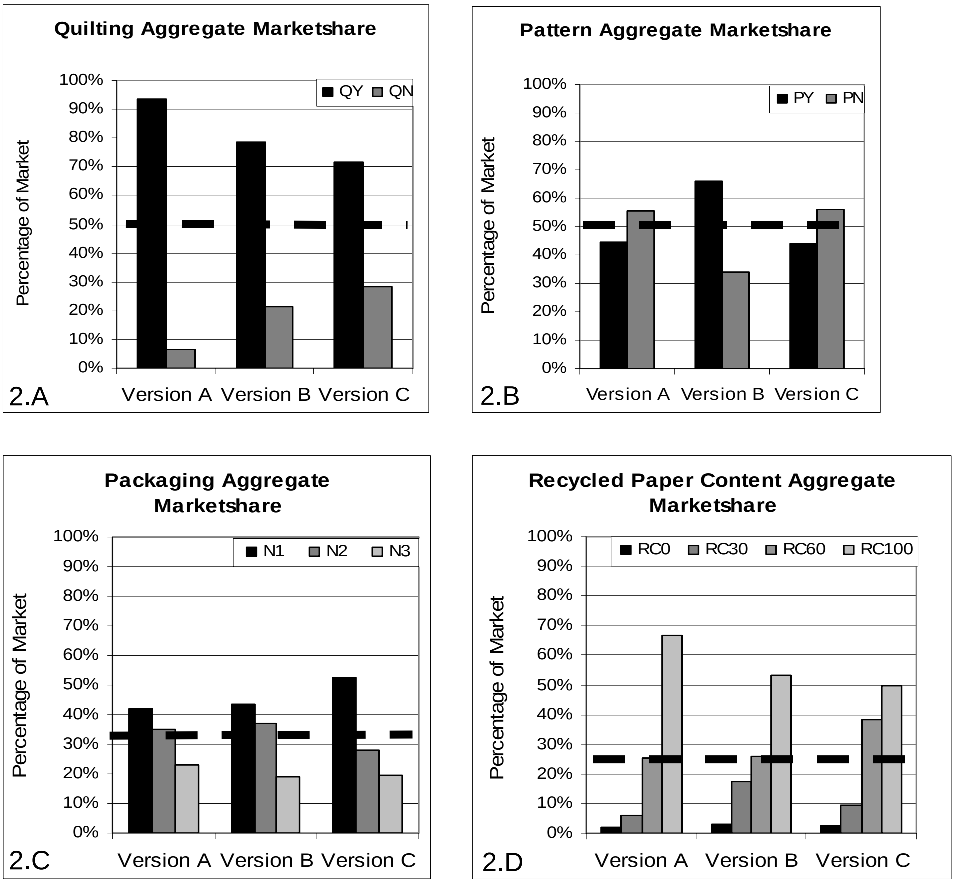

Figure 2. Aggregate full factorial market shares

Figure 2.D shows the aggregate full factorial market shares for the other attribute of interest, recycled paper content. At first, it appears that this attribute also declines in importance as respondents gain knowledge of the strength, softness, and absorbency of the paper towel. However, consider Figure 3, in which market share is aggregated in terms of paper towels with 0% recycled paper content and paper towels with greater than 0% recycled paper content, and also by towels with 100% recycled paper content and less than 100% recycled paper content. The preference for towels that contain at least some recycled paper content is extremely high, very important, and almost constant across the three survey versions, but it is not important that a towel have 100% recycled paper content.

We must also investigate the importance of the crux attributes: strength, softness and absorbency. Preference for these attributes can only be estimated from survey version *C*, the only survey version in which respondents chose between paper towels with different levels of the crux attributes. The full factorial aggregate market shares for softness, strength, and absorbency are reported in Figure 4. All three attributes have high importances in product choice, with the best rating (3 out of 3) strongly preferred. For strength and absorbency, the lowest rating (1 out of 3) represented close to 0% of the marketplace. The counts of responses to the two fixed questions, described in Section 4, are reported in Table 7. A chi-squared homogeneity test was performed to test if the three groups of respondents, classified by which version of the survey they answered, responded to the fixed questions in a statistically different manner. As shown in the table, a larger percentage of version *C*'s respondent population preferred a 100% recycled paper towel than that of the other versions' respondent populations, but this difference was not statistically significant.

