The Construction of Preference in Engineering Design and Implications for Green Products

by

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Nomenclature

A, B, C	Product choice scenarios
a	Index referring to absorbency
$\mathbf{b}$	Vector of all consumer towel brands
$\mathbf{c}$	Vector of all consumer towel samples (including all brands)
D	Decision context (vector of all components of context)
D', D''	Decision context manipulations
d_1	Component of decision context
D_o	Vector of components of decision context that are observed in a decision model
D_u	Vector of components of decision context that are unobserved in a decision model
G	Estimated predictor parameter(s) in decision model
h_l	Polynomial used to calculate price part-worth for latent class l
I	Importance of product attribute
i	Towel property index, $i = a, t, s$
J	All products in market
j	Competing product index
k	KermitCo's product index
l	Latent class index $l = PickUps, Traders, Savers$
m_l	Polynomial used to calculate recycled paper content part-worth for latent class l
N	Total number of survey respondents
n	Index for survey respondents
o	Subscript indicating observed decision context
P_j	The probability that j has the highest utility of all available products
$\hat{P}_{\zeta\omega}$	Aggregate full factorial marketshare for a particular attribute/level
p	Price of KermitCo's towel
$q_i(r_k)$	Spline that calculates towel property i for a given r_k
R	Estimated predictor parameter(s) associated with Z
r	Recycled paper content
r_k	Recycled paper content of KermitCo's towel (variable in optimizations)
s	Index referring to softness
t	Index referring to tear strength
U_j	Random utility of product j
u	Subscript indicating unobserved decision context
X	Independent variable(s) in decision model
Y	Dependent variable(s) in decision model
Z	Additional independent variable(s) in decision model
$x_{j\zeta\omega}$	Dummy variable that takes the value 1 for attribute ζ and level ω in product *j*
z	Index of knot δ
$\alpha_{i,\delta_{i,z}}$	Cubic coefficient of spline $q_i'(r_k)$ applied to values of $(r_k - \delta_{i,z})$ between $\delta_{i,z}$ and $\delta_{i,z+1}$
$\beta_{\zeta\omega}$	Part-worth utility of attribute ζ, level ω
$\gamma_{i,\delta_{i,z}}$	Quadratic coeff. of spline $q_i'(r_k)$ applied to values of $(r_k - \delta_{i,z})$ between $\delta_{i,z}$ and $\delta_{i,z+1}$

$\delta_{i,z}$ Knot in spline for towel property i

ε Error term

ε_j Estimated error of utility of product j

ζ Product attribute

$\eta_{i,c}$ Lab measurement of property i for consumer towel sample c

$\boldsymbol{\theta}_i$ Vector of cut-offs for towel property classifications

κ Scaling coefficient for construction of preference (variable in proactive optimization, parameter in reactive optimization)

$\lambda_{i,\delta_{i,z}}$ Linear coefficient of spline $q_i'(r_k)$ applied to values of $(r_k - \delta_{i,z})$ between $\delta_{i,z}$ and $\delta_{i,z+1}$

$\mu_{i,b}$ Average survey respondent rating of towel property i for towel brand b

v_j Measurable utility of product j

Π Subject pool in decision context experiment

π Individual subject in subject pool Π

$\rho_{i,b}$ Normalized average respondent rating of towel property i for consumer towel brand b

Ξ Subject pool in decision context experiment

$\tau_{i,\delta_{i,z}}$ Intercept of spline $q_i'(r_k)$ applied in between $\delta_{i,z}$ and $\delta_{i,z+1}$

$\varphi_{i,c}$ Normalized measurement of towel property i for consumer towel sample c

ω Attribute level

Ω Number of levels for a given attribute

Chapter 1. Overview and background

1.1. Introduction

Research from behavioral psychology and experimental economics asserts that individuals construct preferences on a case-by-case basis when called to make a decision, a theory termed the *construction of preferences* (Slovic 1995). This dissertation incorporates the construction of preference into engineering design, offering a framework for understanding construction of preference, expanding interdisciplinary design optimization to include construction of preference, and introducing a new preference-experiment design method.

If preferences are constructed in response to decisions, rather than existing a priori, then user preferences elicited in the design process may be different from those formed during product purchases, and preferences formed during product purchase may be different than those formed during product use. Failure to note construction of preference in design methods results in products that are tailored to be preferred in one decision context, but may not be preferred in other contexts. Therefore, products designed based on preferences that customers exhibit during design-phase data collection may not be preferred by customers during purchase and use, where they construct their preferences differently.

While ignoring preference construction and assuming a priori preferences simplifies the task of incorporating customer preferences into the design process, it may result in products that people do not buy or use. Preference construction is a problem for designers, who want to design products that people reliably prefer over others. Furthermore, construction of preference can be used in design experiments and methods as a new tool for learning about the relationship between the product and user, the role of user perception in this relationship, and the messages and information that a product communicates to the user. It is these problems and opportunities that this dissertation will address.

Some elements of decision context are more influential to a particular preference construction than others, and experimental research has documented some particularly influential elements, such as phrasing of the decision and available outcomes (Kagel, Roth 1995). Also, the subject matter of the decision can cause more or less preference construction inconsistency between decision contexts. The case study in this dissertation focuses on decisions about environmental impact, namely purchase and use decisions for green products. Research in behavioral and environmental psychology as well as environmental valuation shows that customer preference for green product attributes is inconsistent across different preference elicitation scenarios. For example, two effects of inconsistent preference construction have been linked to environmental concerns: social desirability bias, a propensity for people to answer a survey in a manner congruent to "good" social behavior (Bennett, Blamey 2001); and embedding effects, a difficulty in nesting willingness-to-pay measures for a group of purchases. For example, it may be that a respondent states that they are willing to pay a fifty cent premium for a recyclable yoghurt container, when in fact they are willing only to add fifty cents to their weekly shopping bill to purchase green goods (Kahneman, Knetsch 1992). Because interactions with customers during the design process typically focus on one good, the willingness-to-pay metric may be skewed due to an embedding effect. For these reasons and many more to be discussed, the preferences elicited during design-phase interactions with potential customers are likely to be different than those the customer will construct in the market, presenting a daunting challenge for designers, particularly designers of green products.

