

The construction of preferences for crux and sentinel product attributes

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Designers often attempt to find preferences that users have for products and their attributes. 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 to assess and have a perceived association with a crux attribute. A relationship between crux and sentinel attributes is proposed, supported by the results of a case study involving design of paper towels, where a discrete choice survey is analysed using a new technique called the full factorial marketplace. We generalise our approach to a constructed preferences design method that can be used to identify crux/sentinel relationships between product attributes.

Keywords: product design; construction of preferences; context effects; discrete choice; conjoint analysis; stated-choice; preference model; inferences

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 behavioural psychology asserts that needs, specifically preferences, do not rest latent in the customer waiting to be found. Rather, the customer constructs them on a case-by-case basis when making related decisions. Behavioural psychologists and economists have discovered many situations where people assert wanting one thing when asked in one manner, and wanting another when asked in a different manner (Slovic 1995). This paper demonstrates that even small modifications to a preference elicitation technique in a design process can cause large inconsistencies in customers’ constructed preferences. We can elicit a variety

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of inconsistent constructed preferences by making small modifications to a customer survey, specifically, a discrete choice question framework.

Preference sensitivity to the elicitation technique may initially cause trepidation in the designer, as collecting preference information would 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 products that ensure demand through robust design for varying preference constructions, or a combination.

In a companion article (MacDonald *et al.* 2007b), we introduce a new framework of different types of preference inconsistencies: within-respondent inconsistency and three types of across-respondent inconsistencies termed comparative, external, and internal. The research in the present article is an example of a comparative preference inconsistency, which is identified by comparing preference constructions of different groups of respondents in response to similar preference elicitation procedures. Psychologists and marketers sometimes call this a context effect (Sudman *et al.* 1996, Kagel and Roth 1995).

Here we develop a set of hypotheses expressed as inequalities between compared preference constructions that define the customer's conceptualised 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 describe the terms crux and sentinel attributes, the relationship between them using five hypothesised inequalities, and the techniques used to explore these hypotheses. Next, we apply these techniques to an example product, describe the survey method used, and report the survey results and analysis of the hypotheses. In the discussion section, we offer an explanation for the findings, a generalised design method 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 findings and discussion of future work.

2. Crux attributes influence preference construction

The terms crux and sentinel are intentionally new to designers. We seek to distance the terms from other more general terms such as 'primary' and 'secondary' because the relationship between crux and sentinel attributes is specific, measurable, and hypothesis-based. 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.' As people perceive that a sentinel attribute 'stands guard' for its crux attribute, which is a 'chief problem' and 'difficult to interpret', we submit this terminology as appropriate (Oxford English Dictionary 2007).

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 visualise. 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, airbags may appear very important to automobile customers, but what they really care about is avoiding injury during a crash. Asking customers 'How crashworthy would you like your car to be?' is pointless. Therefore, designers present crashworthiness as a bundle of

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
Non-sentinel	Configurable	Configurable	Configurable

attributes, such as airbags, that customers can use to articulate preferences for crashworthiness, and trade-off with, say, stereo system power under a cost constraint.

We postulate that apportioning a crux attribute into sentinel attributes is not always accompanied by a representative apportioning of the product decision into the sentinel attributes. Without mentioning a crux attribute, a representative sentinel attribute may become more important in product decisions than what the crux attribute would have been, had it been mentioned. The behavioural literature has documented a related finding in judgements of frequency (Fischhoff *et al.* 1978). To study the crux-sentinel relationship in the context of consumer choice, we investigate the preferences elicited from three related discrete choice question frameworks that influence the customer's (survey respondent's) construction of preferences with respect to crux and sentinel attributes (Table 1). Table 1 gives the general structure of the experiment and shows the relation of the three discrete choice question frameworks. In Table 1, attributes have one of three classifications in each choice scenario. 'Not mentioned' means that the attribute is not mentioned at all in the choice scenario; 'Fixed' means that the attribute is described/configured in the exact same way in each option in the choice scenario; and 'Configurable' means that the attribute will have one of several configurations in any given option in the choice scenario. In scenario A, crux attributes are not mentioned and sentinel attributes are configurable. In scenario B, crux attributes are fixed and sentinel attributes are configurable. In scenario C, both crux and sentinel attributes are configurable. All three scenarios also contain other attributes that are not involved in the crux/sentinel relationship. These attributes are referred to as 'Non-sentinel', and they are configurable in all three scenarios. Hypotheses are stated in terms of the three scenarios in Table 1 to facilitate their description in the context of the present study.