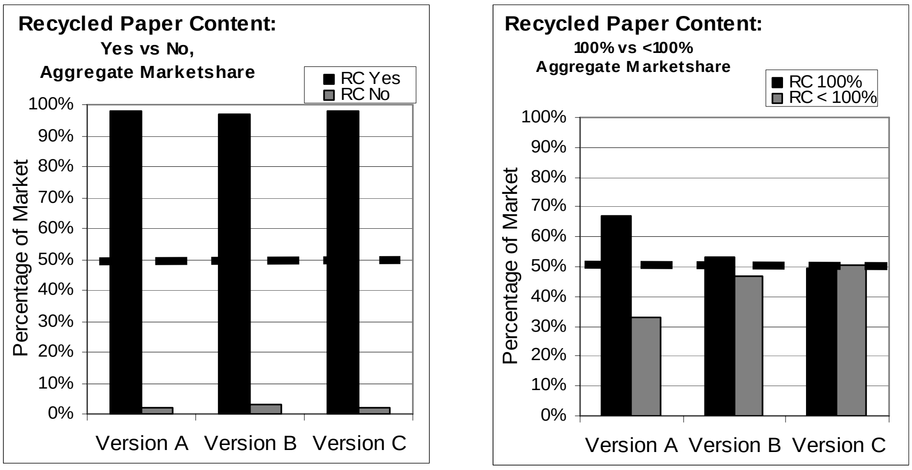

Figure 3. Aggregate market share in the full factorial marketplace for recycled paper

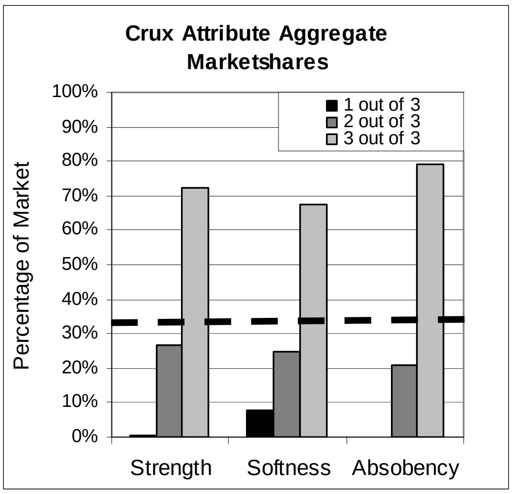

Figure 4. Full factorial aggregate market shares for strength, softness, and absorbency

Table 7. Counts of responses to Fixed Questions One and Two across survey versions

	Level of RPC	Count (%) Version *A*	Count (%) Version *B*	Count (%) Version *C*	Significance
Fixed Question One	0%	6 (9%)	9 (12%)	6 (8%)	0.800
	30%	14 (20%)	13 (18%)	9 (12%)	
	100%	43 (61%)	42 (58%)	49 (66%)	
	NOA	7 (10%)	9 (12%)	10 (14%)	
Fixed Question Two	30%	11 (16%)	12 (16%)	3 (4%)	0.274
	60%	13 (19%)	10 (14%)	12 (16%)	
	100%	37 (53%)	42 (58%)	48 (65%)	
	NOA	9 (13%)	9 (12%)	11 (15%)	

6 DISCUSSION

6.1 Discussion of Results

Quilting was identified as a sentinel attribute for the crux attribute of absorbency in paper towels, as the relationship between the importance of the two attributes under various preference construction scenarios conforms to Eq. (1-5). The relationship can be summarized as follows.

In the absence of information about a crux attribute, the customer identifies one or more sentinel attributes and makes perceived associations between the sentinel and crux attributes. These associations cause the customer to construct preferences in the absence of choice control over the crux attribute such that the importance of the sentinel attribute is exaggerated. Once the customer receives some information on the crux attribute, the importance of the sentinel one begins to decrease. In a product choice in which the customer has full control over the crux attribute, the initial importance of the sentinel is transferred to the crux and the importance of the sentinel falls to the range of other unimportant attributes in the product choice decision.