1.2. Background in psychology and engineering

The details of a specific decision case are termed *decision context*. Researchers have repeatedly used *context effects*, a particular type of preference inconsistency test, to discredit theories and assumptions of psychology and economic behavior. Slovic (1995), and Kagel and Roth (1995) offer excellent literature reviews. Preference reversals are well-documented with the help of context effects, observed when different phrasings of a choice question and/or available choice options are shown to result in different experimental outcomes. Arguably, if a user appealed to an internal database through a query, the same preference should emerge independent from particular contextual variables; instead, a systematic bias is exhibited. The finding that different choices result from manipulations of context is taken as evidence that users do not query a database but rather construct their preferences. In the contributions of this thesis, we focus on the fact that preferences *are* constructed rather than queried, and address *why* they may be constructed in certain inconsistent manners, but do not discuss *how* they are constructed.

A classic example of preference reversal is that “it is possible to construct pairs of lotteries with the property that many people, when asked at what price they would be willing to sell (or buy) the lotteries, put a higher price on one, but when asked to choose which they would prefer to participate in, choose the other” (Kagel, Roth 1995). Display effects, such as horizontal vs. vertical positioning of choice sets, have also been demonstrated (Kagel, Roth 1995). In multiple-choice surveys, such as discrete choice, it has been found that “how one feels about an attribute level (say, 35 mpg) depends critically on the competing levels of the other alternatives (say, 30 or 40 mpg)” and “continuous attributes are biased upward compared with categorical attributes” (Fitzsimons et al. 2002).

The experimental economics community has demonstrated that willingness to pay, and thus utility theory, is contingent upon different context effects and preference constructions. Tversky and Kahneman employed context effects to discredit rational choice behavior modeling, introducing Prospect Theory and the concept that losses loom larger than gains (Kagel, Roth 1995, Kahneman, Tversky 1979). The experimental economics community has documented violations of both “description invariance” and “procedure invariance,” both terms coined by Amos Tversky, which claim that despite different representations and elicitation procedures, the same choice problem should always result in the same preferences. Camerer, an experimental economist, explains: “Invariance violations are especially troublesome for utility theories… The most famous violations of description invariance are 'framing effects.' Reversals of preference are induced by changes in the reference points… the most pressing question is whether framing effects are systematic and predictable. The evidence is mixed;” quoted in (Kagel, Roth 1995). As in the findings above, when preference is inconsistent in a predictable manner based on an identifiable element of decision context, it is here referred to as non-random preference inconsistency.

Research in the engineering design community has previously addressed random preference inconsistency. Random inconsistency in preference is due to elements of decision context that cannot be predicted, including such influences as mood and the weather. Luo et al. (Luo et al. 2005) and Besharati et al. (Besharati et al. 2006) contended with random preference inconsistency by using robust design to address the variance of consumer preference parameters in interdisciplinary marketing and engineering design optimization. As such frameworks accept variance in parameters, random preference inconsistencies can be dealt with in this approach; however, non-random inconsistencies cannot, as these inconsistencies manifest not necessarily in model variance but in model parameters, with potential implications in variance and error terms as well. This manifestation will be detailed in Chapter 4.

Pullman et al. notice the effects of non-random preference inconsistency, without noting it as such, in their comparison of preferences elicited from Quality Function Deployment and conjoint analysis, stating that optimal products designed using the two different preference elicitation processes varied on important features. They claim the difference stems from "what customers say they want and what managers think will best satisfy customer needs," which is another way of stating that managers are attempting to compensate for preference inconsistencies between point of evaluation, purchase, and use (Pullman, Moore & Wardell 2002).

The effects of non-random preference construction are highlighted in the grey overshadow of two design methodology frameworks proposed by Michalek (Michalek 2005) and Wassenaar (Wassenaar et al. 2005), Figures 1.1 and 1.2, respectively. The figures demonstrate how preference construction propagates in design processes. Michalek's framework takes only one measurement of customer preference, so designers could not identify preference inconsistency without adding another. Wassenaar's framework includes three sources of preference construction and, with some modification, allows designers to identify preference inconsistencies; for example, comparing collected customer preferences and existing market data can identify inconsistencies.

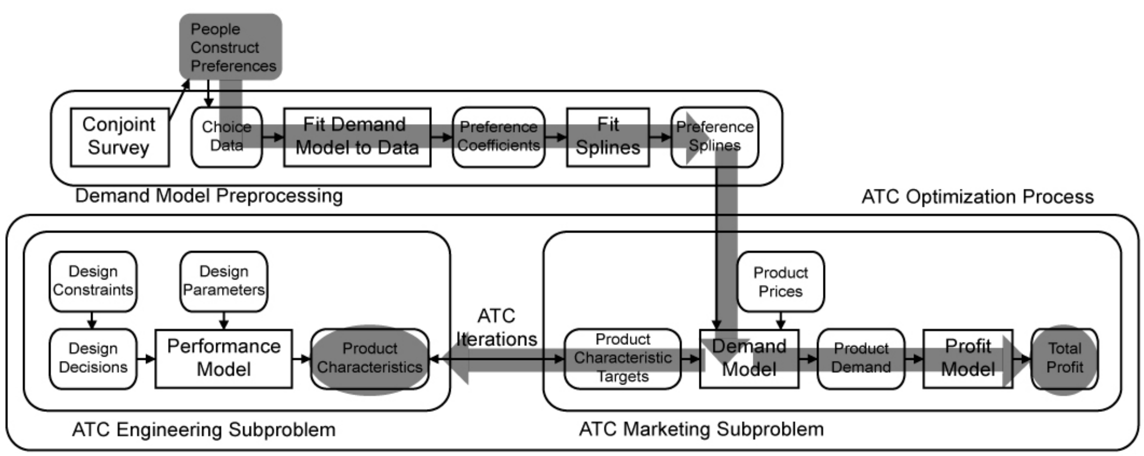


Figure 1.1 Propagation of preference construction through Michalek's engineering/marketing ATC Formulation.