The following inequalities are postulated to hold for the crux–sentinel relationship:

- 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.

$$I_{Sentinel,A} > \max_{i=B,C} \{I_{Sentinel,i}\}. \quad (1)$$

- In scenario A, where the sentinel attribute stands-in for the crux attribute, the sentinel attribute should have a high importance in choice. This importance should be at least as high as that of the crux attribute *Crux* in scenario C. For the purposes of easily testing the statistical significance of the hypothesis, we will test for strict inequality. Thus, the importance of a sentinel attribute in product choice scenario A is greater than that of the associated crux attribute in scenario C.

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

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

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

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

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

- Equation 5 requires the designer to predict the nature of the relationship between the crux and sentinel attribute. Specifically, the designer predicts the configuration of the sentinel attribute in scenario A that has the highest *part-worth utility* β , due to its perceived association with preferred configuration(s) of the crux attribute. Part-worth utility will be discussed later in Section 3. In scenario A, the configuration of the sentinel attribute hypothesised as being associated with the preferred configuration of the crux attribute must have the highest utility. This hypothesis is crucial to experimental validation: it forces the designer to be specific in the relationships they test and decreases the possibility of ‘hunting’ for relationships in findings.

$$\beta_{Sentinel\ configuration\ predicted\ to\ be\ most\ preferred,A} > \beta_{Other\ sentinel\ configurations,A}. \quad (5)$$

These inequalities will be tested in the case study.

3. Evaluating the construction of preferences

3.1. Discrete choice analysis

We choose utility theory to evaluate the above hypotheses because it is commonly used in preference estimation. Also, the assumptions underlying utility theory allow behavioural psychologists and economists to conclude that preferences are constructed (Slovic 1995). According to utility theory, when a person decides between two choice outcomes, the model assigns the chosen outcome the higher utility. There is no absolute scale of utility; it can only be measured relatively in the presence of choices (in this case, products) and of at least one person (in this case, a potential customer for the product).

The random utility U_j of product j is the sum of two components: a term v_j , which can be measured and is systematically related to the attributes of the items in the choice set, and an error term ε_j , which cannot be measured and models the stochastic nature of observed choice data.

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

To estimate v_j , we use a discrete choice survey analysed with a multinomial logit model. Louviere *et al.* (2000) provide an excellent, comprehensible explanation of the multinomial logit model. In the design literature, the multinomial logit model paired with a discrete choice survey is referred to as discrete choice analysis or conjoint analysis. For different uses of discrete choice analysis in design, refer, for example, to Michalek *et al.* (2005) and Wassenaar *et al.* (2005). The utilities of products are estimated by fitting a model to the choices customers make in a multiple choice survey about product scenarios. The most preferred choice is modelled so that it receives the highest utility, described in Equation (7) as the probability that product j has the highest utility U_j of all available products.

$$P_j = P[U_j > U'_j \text{ for all } j' \neq j]. \quad (7)$$

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 (Equation (8)). 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 Equation (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 Equation (9) (Louviere *et al.* 2000). We estimate Equation (9) using a hierarchical Bayesian analysis package (Sawtooth 2007b).

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

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

3.2. A new approach: full factorial marketplace analysis

To test the hypotheses about preference construction and subsequent changes in attribute importance, we must compare results across survey versions. Utility is not estimated on an absolute scale, and so we cannot compare part-worths across survey versions directly when the parameters are estimated separately. However, we can normalise utilities to the same scale in the form of choice share per product using Equation (9). Typically, Equation (9) is used to predict the choice share of several competing products; we diverge from the typical use of this equation by introducing the concept of 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 Equation (9) in the full factorial marketplace becomes the exponential of our product’s utility over the sum of the exponentials of every possible product’s utility. The more an attribute/level is preferred *vs.* other attribute/levels, the higher its part-worth utility will be, 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 is a normalising procedure for the part-worths, 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 Equation (10), which is a summation of the choice shares of all products in the full factorial marketplace that contain a particular attribute/level. If one level of a product attribute has a higher estimated utility than another level, the one with the higher utility is said to be preferred over the other by the survey respondents. Likewise, if one level of a product attribute has larger full factorial aggregate market share, it is said to be the preferred 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 introduce an aggregate measure, the full factorial marketplace, as a new technique to investigate the effects of preference construction on the relative importance of attributes in product decisions. We define importance in the full factorial marketplace as the percentage of a product choice determined by a specific attribute. A larger percentage implies a higher importance in the decision. Quantitative measurements of importance have been suggested previously (Orme 2005). 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 Equations (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 not very important in predicting product choice, the estimated part-worths for these levels approach 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 among the attribute's levels will approach equality at n^{-1} , where n equals the number of levels for the attribute. (A rigorous proof of this principle and that aggregate market shares for attributes in the full factorial marketplace have the same values in certain fractionally factorial marketplaces is left for a follow-up publication.) If a no-choice option is included in the survey, this principle only applies if this option is not included in the full factorial marketplace or comprises an insignificant choice share in it. In this study, the no-choice option would have constituted a very small choice share ($<0.1\%$) and was thus excluded. Following this principle, summing the squared deviations of the levels' aggregate full factorial market shares from their respective n^{-1} equality shares for each attribute is a measure of attribute importance (Equation (13)).