Recycled paper content was not identified as a sentinel attribute for any of the three crux attributes. A possible explanation is *social desirability bias*: the tendency to answer a survey in a manner that social norms would deem "correct," but not in a manner that actually reflects one's own sentiments [12]. Other findings we present in [2] suggest that preference for recycled paper content is susceptible to this bias. We also speculate that recycled paper content may have a very strong sentinel relationship with another attribute not discussed in the survey, such as environmental friendliness. As the survey does not address environmental friendliness as an attribute, recycled paper content could have served as the sentinel for that potentially-crux attribute, and therefore maintained a high importance level. The full factorial market share aggregations revealed that in all three survey versions, paper towels with at least 30% recycled paper content accounted for over 97% of the marketplace. It is also worth studying whether one attribute can be a sentinel for two different crux attributes at the same time. Even though customers may perceive a relationship between recycled paper content and paper towel quality, this perceived relationship may lay dormant, with customers focused on recycled paper content as a sentinel attribute for environmental friendliness. Another explanation may be that sentinel attributes can only function in positive relationships (the more quilting, the more absorbent). Recycled paper content may not serve as a sentinel attribute due to a perceived negative correlation with strength, softness, and absorbency.

6.2 Generalized Constructed Preference Methodology for studying attribute relationships

The hypotheses, survey instrument, and analysis presented above can be generalized to identify crux and sentinel attributes in other products, and investigate the relative importance of attributes in product decisions. We propose a constructed preference methodology for studying attribute relationships in any product. The relevant material from this paper is included in parentheses.

1. Identify product attributes for study (crux/sentinel attributes)
2. Hypothesize relationships between the importances of the attributes (Eq. (1-5))
3. Choose a set of preference elicitation scenarios to test the hypotheses (Table 1)
4. Use these scenarios to design an experiment (Section 4)
5. Administer the preference elicitation experiment (Section 4)

6. Analyze results, estimate preferences (as part-worths using Eq. (7-9), results in Table 5)
7. Check that the three scenarios elicit statistically different preferences (see below)
8. If applicable, calculate full factorial aggregate market shares (Eq. (10))
9. Calculate attribute importances in the various scenarios (Eq.(13), results in Table 6)
10. Numerically test hypotheses, accept or reject (Section 5)
11. Graphically analyze results to understand findings (Figures 2-4)
12. Discuss implications of results (Section 6.1)

As a note to Step 7 above, our approach was to check that: (1) estimating three separate sets of part-worth values for the three versions of the survey gave a statistically significantly better fit to the data than estimating a combined model, where all three versions shared the same part-worth values (2) the variance on the parameters were in the same range, and (3) the differences between estimated part-worths across versions fit our hypotheses about the relationship between crux and sentinel attributes.

6.3 Implications of the Construction of Preferences in Design Methodology

Previously unexplored in the field of engineering product design, the construction of preferences allowed us to test the hypotheses presented in this paper, and in general, will allow the testing of many possible relationships between product attributes in the minds of customers. Despite the fact that this theory has been discussed in psychological literature for decades, it has received little or no attention in engineering, while design engineers devote a large amount of effort to "collecting" customer needs and preferences in the early-stage design process. The construction of preferences partially explains why many products designed to fulfill a need "found" in the design process are unsuccessful in the marketplace. The customers' construction of preferences in the two situations, the design process and the point-of-purchase, were significantly different and the product was therefore not purchased. Designers have, at times, blamed this unfortunate outcome on the method of need-finding, and have spent much research time seeking that one special method of need-finding that will be most accurate. The theory that people construct preferences in relation to the situation in which they are elicited explains why different need-gathering techniques find different needs. It also implies that no single best need-finding procedure exists, as no customer interaction with the design process can exactly replicate the purchase scenario such that the customer's preferences are constructed in a manner identical to when they face a purchase decision. The construction of preferences has far-reaching impacts on the engineering design process, where there are many forms of interaction with customers, such as interviews and observed behaviour, in which preference construction has not yet been considered by design researchers.