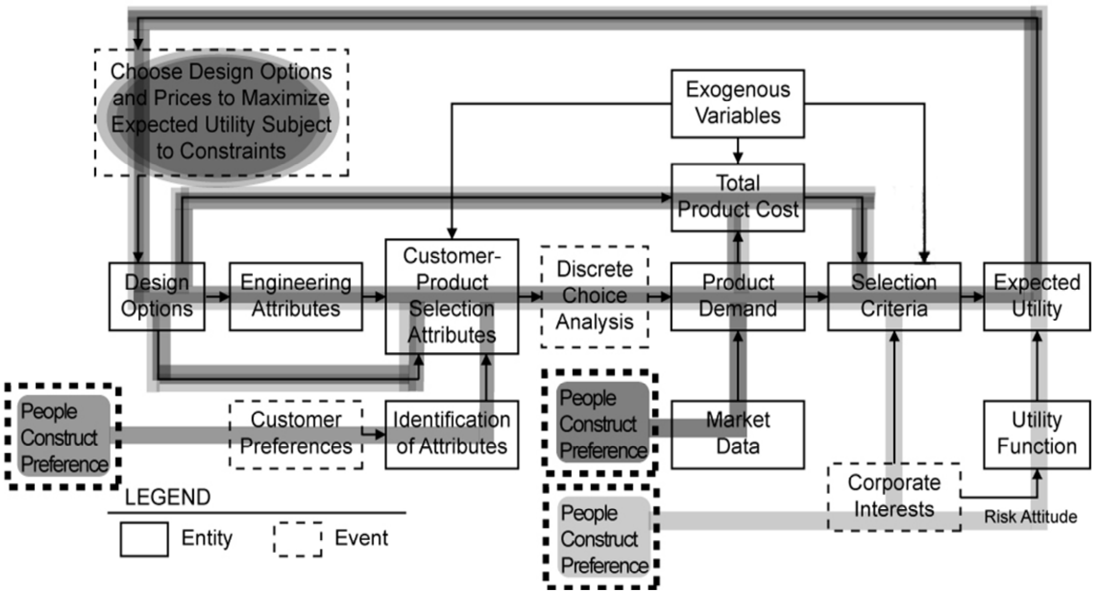


Figure 1.2 Propagation of preference construction through Wassenaar et al.'s decision-based-design flow chart.

Designers typically decide among their own conflicting preferences in the design process, and preference structure inconsistencies may lead to different products. Rewording questions can change indifference points and resulting preferences between two alternatives, impacting design decisions based on the hypothetical “equivalents-inequivalents” approach of See et al. (See, Gurnani & Lewis 2004), who state that “a designer’s stated preferences may result in intransitive preference structures.” This is a typical result of the context effect experiments mentioned previously. One may combat intransitivity or dampen preference inconsistency by asking designers to explain their preferences, but this leads to confirmation bias and bolstering, in which people reconstruct their preference structures after making a decision in order to substantiate their choice (Nickerson 1998, Tetlock, Skitka & Boettger 1989). Kulok and Lewis (Kulok, Lewis 2005) developed a method to correct for this random preference inconsistency without requiring designer input. Interestingly, Gurnani and Lewis (Gurnani, Lewis 2006) found that relaxing the assumption of rationality by introducing error into a model of designer decisions (the construction of preferences) leads to convergence and optimality in decentralized design.

1.3. Contributions

First, this dissertation aims to help designers understand construction of preference and the typical experimental approaches that can identify it by introducing a new theoretical framework for preference inconsistency experiments. Next, it demonstrates how construction of preference can be incorporated into an existing quantitative design method, a linked marketing/engineering design optimization, resulting in a product that will be more successful in the market than if construction of preference is ignored. Finally, it uses construction of preference to create a new design method that can identify perceptual relationships between product attributes, offering a specific methodology for identifying what is termed the *crux/sentinel* product attribute relationship. More specifically:

Inconsistent construction of preference can be identified through a comparison of estimated terms in decision models in response to decision context manipulations. Chapter 4 offers a framework for investigating preference inconsistencies, distinguishing between *random* (expressed as error parameter(s) in a preference model) and *non-random* (evident in the estimated structural parameter(s) of the model) inconsistencies. A decision-context framework is created to discuss the three main inconsistency tests used in psychology, marketing, and economics literature. The differences and commonalities between estimating heterogeneity and preference inconsistency that are of particular concern to designers are also discussed in terms of decision context manipulation. The discussion is accompanied by an example of green product preference analysis, which offers a practical demonstration of model structure considerations and preference inconsistency findings. A general contribution here is an examination of how decision model theory applies to design work, and how designers can assess different theoretical explanations of customer data.

Once inconsistent preference is discovered for a given product, it must be incorporated into design methods to relax the assumption that preferences exist a priori. Chapter 6 incorporates inconsistent construction of preference into a linked engineering and marketing design optimization model for a green product. One approach, termed *reactive*, assumes the inconsistent preference is an uncertain design parameter. Another approach, termed *proactive*, models the inconsistent preference as a configurable design variable, assuming that careful design can trigger certain preference constructions in customers.

Chapter 7 offers a design method that uses construction of preference to identify the crux/sentinel product attribute relationship. This design method can be used to identify other attribute relationships that users perceive as existing between product attributes. The method tests related hypothesized relationships between the importance of product attributes in different choice decision contexts by identifying preference inconsistency using discrete choice analysis and the multinomial logit (mnl) model, a commonly employed quantitative customer preference estimation technique in engineering design. The full factorial marketplace is introduced as a way to compare estimations from separate mnl models. The case study application of the technique serves to demonstrate the method and offers a starting point for identification of green-preference triggers that are assumed possible in Chapter 6.

The document is organized as follows: Chapter 2 details the example problem, green product design, providing a literature review of different explanations offered by researchers from marketing, psychology, environmental psychology, consumer studies, and political science as to why people's concerns for the environment do not manifest in their behaviors, and suggestions of how designers can use this information. Chapter 3 outlines the paper towel design case study and its assumptions. Chapter 4 discusses a framework for understanding preference inconsistency and heterogeneity in response to decision context manipulations, applying the discussion to the case study's marketing model. Chapter 5 details the creation of the paper towel engineering model for the case study. Chapter 6 integrates the engineering model with the marketing model, exploring heterogeneity in preference inconsistency as well as proactive and reactive incorporations of preference construction. Chapter 7 provides a design method that tests for preference inconsistencies using separate multinomial logit models to identify product attributes that can trigger specific constructions of preferences. Chapter 8 discusses conclusions and future directions.

Chapter 2. Construction of environmental preferences: Why people (don't) buy green products

This chapter describes a central motivation for this dissertation: Examining why people express concern for environmental problems but do not demonstrate this concern in their product purchasing decisions, and how designers can address this disconnect. This subject is of critical concern for the field of green design and product designers in general, as it demonstrates a disjoint between stated customer concerns and market behavior for one of the seminal human concerns of the twenty first century. A *non sequitur* of this magnitude demands an investigation.