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

4. Survey instrument design and administration

A discrete choice survey and analysis of preferences for paper towels were conducted to demonstrate the above ideas. Paper industry and consumer information were used to identify the crux attributes for paper towels: strength, softness, and absorbency (Atkins 2004, Consumer Reports 1998). We investigated 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 hypothesised that attribute 'quilting' was sentinel for the crux attribute 'absorbency'. We specifically predicted that towels that included quilting would be preferred over those that do not when no information about the towels' absorbency was available (scenario A). 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 (Consumer Reports 1998). Here, we assume 'quality' refers to strength, softness, and/or

Table 3. Details of variation in preference elicitation technique.

Attribute (identifier)	Version A	Version B	Version C
Strength (crux)	Not mentioned	Fixed configuration	Three configurations
Softness (crux)	Not mentioned	Fixed configuration	Three configurations
Absorbency (crux)	Not mentioned	Fixed configuration	Three configurations
Quilting (sentinel)	Two configurations	Two configurations	Two configurations
Recycled paper content (sentinel)	Four configurations	Four configurations	Four configurations
Pattern (non-sentinel)	Two configurations	Two configurations	Two configurations
Packaging (non-sentinel)	Three configurations	Three configurations	Three configurations

Table 4. Attribute/levels (Abbreviation) presented in combinations in discrete choice survey.

Attribute	Levels
Quilting	Quilted, not quilted
Pattern	Patterned, not patterned
Recycled paper content	0%, 30%, 60%, 100%
Packaging	One roll 150 sheets, two rolls 75 sheets, three rolls 50 sheets
Strength	1 out of 3, 2 out of 3, 3 out of 3
Softness	1 out of 3, 2 out of 3, 3 out of 3
Absorbency	1 out of 3, 2 out of 3, 3 out of 3

absorbency. We predicted that towels with no recycled paper content would be most preferred when no information on strength, softness, or absorbency was available (scenario A). Table 3 repeats Table 1 as applied to the towel study, in which three versions of a discrete choice survey, with 10 multiple choice tasks each, were used as the three scenarios described in Table 1. The attribute/levels available for choice in the survey are presented in Table 4. More specifically,

- In Version A of the survey, respondents were given no information on strength, softness, and absorbency. They 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). They 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*. They made their choices based on strength, softness, absorbency, quilting, pattern, packaging, and recycled paper content. Total respondents: 74; average age: 48; male respondents: 43%.

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 (2007a, b), and Luth Research (2007) 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. The recruitment notice 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 participation screening question that selected people who were over the age of 18 and had purchased paper towels in the past 6 months. We believed that respondents would answer

Which one of these paper towels would you prefer to purchase?

Quilted	Not Quilted	Quilted	None of the above
Patterned	Not Patterned	Patterned	
0% Recycled Paper Content	100% Recycled Paper Content	30% Recycled Paper Content	
Packaged as 3 rolls with 50 sheets per roll	Packaged as 1 roll with 150 sheets per roll	Packaged as 2 rolls with 75 sheets per roll	
\$2.50	\$2.50	\$2.50	
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 1. Sample discrete choice question from survey version A.

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.

Price was not included as an attribute in any version, and respondents were told that all paper towels cost \$2.50 for 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 follows:

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 doughnut).

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 was identical for all survey versions and all respondents. 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 10 multiple choice questions and asking for their choices between products. Eight of the 10 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 respondents (Sawtooth 2007a). Two of the 10 questions were identical, or fixed, across all respondents. In fixed question 1, all attributes were held constant across the three product choices (quilted, not patterned, two rolls, and average strength, softness, and absorbency (in Versions B and C)) except for recycled paper content, which varied as 0%, 30%, and 100%. Fixed question 2 was similar, but all three towels were patterned, and recycled paper content varied by 30%, 60%, and 100%. Responses to these fixed questions were not included in the preference estimation.

5. Survey results and analysis

The results were analysed as described in Section 3. Three hierarchical bayesian estimations of the multinomial logit models were performed using Software's CBCHB program (Sawtooth 2007b). The hierarchical bayesian 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. The results were also estimated with Sawtooth's log likelihood (LL) maximisation, a more 'traditional' approach than hierarchical bayesian estimation (Sawtooth 2007a, Louviere *et al.* 2000). The relationships between attribute importances were the same using both estimation techniques, but only the hierarchical bayesian estimate gave significance at the 0.05 level for most of the hypotheses in Equations (1) to (5), as detailed in the paragraph below. A hierarchical bayesian approach produces estimates with better statistical properties than an LL maximisation when there are a small number of data points. With only approximately 70 subjects in each group, and only eight questions answered by each subject (plus two fixed questions that were not analysed), the hierarchical bayesian approach had much less variance in its estimated parameters.