7 CONCLUSION

In this study we quantitatively examined the relationship between important, complex product attributes, termed crux attributes, and perceptually-related but less-important attributes, termed sentinel attributes. The quantitative value of sentinel attributes was found to be critically high in a marketplace where customers do not have access to information about crux attributes: in such a hypothetical marketplace where customers can choose whatever product they want, products lacking sentinel attributes are predicted to have only about a two percent chance of being purchased. In product choices, as the amount of control customers have over crux attributes increases, the importance of sentinel attributes in their choices decreases, and the importance of crux attributes in their choices increases. Suggestions for future work on crux and sentinel attributes include exploring the impact of social desirability bias on crux and sentinel attributes, examining the difference between a "positive" and "negative" crux/sentinel relationship, and addressing the possibility that one attribute cannot serve as a sentinel for two different crux attributes at the same time.

While exploring the relationship between crux and sentinel attributes, we demonstrated how the construction of preferences manifests itself as inconsistent responses to slightly different discrete choice surveys. The full factorial marketplace and attributes' aggregate market shares in the marketplace were introduced as normalizing tools that allowed comparison of preference construction across separate preference estimations. A new measurement called full factorial importance was introduced as a way to compare importances of attributes. Future work in the full factorial marketplace may include rigorous proofs as mentioned previously, as well as formulas for computing the variance of aggregate market shares and full factorial importances when the technique is used with a multinomial logit model.

Steering away from need-finding towards an acceptance of the construction of preferences will clear paths to many new fields of research in the engineering design community. For example, a quantitative exploration of users' perceived relationships between product attributes will bring a behavioral psychology perspective to the field of emotional design [13, 14]. Researchers can explore how designers construct their own preferences in the design process and the implications of these constructions. There is call for the introduction of new design methodologies that consider the construction of preferences in the design process. Designs can be geared to proactively attempt to control preference construction, or reactively attempt to be preferred under a variety of preference scenarios, or they can represent a combination of the two strategies. As we strive to create designs that fulfill needs, we must accept that these needs are reflexive and discuss, both quantitatively and philosophically, how design interacts with constructed preferences.

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REFERENCES

[1] Slovic P. The Construction of Preference. *Am. Psychol.,* 1995, 50, pp. 364-371.
[2] MacDonald E., Gonzalez R., and Papalambros P. Preference Inconsistency in Multidisciplinary Design Decision Making. To be published in *2007 ASME Design Technical Conferences*, DETC2007-35580, Las Vegas, September 2007 (ASME).
[3] Sudman S., Bradburn N. and Schwarz N. *Thinking about Answers: The Application of Cognitive Processes to Survey Methodology,*1996 (Jossey-Bass Publishers, San Francisco).
[4] Kagel J. and Roth A. *Handbook of Experimental Economics,* 1995 (Princeton University Press, Princeton).
[5] Oxford English Dictionary, http://www.oed.com/. (6/1/07)
[6] Louviere J., Hensher D. and Swait J., *Stated Choice Methods,* 2000 (Cambridge University Press, Cambridge).
[7] Anonymous. The CBC/HB System for Hierarchical Bayes Estimation Version 4.0. *Sawtooth Software Technical Paper Series.* Available: http://www.sawtoothsoftware.com/download/techpap/hbtech.pdf
[8] Orme B.K. *Getting Started with Conjoint Analysis,* 2005 (Research Publishers, Madison).
[9] Atkins J. A Beginner's Guide To Towel and Tissue, Part 1. *Solutions!: For People, Processes, and Paper,* 2004, 87, pp. 32-36.
[10] Anonymous. The best picker-uppers. *Consumer Reports,* 1998, 63, p. 52.
[11] Anonymous. Choice-based conjoint technical paper. *Sawtooth Software Technical Paper Series.* Available: http://www.sawtoothsoftware.com/download/techpap/cbctech.pdf
[12] Bennett J. and Blamey R. Yea-saying and validation of a choice model of green product choice. In *The Choice Modelling Approach to Environmental Valuation* Bennett J. and Blamey R., Eds., 2001, pp. 178-201 (Edward Elgar, Cheltenham).
[13] Norman D. *The Design of Everyday Things,* 1998 (Doubleday, New York).
[14] Krippendorff K. and Butter R. Product Semantics: Exploring the Symbolic Qualities of Form. *The Journal of the Industrial Designers Society of America,* 1984, Spring, pp. 4-9.

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