The case study used as a demonstration piece throughout this dissertation serves to illustrate how incorporating construction of preference into design can improve the design of green products. The working definition of *green* used throughout the dissertation is: *a product that is intentionally designed to decrease environmental impact versus the status quo, be that a competing product or an otherwise-defined baseline, using the scientifically-based impact assessment tool of the designer's choosing.* The case study centers around a single-facility towel producer that wishes to enter the market with a new product, a green paper towel. They are considering including recycled paper content in the towel in conjunction with a life cycle assessment of the towel's environmental impact, but have three concerns: (1) that their potential customers will say they want a green towel but not buy it; (2) that there is a perception of low quality in towels with recycled paper content; and (3) that designing a towel for a fickle customer base that appears to value strength, softness, absorbency, and price as well as possibly environmental friendliness may not serve to gain them any additional market share over introducing a more standard towel. The case study illuminates many issues that arise in practical implementation of integrated engineering and marketing design process, such as linking quantitative and qualitative data, working with imperfect prototypes and data sources, and effectively utilizing limited access to customer perceptions of products.

Before introducing this case study in greater detail in Chapter 3, this chapter discusses why construction of preference for green products may be inconsistent based on a discussion of the relationship between attitudes and behaviors, and how designers can use the possible explanations to design better green products. A literature review was conducted across the fields of environmental psychology, behavioral environmental psychology, consumerism, and environmental political science to identify possible reasons for inconsistent construction of green preference. This chapter first defines assumptions that set the boundaries of the literature review. Then it gives an overview of relevant psychological terms such as attitude and behavior. The rest of the chapter is devoted to explanations of eight cognitive intermediaries between pro-environmental attitude and pro-environmental behavior, interspersed with practical, perhaps whimsical, recommendations for designers.

2.1. Assumptions and problem definition

The central question "If people care about the environment, why don't they buy green products?" contains four sub-questions: (1) Do people care about the environment? (2) How can they act on this concern? (3) Are green products available for purchase? and (4) Why don't people buy these green products? To progress from Question 1 to Question 4 requires assumptions.

Assumption 1: People are concerned about the environment

Statistical support both for and against this assumption is readily available and is evidence that construction of preference is important when polling the populace for their opinion on environmental issues and decisions. Guber (Guber 2003) gives an excellent summary of public opinion concerning the environment. She demonstrates that the documented level of public concern for the environment varies widely, both by date and by survey framing. A number of polls that she discusses find that while environmental concern is a top concern of U.S. citizens, it is not the top concern. They also suggest that people feel ambivalent and unresolved about how strongly environmental issues should be addressed, especially when they consider other values and concerns. Here, we assume that people do care about the environment and that they are concerned that their actions may negatively impact the environment.

Assumption 2: People have interest in acting on these concerns in the market

People have a number of options for acting on their environmental concerns. They can act politically through voting and protesting. They can *c*urtail their use of environment resources through modifying their behavior, such as recycling their waste and biking instead of driving.

They can also leave their behaviors unchanged but modify the resources needed to perform these behaviors to be more efficient, such as driving a more fuel-efficient vehicle or buying products in recycled packaging (assuming they do not also—or as a result—drive more or buy more packaged products). These three options are referred to as *political behavior*, *curtailing behavior*, and *efficiency behavior*. This thesis focuses on participation in efficiency behavior as expressed through product purchases. We assume that people are open to expressing their concerns for the environment through product purchases that make more efficient use of natural resources. Guber devotes a chapter of her book to the issue of why people are more likely to act on their environmental concerns in the market than in the voting booth (Guber 2003), lending support to the assumption that an efficiency behavior (green purchase) is a plausible course of action for environmental concerns.

Assumption 3: Green products are available for purchase

A slightly tightened of the working definition of green product given in the introduction of this chapter is as follows: A green product is a product designed with a conscious effort made to reduce environmental impact on a measurable and scientific metric, including such metrics as energy efficiency, life cycle analysis, and carbon usage. It does not include products that just happen to be more energy efficient. In a given product category, it is assumed that at least one such green product exists.

2.2. Between attitudes and behaviors

Given the above assumptions, we will discuss the question that remains, “Why don’t people buy green products?”, from a social science perspective. A behavioral psychologist would classify a positive feeling for the environment as an *attitude*, a like or dislike. That one thinks an action negatively impacts the environment requires a *belief* in the validity of this statement, as one cannot personally prove this. For example, a person may believe that the world is slowly warming due to increased levels of greenhouse gases in the atmosphere, but does not have the scientific knowledge to prove this. They choose to believe the evidence presented to them, or the opinions of other people who have assessed the evidence. A favorable attitude towards the environment paired with a belief that it is degrading forms a *concern* for the environment. One may have the *intention* to perform a certain action in order to protect the environment. The performance of an action is referred to as a *behavior*. If this action is favorable to the environment it is called a *pro-environmental behavior* (PEB). As previously stated, this investigation focuses on pro-environmental efficiency behaviors. Rephrased in the above terminology, the question at hand is “Why don’t pro-environmental attitudes, paired with environmental deterioration beliefs, lead to pro-environmental efficiency behaviors?”

Attitudes and concerns may or may not influence behavior

The relationship between attitude and behavior is unclear in the literature, both at a general level, in that many attitudes are not found to correlate with behaviors, and also specifically for environmental attitudes and behaviors. Environmental attitude alone is not a good predictor of behavior, as indicated by a number of examples given by McKenzie-Mohr (2000). For example, under specific cognitive stresses, something counterintuitive occurs: behaviors can lead to attitudes through cognitive dissonance, as will be discussed. Researchers have taken many different rigorous approaches to describing a mental “path” between environmental attitude and behavior. In the realm of environmental psychology, Vining and Ebreo (2002) review a number of studies to conclude that “measures of environmental concern are only weakly related to PEB."

Intention may or may not predict behavior

Although intentions formed directly before behaviors have been found to be the strongest indicator of behavior, results are mixed on the link between the two for environmental behaviors specifically (Koehn 2006). One reason that good intentions may not be acted upon is lack of knowledge of the complexities of environmental issues. This suggests a lack of complementarity between intention and behavior: the intention to understand the decisions at hand and the behavior of knowledge-gathering on these decisions. The execution of this knowledge-gathering behavior is a daunting task for the majority of the population, and will be discussed further.