Table 5. Part-worths (standard error) estimated in hierarchical bayesian multinomial logit model.

Attribute	Level	Version A		Version B		Version C	
Quilting	Quilted	1.36	(0.038)	0.65	(0.038)	0.46	(0.086)
	Not quilted	-1.36	(0.038)	-0.65	(0.038)	-0.46	(0.086)
Pattern	Patterned	-0.11	(0.036)	0.33	(0.035)	-0.12	(0.050)
	Not patterned	0.11	(0.036)	-0.33	(0.035)	0.12	(0.050)
Recycled paper content	0% recycled paper content	-1.85	(0.150)	-1.65	(0.160)	-1.85	(0.239)
	30% recycled paper content	-0.65	(0.074)	0.04	(0.076)	-0.39	(0.153)
	60% recycled paper content	0.76	(0.056)	0.44	(0.065)	0.99	(0.123)
	100% recycled paper content	1.74	(0.144)	1.16	(0.174)	1.25	(0.183)
Packaging	1 roll 150 sheets	0.26	(0.059)	0.33	(0.093)	0.54	(0.090)
	2 rolls 75 sheets	0.07	(0.041)	0.16	(0.050)	-0.09	(0.076)
	3 rolls 50 sheets	-0.34	(0.056)	-0.49	(0.088)	-0.46	(0.098)
Strength	1 out of 3	N/A	N/A	N/A	N/A	-2.75	(0.203)
	2 out of 3	N/A	N/A	N/A	N/A	0.88	(0.095)
	3 out of 3	N/A	N/A	N/A	N/A	1.87	(0.122)
Softness	1 out of 3	N/A	N/A	N/A	N/A	-1.10	(0.148)
	2 out of 3	N/A	N/A	N/A	N/A	0.05	(0.110)
	3 out of 3	N/A	N/A	N/A	N/A	1.05	(0.099)
Absorbency	1 out of 3	N/A	N/A	N/A	N/A	-3.79	(0.282)
	2 out of 3	N/A	N/A	N/A	N/A	1.23	(0.108)
	3 out of 3	N/A	N/A	N/A	N/A	2.56	(0.149)
None of the Above		-1.54	(0.494)	-4.48	(1.471)	-1.07	(1.076)

Table 6. Importances (standard error) of aggregate full factorial market shares.

I_{ζ}	Version A		Version B		Version C		Range
Quilting	0.38	(0.040)	0.16	(0.075)	0.09	(0.091)	0.29
Pattern	0.01	(0.021)	0.05	(0.054)	0.01	(0.027)	0.05
Recycled paper content	0.26	(0.091)	0.13	(0.085)	0.15	(0.055)	0.13
Packaging	0.02	(0.025)	0.03	(0.036)	0.06	(0.064)	0.04
Strength	N/A		N/A		0.26	(0.088)	N/A
Softness	N/A		N/A		0.19	(0.095)	N/A
Absorbency	N/A		N/A		0.34	(0.093)	N/A

Full factorial aggregate market shares for each attribute in each of the three estimated models were calculated according to Equation (10). Table 6 reports importance metrics computed with Equation (13) and their standard errors, estimated using the δ method (Rice 1995). Higher numbers indicate higher importance in the respondent choice decision. The hypothesised sentinel attribute of quilting in Version A received the maximum importance value of 0.38, although this value was not significantly different from that of absorbency in Version C – refer to Equation (15). The computed metrics satisfy the hypothesised inequalities, Equation (1) to (5), on the relationship between the sentinel attribute *quilting* and the crux attribute *absorbency*:

$$\text{Equation (1) : } I_{Quilting,A} = 0.38 > 0.16 = \max_{i=A,B,C} \{I_{Quilting,i}\} \quad (p < 0.05), \tag{14}$$

$$\begin{aligned} \text{Equation (2) : } I_{Quilting,A} = 0.38 > 0.34 \\ = I_{Absorbency,C} \text{ (cannot reject hypothesis that these values are equal) .} \end{aligned} \tag{15}$$

Equation (3) for the non-sentinel attribute *packaging*:

$$\begin{aligned} \max_{i=A,B,C} \{I_{Quilting,i}\} - \min_{i=A,B,C} \{I_{Quilting,i}\} > \max_{i=A,B,C} \{I_{Packaging,i}\} - \min_{i=A,B,C} \{I_{Packaging,i}\}. \tag{16} \\ \text{Simplifies to: } I_{Quilting,A} + I_{Packaging,A} = 0.40 > 0.15 = I_{Quilting,C} + I_{Packaging,C} \quad (p < 0.05). \tag{17} \end{aligned}$$