Behavior may not predict behavior

Research conclusions are mixed on whether or not a person's performance of one pro-environmental behavior is a predictor of the same person's performing another pro-environmental behavior. There is evidence of spillover between curtailing behaviors, such as a study by Hutton that found that distributing water-flow restrictors with energy-saving pamphlets to households led to a decrease not only in the amount of water they used, but also in the amount of energy and heat they used as well (Hutton 1982). However, in a study of Danish consumers, Thøgersen found that there is variable spillover of environmental behaviors, and that the behaviors within different categorizations (such as recycling vs. buying organic food) are not closely related in people's minds (Thogersen 2003). The literature review in their article cites other studies that support either spillover or the lack thereof.

2.3. Cognitive intermediaries

The cognitive process between attitudes, intentions and behaviors must include intermediaries that influence that translation of attitudes into behaviors. Eight *cognitive intermediaries* were found in the literature that appear to influence significantly this translation—some rigorously studied, some hypothesized but untested, and some anecdotally reported. These intermediaries are: a sense of responsibility; complex decision-making; heuristics; trust; cognitive dissonance; guilt; motivation; and altruism. This section provides explanations and examples of these intermediaries, with recommendations for design accommodations.

Sense of Responsibility

The term "tragedy of commons" is most famously addressed in an article by Hardin in *Science* (Hardin 1968). In Hardin's parable, there is a common pasture to which herders are able to add sheep. Each additional animal subtracts from the overall quality of the pasture while adding to the individual wealth of the herder. If each herder acts rationally to increase wealth (in the short term), then the pasture will degrade to the point that no one is wealthy. In this parable, it is important to keep in mind that each individual herder could adjust their measurement of wealth by a factor that would accommodate the maintenance costs of the pasture. But, both in this parable and in the real world of communal resource sharing, it is typically common action that prevents a tragedy, and not individual actions (De Young 1999). Environmental resources are a communal resource that must be carefully shared and managed. De Young, referenced above, reviews a number of successful attempts to address environmental problems through commons solutions.

Pro-environmental efficiency behaviors, in the form of product purchases, represent individual efforts to address a tragedy of the commons. Curtailing behaviors can also be individual, such as recycling. An individual political action such as voting may make efficiency and curtailing behaviors common actions through the use of laws and regulations that influence curtailing and efficiency on a common-scale. While an individual sense of responsibility for environmental issues is beneficial to the green product industry in some ways, it could also potentially hurt sales in its manifestations. As will be discussed later, individual responsibility that is felt as blame and subsequently guilt can have potentially negative effects on motivating pro-environmental behavior.

People may also think that industry and government are already taking responsibility for environmental problems. Guber studied the results of a variety of consumer polls and concluded that the majority of people think that commons solutions to environmental management are already in place in both governments and businesses (Guber 2003). Allan and Ferrand found that people do not feel like they have any control over the problem (Allen, Ferrand 1999).

Maniates (2002), a social scientist who studies consumerism, asserts that people silently believe that the solution to the environmental tragedy of the commons should come through common action, not individual measures: "[w]e think aloud with the neighbor over the back fence about whether we should buy the new Honda or Toyota hybrid-engine automobile now or wait for a few years until they work the kinks out. What we really wish for, though, is clean, efficient and effective public transportation of the sort we read about in science fiction novels when we were young...." If people do not have an individual sense of responsibility for the maintenance of environmental resources, if they instead believe that environmental resources management should have a commons-type management approach, it is unlikely they will purchase green products without the existence of a commons-type incentive.

Because of their secret desires for common solutions, people may be receptive to the messages of hard-core environmentalists and others who actively attempt to undermine a sense of individual responsibility for the problem, viewing individual action as ineffective (Maniates 2002). People may be confused about the intersection of public policy and personal choice and responsibility. They are concerned enough about the issue to desire government to do something about it, but they themselves would prefer to make only voluntary changes as a result of this public policy. A 1997 CBS/New York Times poll found that 81 percent of respondents said steps to counter global warming should be taken right away, while a poll from Charlton Research Company found that 78% of respondents believed that the United States should "wait to make any treaty commitments" and pursue only "voluntary programs" (Guber 2003). Of course, these statistics may be different if the poll were given now, but they serve to illustrate people's capacity to believe that the problem requires a common solution while not wishing to be obliged to participate in this solution, an individualistic tendency.

If people think the tragedy should have a commons solution, and if they tend to think commons-players such as governments and businesses are already addressing the problem, then why is an individual solution approach so often emphasized by environmental advocates (Maniates 2002)? Maniates claims it is a combination of four factors. First, historical baggage from the mainstream environmentalism persists. Naturalists popularized the environmental movement in the sixties by authoring books such as Rachel Carson's *Silent Spring* (Carson, Darling & Darling 1962). These books used generalizations and shock value, later termed a "shame and blame" strategy, to make readers feel an individual sense of responsibility for environmental problems. While these tactics served effectively to garner mass attention for the environmental movement, they streamlined and exaggerated complex issues. They left the reader with a sense of guilt for her own ignorance of consequences of her behavior, but offered no way to assuage this guilt. Maniates also cites the core tenents of liberalism, the ability of capitalism to commodify dissent (i.e., buying a "save the whales" T-shirt), and the fact that the environmental movement evolved during the individualistic 1980s as contributing to the sense of individual responsibility for performing pro-environmental actions. Guber asserts that "[s]cholars have long shown that certain environmental attitudes are associated with a liberal political ideology" and gives many references (Guber 2003).

Advice for designers:

Guber's and Maniates' findings combined pose a large problem for designers and marketers of consumer products. If a company wants a consumer to perform a pro-environmental efficiency behavior, they first will need to tell the consumer that they, the company, are not doing as much as they could to manage their use of environmental resources. This may have such unforeseen effects as the triggering of cognitive dissonance (to be discussed), but once consumers know that their "secret" desire for commons solutions to the problem is not being realized by industry, they may be more open to developing an individual sense of responsibility for the problem.

A personal sense of responsibility may lie along the path between environmental attitudes and behaviors. A potential opportunity for a business to influence consumers to adopt an individual sense of responsibility is to focus on curtailing opportunities that their product offers when customers use the product, in addition to promoting efficiency (green purchase) behaviors. Customers will thereby have multiple approaches to expressing individual PEBs through products. An example of a curtailing design modification is select-a-size paper towels;

more perforations on paper towels at smaller intervals mean people can choose to tear off a smaller piece of towel for smaller-sized jobs. Instead of highlighting an efficiency (this towel is made from 50% less trees), a product can highlight potential opportunities for curtailing (this towel can help you use 50% less trees). Either way, the product is greener, but the curtailing design feature can build an individual sense of responsibility for the problem.

Complex decision-making skills

Linking one's environmental concerns to one's behaviors requires a good understanding of complex environmental problems and appropriate solutions. Research has documented that the average American citizen has severely limited, if any, understanding of these problems (Koehn 2006), a lack of understanding of eco-labels (D'Souza 2004), and a lack of understanding of Life Cycle Analysis (Erskine, Collins 1997). It should be noted that although the public's understanding of environmental problems may have increased since these studies were published, the associated decisions have become no less complex. Even if one were to understand the complexities of a particular environmental problem and available efficiency behaviors that could combat this problem, the decision between available options remains difficult. For example, consider a trade-off between a car with a diesel engine and one with a hybrid engine. The diesel engine emits more local pollutants, like NOx, but the hybrid engine has worse mileage, emitting more CO_2. How does one prioritize local pollutants in relation to global damage to reach a product decision?

A product decision that considers all sources of environmental impact is surely overwhelming to the average American. The “Reasonable Person Model” suggested by Kaplan (Kaplan 2000) finds this sensation of being overwhelmed a central problem in environmental decisions. Although it is not supported with accompanying experimental research, this mental model is worth considering. It asserts that, because of the way humans evolved, we gravitate towards situations where our information processing capabilities are useful, and avoid situations in which they are not useful. Therefore, if people face a complex and unconstrained product decision, they will avoid this decision altogether, or alternatively structure the decision in a way that is cognitively preferable. For most people, this cognitive simplification would require the removal of environmental concerns from decision criteria. A study by Research International (Levin 1993) found that too much environmental information led to anxiety and confusion.

Kaplan asserts that people can feel helpless in the face of complex environmental decisions when they lack the cognitive abilities required to navigate them. This author disagrees with Kaplan's assertion, because people make complicated decisions every day and are capable of structuring these decisions to include difficult-to-assess, but important, criteria. For example, remove environmental concerns from a car purchase decision and the decision remains complex, yet people do purchase cars. It is not that environmental decisions are too complex, but rather that people are not equipped with the mental tools required to address them.

Advice for designers:

Maniates states that people want marketplace environmental constraints to come about through political action. He believes people do want to make choices that are environmentally significant and beneficial, but that they would prefer if these choices be constrained through political action (Maniates 2002). Companies can influence policy, and if they view environmental policy as helping to constrain complex customer decisions, environmental regulations may seem more appealing and less restrictive to product designers.

Companies can act to improve the environmental decision-making abilities of their customers through scientific education. The model in Chapter 6 could be used to estimate the potential benefit to a product's popularity provided by educating customers. This education must be administered carefully, as providing "quasi-scientific" knowledge can backfire, simultaneously instilling people with more confidence in their decision-making abilities and leading them to make incorrect decisions. One study reviewed by Vining and Ebreo showed that knowledge of conservation activities led to conservation behavior, while others showed that the type of knowledge was important (Vining, Ebreo 2002). Other researchers, noting a weak link between environmental attitudes and behavior, found that "enhanced knowledge and supportive attitudes often have little or no impact on behavior" (McKenzie-Mohr 2000).

Education can change the way people spend money on their concerns over environmental issues. This may cause conflict within the product design community. For example, research has shown that large one-time investments, such as in a replacement appliance or increased insulation, can save dramatically more energy that repeated minor actions, such as turning off the lights when not in use (Oskamp 2000). If a business designs movement sensitive light switches and water heaters, the above statement may be viewed as education they wish to keep away from the customer. Product designers must be careful not to send mixed messages to the consumer by intentionally leaving out some green design features that are not as efficient as others for the sake of saving design costs. Green features should be presented in tandem whenever possible. The author recommends that no pro-environmental behavior should be represented as unhelpful if it has at least some small benefit. Doing so would only reinforce feelings that behavior "spillover" is unnecessary ("I already do X, I don't need to do Y").

Designers can attempt to constrain a complex decision by making their product comparable to others on a comprehensible but environmentally important dimension, using a simple heuristic (described below). The stress that results from a green product choice may also be alleviated with a variety of marketing approaches, including trial periods with the product and refund guarantees.

Formation of decision heuristics

Decision heuristics are “shortcuts” that exist in one’s mind in order to simplify judgments and decisions. They are simple, general, efficient rules that develop either through one’s own experiences or perhaps are hard-coded via evolution. The term was popularized in the judgment and decision-making community by Kahneman and Tversky (1974). The concept provides explanation for how people make decisions, come to judgments, and solve problems when faced with complex or incomplete information.

Heuristics help people make "fast and frugal" decisions (Gigerenzer 2004) and usually lead to good decision outcomes, but they can also lead to irrational and/or erroneous judgments and decisions. Several heuristics have implications in green product purchase decisions. For example, the level public concern for occurrences that are highly damaging to the environment is not aligned with the actual environmental threats these occurrences pose (Slimak, Dietz 2006). One explanation may be the availability bias and heuristic. People use the availability heuristic to assess the likelihood of a given event occurring based on the ease of recollection of similar events. This can result in an availability bias. For example, people tend to think more words begin with r than have r as their second letter, as it is much easier to recall words that begin with r than it is to recall words that have r as their second letter (Tversky, Kahneman 1974). Oil spills, nuclear plant accidents, poisoned drinking water, and barges full of trash lend themselves to sensationalist reporting and have therefore received much media attention over the past two decades. This attention makes these environmental disasters easy for most people to remember, and thus people assess the resultant threat to the environment as more likely and possibly more severe than subtler environmental consequences, such as global warming, which have received less mainstream attention (until recently). People also use their own perceptions to determine availability, leading to predictable outcomes: Guber reports that poll respondents are much more likely to be worried about air and water pollution—perceptible forms of pollution—rather than global warming, ozone depletion, and deforestation (Guber 2003). In fact, logging companies specifically keep strips of trees intact next to highways (Winter 2000), no doubt in order to prevent travelers from using the availability heuristic to judge the level and impact of deforestation.