Equation (3) for the non-sentinel attribute *pattern*:

$$\begin{aligned} \max_{i=A,B,C} \{I_{Quilting,i}\} - \min_{i=A,B,C} \{I_{Quilting,i}\} > \max_{i=A,B,C} \{I_{Pattern,i}\} - \min_{i=A,B,C} \{I_{Pattern,i}\}. \tag{18} \\ \text{Simplifies to: } I_{Quilting,A} + I_{Pattern,A} = 0.39 > 0.14 = I_{Quilting,C} + I_{Pattern,B} \quad (p < 0.05). \tag{19} \end{aligned}$$

$$\text{Equation (4) : } I_{Quilting,C} = 0.09 < 0.34 = I_{Absorbency,C} \quad (p = 0.068 < 0.10). \tag{20}$$

$$\text{Equation (5) : Preference}_{A, 'Quilted'} = 1.36 > -1.36 = \text{Preference}_{A, 'Not Quilted'} \quad (p < 0.05). \tag{21}$$

Equations (14), (17), (19), and (21) are statistically significant at the $p < 0.05$ level using a Z-distribution Wald test¹. Equation (15) does not meet the statistical criterion, but the estimated importance parameter values conform to the inequality. Equation (20) is statistically significant at the $p < 0.10$ level. This is acceptable for the illustrative purposes of this case study, but for an industrial application, it would be wise to include additional subjects in the experiment in order to verify the statistical significance of the hypothesis at the $p < 0.05$ level.

However, we observed a reversal of the predicted direction of inequality in Equation (5) for the hypothesised sentinel attribute of recycled paper content: the level hypothesised to be associated

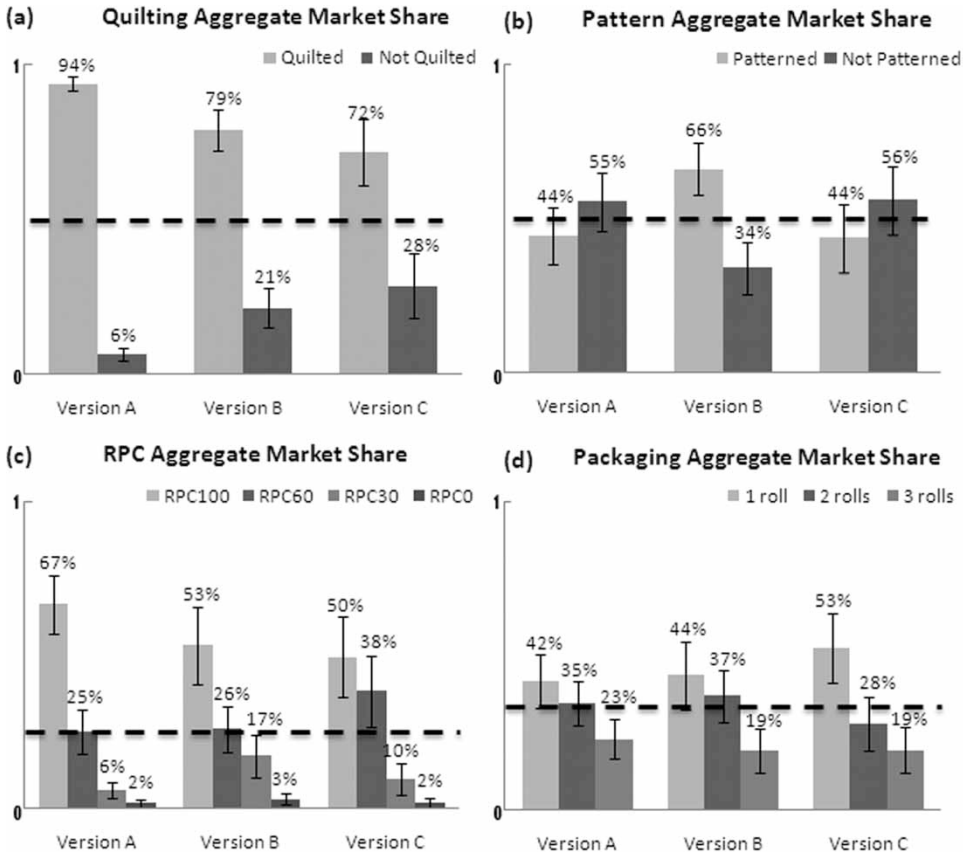


Figure 2. Aggregate full factorial market shares.

with the more-preferred levels of the crux attributes, 0% recycled paper content, was in fact less-preferred as compared with other levels (30%, 60%, 100%). As this violates the hypothesis of Equation (5), we find that recycled paper content is not a sentinel attribute for strength, softness, or absorbency. We address implications and explanations in Section 6.1.