The affect heuristic may cause a person to judge the likelihood of the occurrence of a decision outcome based on the emotions they feel about that outcome. If the decision outcome is described positively, judgment of the likelihood of achieving the outcome is higher than if the outcome were framed negatively (Slovic et al. 2004). Much information on the environmental impacts of products is framed negatively, in terms of the product's degrading effects on the environment, and therefore the impact of purchases meant to address this information may be judged as less likely.

Advice for designers:

To make an accurate assessment of the environmental impact of a product, consumers must perform a complex analysis or trust another source of information. Although thorough research is appropriate for large purchases, such as cars or refrigerators, it is likely that consumers will use “fast and frugal” heuristics to assess the environmental impact of most products. Some green products take advantage of what may be nascent green heuristics, such as rough unprocessed-looking fabrics, brown paper, the “recycled” symbol, matte finishes, and neutral colors or green and blue hues. Eco-labels can serve as a heuristic to some extent, but, as mentioned before, they are not well-recognized or understood. Heuristics have the potential to make green product decisions more manageable and palatable, but also have the potential to create bias for products that are not actually green but "look green." Heuristics can also make environmental assessments easier to understand. Winter cites an effective home energy audit that describes the amount of energy lost through poor insulation as "the equivalent of a hole the size of a football in your living room" (Winter 2000). It is important to have fundamentally good green design behind the heuristics; "greenwashing" will undermine efforts to build useful heuristics.

There is no body of literature devoted to the study of decision heuristics in product purchases, although heuristics are most likely used in product choice decisions and other product judgments. Related fields of study include emotional design (MacDonald et al. In press), product semantics (Krippendorff 2006), and such books as Norman’s *The Design of Everyday*

Things (Norman 1998). Chapter 7 uncovers a product-specific heuristic, termed the crux/sentinel product attribute relationship, and the design method presented can be used to identify other product heuristics, such as green product heuristics.

It is mentioned above that people's environmental concerns do not align with the most important environmental problems. Even though their concerns are misguided, it is important that engineers and designers not ignore them. If a design solution addresses a fundamental environmental problem, but worsens a "superficial" environmental problem that has a media presence or perceptual availability, the solution is unacceptable. It must be modified to address the superficial problem as well. Designers should not assume that education can retrain previously formed heuristics.

Trust

The complexity of assessing the environmental impact of a product paired with the lack of well-developed green heuristics may lead consumers to look for an alternate source of assessment from an expert opinion. Yet people tend to value their own judgment abilities above those of others, including experts'. Furthermore, the potential sources of expert opinion have had problems gaining the trust of consumers. A number of researchers have concluded that people do not fully trust in the assessments of the environmental movement. In her analysis of the results of a number of polls, Guber came to the conclusion that “[b]y downplaying environmental progress and using exaggerated doomsday warnings to motivate public awareness and concern, the environmental movement has sacrificed its own credibility by giving into the politics of chicken little” (Guber 2003).

D’Souza notes that several researchers have documented a lack of trust in eco-labels (D'Souza 2004). Eco-labels on products or product packaging are a form of “direct persuasion” advertising, as is any other form of information provided by the companies offering the products for sale. Even if the environmental information is accurate and useful to the consumers in aiding their purchase decision, direct persuasion techniques will lead consumers to think that the change in purchase habit is in the best interest of the persuader (and perhaps not in their own best interest). Direct persuasion may also shift responsibility for the action, leading consumers to think that ultimate blame for consequences of their environmental decisions rests on another party, namely, the persuader (Geller 2002).

Advice for designers:

Industrial designers have been taught to instill trust through the form of a design. They utilize the theory and analysis of design semantics (Krippendorff 2006) to create a perceptible sense of trust in the visual lines of the product. But designers should avoid greenwashing at all costs; they should not include green heuristics in the product unless they can document that the product is greener than alternative products by the scientifically based eco-design metric of their choice. Designers should be wary of eco-labels and conduct customer research to investigate the implications of including such labels. In certain situations they are helpful, but in others, they can be damaging to trust; for example, if other products that use the same label are found guilty of greenwashing, those labels become compromising to the product.

Cognitive Dissonance

There are many approaches to assessing environmental impact that may lead people to conclude they are performing pro-environmental efficiency behaviors when they are not. One's behavior may not match one's concerns for the environment; noticing this mismatch or inconsistency between concern and behavior may inspire a strong urge to reconcile the two, an experience psychologists term *cognitive dissonance* (Festinger, Carlsmith 1959).

Psychological experiments have manipulated decisions to create inconsistencies between cognition and behavior and then studied how people resolve their cognitive dissonance when confronted with these inconsistencies. One manner in which this dissonance can be resolved is by changing behavior to match cognition. Those attempting to influence people to buy green products can advance their goals by using the strong desire to resolve cognitive dissonance. For example, one study found that a door-to-door campaign in which subjects agreed to send a personal pro-recycling postcard to a friend, or alternatively completed a survey on recycling, increased the recycling activities of the subject (Winter 2000). Behavior changed to match the intentions expressed in the postcards or the surveys. When spillover between pro-environmental behaviors occurs, it may be a resolution of cognitive dissonance; in essence, if you are environmentally conscious during one activity, in order to be consistent you must be environmentally conscious during all activities.

However, people can also resolve cognitive dissonance by changing intentions and related emotions and perceptions to match behavior (Vining, Ebreo 2002). A focus group conducted by the American Geophysical Union provides anecdotal evidence of this phenomenon (Immerwahr 1999):

> When people are blocked and see no outlet for their concerns, their opinions can change quickly and easily, as they seek a way out of an uncomfortable situation. One of the most interesting exchanges we heard was in the Phoenix focus group. The initial discussion of global warming sounded much as we heard in other cities, with global warming caused by pollution which is caused by irreversible moral deterioration. At one point, one the respondents, the principal of an elementary school, said: 'I don't think the weather has changed. Some of my students were at a conference where they had a debate. And what they learned was that there is scientific evidence to show that the earth is not warming, in fact it is cooling. We go through cycles, but sometimes people have short memories.' After this story, the respondents immediately changed their views and agreed that there is no such thing as global warming. The point is that when people are stuck and frustrated, their views change quickly, especially if they have an opportunity to resolve some of the tension.