We now examine the aggregate full factorial market shares for all attributes (Figure 2). Figure 2a shows the aggregate full factorial market shares of quilted towels and not quilted towels across the three survey versions (A, B, C); Figure 2b shows the same for pattern; Figure 2c for recycled paper content; and Figure 2d for pattern. The graphs indicate the equal market share of n^{-1} 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 have in the product decision. As shown in Figure 2a, 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 all with equal absorbency (Version B) placed less importance on quilting, but still preferred quilted to not-quilted. Respondents with the option to choose strength, softness, and absorbency (Version C) placed even less emphasis on quilting; it approaches the importance of pattern in Version B. Figure 2b shows that 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 2c shows the aggregate full factorial market shares for 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, Figure 3 shows market share aggregated in terms of towels with 0% and greater

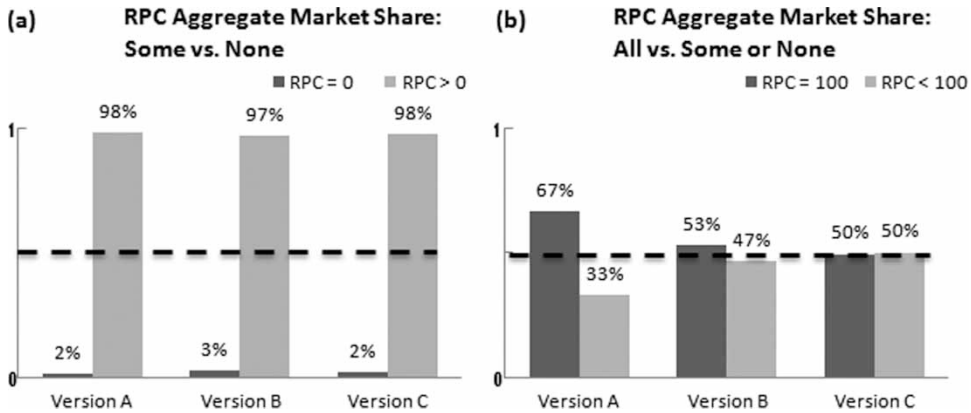


Figure 3. Aggregate market share in the full factorial marketplace for recycled paper.

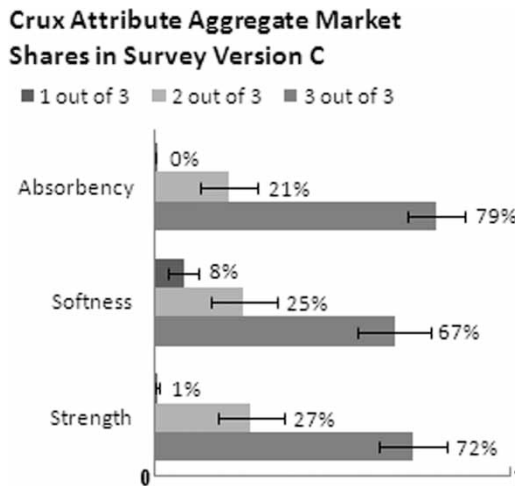


Figure 4. Full factorial aggregate market shares for strength, softness, and absorbency.

than 0% recycled content; and also towels with 100% and less than 100% recycled content. The preference for towels with at least some recycled content is extremely high; it is very important and almost constant across the three survey versions. But it is not important that a towel has 100% recycled paper content.

Differences in attribute importance must be accompanied by differences in attribute preference, or preference inconsistency, which Figure 2 also shows. In this study, preference inconsistency can only be demonstrated at the group level, as no one respondent took more than one survey. In Figure 2d, the preferences for packaging are consistent within the three different survey versions: the full factorial aggregate market share for ‘1 roll’ (shown in the lightest grey in the figure), and thus the preference for ‘1 roll’ does vary significantly across the survey version. However, in Figure 2a, the full factorial aggregate market share for ‘Quilted’ (shown in the lightest grey) is significantly different between survey Versions A and C, indicating a preference inconsistency.

We also investigate the importance of the crux attributes, strength, softness and absorbency. Preference for these attributes can be estimated only from survey Version C, the survey version in which respondents chose between towels with different levels of crux attributes. The full factorial aggregate market shares for softness, strength, and absorbency are reported in Figure 4.

Table 7. Counts of responses to fixed questions 1 and 2 across survey versions.

	Count (%) Level of recycled paper content	Count (%) Version A	Count (%) Version B	Version C	Significance
Fixed question 1	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 2	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%)	

All three have high importance metrics 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 χ^2 homogeneity test was performed to test whether the three groups of respondents, classified by the version of survey answered, responded to the fixed questions in a statistically different manner. As shown in the table, a larger percentage of Version C respondent population preferred a 100% recycled paper towel than that of the other versions' respondent populations, but this difference was not statistically significant.

To investigate if respondents perceived dependencies between attributes that were not related to the crux/sentinel relationship, main effects were analysed with Sawtooth's SMRT 'Counts' routine (Sawtooth 2007a). We tested whether any attributes or combinations of attributes (independent variables) predicted choice (dependent variable). In Version A, recycled paper content and quilting were significant predictors of choice ($p < 0.01$), whereas the other attributes were not. In Version B, recycled paper content and quilting had a significant effect ($p < 0.01$). In Version C, strength, softness, absorbency, and recycled paper content were all significant predictors of choice ($p < 0.01$). No combination of any two attributes was a significant predictor of choice, an indication that respondents evaluated the attributes as independent from each other.

These results enforce the hypothesis of Equation (4) in our experiment, as when absorbency is present, quilting is not a significant predictor of choice. They also demonstrate that packaging and pattern were indeed non-sentinel attributes. Furthermore, the results highlight the difference between quilting and recycled paper content in the experiment – whereas quilting is a significant predictor only in Versions A and B, recycled paper remains a significant predictor across all three versions.

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 metrics of the two attributes under various preference construction scenarios conforms to Equation (1) to (5). The relationship can be summarised as follows.

In the absence of information about a crux attribute, the customer identifies one or more sentinel attributes and makes perceived associations between sentinel and crux attributes. In the absence of choice control over the crux attribute, these associations cause the customer to construct preferences 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 attribute 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 within 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, because the hypothesis in Equation (5) was not satisfied. 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 (Bennett and Blamey 2001). Other findings presented in MacDonald *et al.* (2007b) suggest that preference for recycled paper content is susceptible to this bias. One may speculate that recycled paper content has 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, towels with at least 30% recycled 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 content and towel quality, this perceived relationship may lie dormant, with customers focused on recycled 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.

We have found difference in importance of attributes across survey versions, but how can we be sure that this difference is due to the experimental construct, as opposed to differences between the different groups of subjects who took the survey? This assumption, that differences are due to experimental construct, is a common one in psychological experiments. It is included in the framework of statistical significance testing as seen in the partitioning of error terms. Again, the case study as presented here would be a good start in an industry application, but further testing would be required to more firmly establish that a crux/sentinel relationship exists between quilting and absorbency.

To verify the results, the experiment could be repeated with a larger number of subjects in each experimental condition. Or, the experiment could be changed slightly so that the three different versions of the survey were given to the same group of people with a time interval of a week or two in between the administration of survey version. This timing may have other impacts on the construction of preference, and it is a more costly approach.

6.2. Generalised constructed preference design method for studying attribute relationships

The hypotheses, survey instrument, and analysis presented above can be generalised to identify crux and sentinel attributes in other products and to investigate the relative importance of attributes in product decisions. A constructed preference design method for studying attribute relationships in any product is given below, with relevant material from this article included in parentheses.

- (1) Identify product attributes for study (crux/sentinel attributes).
- (2) Hypothesise relationships between the importance metrics of the attributes (Equation (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) Analyse results, estimate preferences (as part-worths using Equations (7) to (9), results in Table 5).

- (7) Check that the different scenarios elicit statistically different preferences (see below).
- (8) If applicable, calculate full factorial aggregate market shares (Equation (10)).
- (9) Calculate attribute importance metrics in various scenarios (Equation (13), results in Table 5).
- (10) Test hypotheses numerically; accept or reject (Section 5).
- (11) Analyse results graphically to understand findings (Figures 2–4).
- (12) Discuss implications of results (Section 6.1).

As a note to Step 7, our approach in the present study was to check that: (1) estimating separate sets of part-worth values for the different versions of the survey gave a statistically significant better fit to the data than estimating a combined model, where all three versions shared the same part-worth values²; (2) the variance in the parameters was in the same range; and (3) the differences between estimated part-worths across versions fit the hypotheses about the relationship between crux and sentinel attributes.

One can use the generalised method described above for products that are much more complex than paper towels. A complex product can be broken into subsystems that can be tested using a discrete choice survey. For example, for a car, the survey could be only about the dashboard or the safety features. It is key that the designer already have some relationships/hypotheses in mind when they begin to design the experimental procedure. A small number of attributes can be handled using a discrete choice survey, but if the designers wish to test relationships between many product attributes, a different decision prediction tool should be used in the method. The general form of the method allows for this flexibility.

In the example at hand, there are most likely multiple sentinel attributes for absorbency: quilting, brand, and possibly price. The generalised constructed preference design method allows for the isolation and testing of one of these sentinel attributes, and, with modifications to the hypothesis presented in this case study, could also test for multiple sentinel attributes. The modifications required for the testing of multiple sentinel attributes would follow from the design of the experimental hypothesis and would likely increase the complexity of the data analysis and statistical testing. Such concerns are left for future research.

6.3. Implications of the construction of preferences in design methods

Previously unexplored in the field of engineering product design, the construction of preferences allowed us to test the hypotheses presented in this paper, and more generally allow testing of possible relationships between product attributes in the minds of customers. Despite the fact that this theory has been discussed in the psychology literature for decades, it has received little 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 fulfil 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, may lead to a preferred product in one situation (design) not being viewed as desirable in a different situation (purchase). Designers have, at times, blamed this undesirable outcome on the method of need-finding and have spent much effort seeking the one special method of need-finding that will be the 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. There is accommodation of the construction of preference in some design methods, though it is not explicitly stated as such. In methods where the designers assess customer preference indirectly, such as in quality function deployment

(QFD), the designers' interpretations of customer requirements and relative importance of these requirements leave room for some accommodation of preference inconsistencies. The authors view QFD as a potential 'dampener' for variable construction of preference. In methods that incorporate a direct measurement of customer preference, this dampener is absent. Pullman *et al.* (2002) noted this difference in approach, without explicitly stating the reason as construction of preference. They compared customer preferences elicited from QFD and directly from conjoint analysis (a discrete choice survey), and the resulting optimally designed products. They noted that the products were different on important attributes and stated that the difference is a result of 'what customers say they want and what managers think will best satisfy customer needs', in other words, the difference between constructed preference and an interpretation of preferences constructed by experts familiar with how these preferences may change over time.

The generalised constructed preference design method detailed in Section 6.2 is directly applicable in the QFD process. If a design team was trying to decide how to assign QFD ratings of importance to two seemingly minor product attributes (*i.e.* quilting or pattern), they could check for substantial relationships to other attributes. A study of how constructed preference importance findings can inform QFD ratings of customer importance is left for future work.

In the example at hand, there may be an engineering relationship between the crux attribute absorbency (a function of the product) and the sentinel attribute quilting (a design solution to accomplish the function), that is, if quilted towels are actually more absorbent. This functional relationship was not tested. However, if there was no functional relationship between quilting and absorbency, or even if there was an opposite functional relationship between quilting and absorbency, quilting would still be a sentinel attribute for absorbency. Crux/sentinel relationships are perceived by the user; they do not necessarily exist in the engineering of the product.

It is also possible that both the crux attribute and sentinel attribute are both functions of the product; it is not necessary that the former be a design function and the latter be a design solution. For example, consider snow skis and the crux attribute of safety (function) in two different product decision contexts: purchase at a ski area where customers can test the ski and purchase using the Internet. In the former purchase context, the customer can test how easy it is to turn the ski quickly, its manoeuvrability. Manoeuvrability (function) may be perceived to be a sentinel attribute related to safety (also a function). The customers will not put themselves purposefully into harms' way to test the crux attribute safety, but will rely on assessing the sentinel attribute of manoeuvrability for their assessment of safety. Now consider the same example within a different decision context: an online ski purchase. In this decision, where the customer can see the ski but not try it, the angle of parabolic curvature of the ski's side (design solution) may be a sentinel attribute for manoeuvrability and in turn a sentinel attribute for safety (function).

In a product redesign, it is sometimes the case that a product attribute becomes superfluous in the performance of a function when a superior design solution is introduced. However, the attribute may still serve a psychological role as a sentinel attribute in the product. The crux/sentinel method, and variations of the generalised constructed preference design method, can help designers decide when functionally superfluous product attributes can be removed from the product without affecting customer's assessment of other product attributes.

7. Conclusion

In this study, we examined quantitatively 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 2% 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 whether one attribute can 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 normalising tools that allowed comparison of preference construction across separate preference estimations. A new importance metric was introduced. Future work in the full factorial marketplace should include rigorous proofs, as mentioned previously, and formulas for computing the variance of aggregate market shares and full factorial importance metrics 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 behavioural psychology perspective to the field of emotional design (Norman 1998, Krippendorff and Butter 1984). 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 created to proactively control preference construction, or to reactively gain preference under a variety of preference scenarios, or both. As we strive to create designs that fulfil needs, we must accept that these needs are reflexive and pursue a quantitative and deeper understanding of how designs interact with constructed preferences.

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Notes

1. We also performed Tukey tests on Equations (17) and (19). The results remain significant ($p < 0.05$) even after performing the more conservative test accounting for the distribution of the range.
2. The fit was tested by estimating parameters that the three versions shared (quilting, pattern, packaging, recycled paper content) with LL maximisations of combined and separate models. The combined model had a LL of -2200 and the separate models had LL of -652 , -792 , and -721 for Versions A, B, and C. A χ^2 distribution with eight degrees of freedom was used to determine that the separate models provided a better fit than the combined model ($p < 0.001$).

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