While invoking cognitive dissonance may cause people to align their behavior with their good environmental intentions, it may also backfire and result in people changing their values, attitudes, or beliefs about the environment, as illustrated above. Note that backfiring in one product choice may affect all subsequent product choices in all categories—the person may fundamentally change the way they view environmental problems. It is a situation to be avoided carefully by those marketing green goods. Also note that a person may change their perceptions about the products they currently buy.

Sense of Guilt

People can experience feelings of guilt about negative environmental impacts if they have formed an individualized sense of responsibility, listened to the "shame and blame" tactics of the early environmental movement, or experienced unresolved cognitive dissonance regarding the products they buy. Levin, among others, mentions feelings of guilt regarding environmental behavior in his research (Levin 1993). In motivating pro-environmental behavior, researchers stressed that inducing feelings of guilt should be avoided, as guilt can cause a change in behavior, but it can also cause a disguise or denial of the target behavior. One researcher who implemented a recycling program noted that a man who chose not to participate in the program saw his neighbors' recycling buckets waiting for pickup and decided to put some of their recycling into his bucket—a funny example of a disguise of target behavior (Vining, Ebreo 2002). Although discussed separately from cognitive dissonance by researchers, guilt and cognitive dissonance seem to have similar results, as both may involve shifts in a person's perceptions and values rather than their behaviors.

Proper Motivation

Applied behavior analysis is a sub-field of psychology that includes much research on motivating changes in behavior, particularly in the workplace. Vining and Ebreao (2002) review the three types of motivation for a behavior: (1) intrinsic motivation, in which a person derives satisfaction from performing the behavior; (2) extrinsic motivation, in which person derives satisfaction from a prompt reward given when the behavior is performed; and (3) amotivation, in which a person receives no satisfaction from the behavior, and is unsure why they are performing the behavior. Guilt and/or cognitive dissonance are examples of extrinsic motivators—correcting behavior gives the reward of the removal of an unpleasant cognitive state. Guber found in her analysis of polling results that people participate in pro-environmental behavior (political, curtailing, or efficiency) when there is a tangible incentive and personal sacrifice is slight: extrinsic motivation (Guber 2003). The applied behavior analysis literature directed at promoting pro-environmental behavior concentrates on curtailing efforts, such as recycling and water usage, rather than political or efficiency efforts. The research indicates that specific motivations must be tailored to the desired behavior change.

Advice for designers:

Environmental product purchase decisions would be better motivated with the addition of an external motivator. Geller suggests that this incentive should be both on a short-term (potentially repetitive) time scale and small in size: "[r]eward schedules that are just sufficient to initiate behavior change are more likely to produce longer-term behavior change than more powerful rewards." The reason for this, he explains, is that people infer things about their behavior from the relevant circumstances and the size of the reward. Circumstance and size control inferences such as: "I am doing this because I care about the environment" *vs.* "I am doing this to take advantage of this great rebate."

A large, one-time incentive to motivate PEB causes a person to attribute their pro-environmental behavior to the efforts of the motivator (extrinsic motivation). However, small, repetitive incentives cause a person to attribute the behavior to their own volition (intrinsic motivation) (Geller 2002). If a designer wants to see repeated green product purchases, this is an important distinction. Note that the problem of environmental degradation, as a tragedy of the commons, offers only long-term benefits in averting the tragedy, with no naturally-occurring short term rewards. Noting this, Geller concludes that conservation behaviors, without artificial short-term rewards, will be altruistically based and rare.

Three intermediaries, cognitive dissonance, guilt, and motivation, require the individual to realize their current behaviors should be changed to reduce environmental impact. Cultivating this realization is an area for much greater study by marketers and designers working together. An early suggestion is a behavior analysis by an independent third party available as a "consultant" at point of purchase. Aggressive word-of-mouth marketing campaigns may also serve a purpose, as fear-based messages from friends seem effective in behavior change. Geller calls these "intervention agents"(Geller 2002). Another option is to give messages that are a mixture of positive messages and fear-based motivation from trusted sources at intermittent intervals.

It was mentioned above that a properly designed, small (but not too small), repetitive incentive can cause people to perceive a previously extrinsically-motivated behavior as intrinsically motivated. When applied to a large one-time purchase such as an automobile, providing a small intermittent incentive requires creativity. An example of a good incentive would be that previously provided by the state of California for hybrid cars. Any hybrid sold in California included a sticker that allowed the driver to use carpool lanes with only one passenger in the vehicle. Every time the owner drove in the carpool lane, they received a small incentive: a faster commute time and savings of $2.00 to $4.00. Following the above reasoning, this small repetitive perk is a much better incentive than a one-time purchase price rebate of equivalent monetary value.

As the example demonstrates, repetitive and small incentives can be designed into a product's use phase. Design methods that discover product attributes that delight the customer (Kano 2001, Kano et al. 1984, MacDonald et al. 2006) can be used to investigate what attributes may be able to provide such incentive. The intermittent spacing of the incentive will require design creativity.

The product can convey a message that pro-environmental behavior is easy to do, combating the excuses that are frequently given for not performing pro-environmental behaviors, such as that it is hard to make environmentally friendly choices (Koehn 2006). Product heuristics, or emotional design, that read as "easy" or "simple" can be built into design features to motivate pro-environmental behavior.

Altruism

It follows from Geller's conclusion that both ego and altruism play a role in current pro-environmental behavior, and other researchers have tested and found this relationship in willingness to pay survey analysis (Stern, Dietz & Kalof 1993). Individuals must focus beyond themselves and act out of concern for others to find motivation for PEB. Altruistic motivation may be accompanied by an implicit message of sacrifice and impoverishment for the sake of others. Kaplan (Kaplan 2000) postulates that "[t]he focus on altruism brings with it the implicit message that living with less will result in an impoverished and joyless future," and wonders how a purchase can be seen to serve both a self-interested and an altruistic purpose. Self-interest, a typical reason for a product purchase, and altruism may therefore be viewed as opposites. If a person perceives a link, perhaps a heuristic, between higher levels of consumption and greater happiness, and furthermore, avoids making changes that reduce their quality of life, then one cannot assume that altruism is an adequate motivator for their green product choice.

Advice for designers:

It is important to frame the green product decision in a manner that highlights that every complex product decision involves trade-offs. If the feeling of altruistic sacrifice manifests as price sensitivity, careful framing of choices can also make the compromise easier to swallow. Guber explains that one "team of scholars finds that the use of symbolic framing (such as appeals to environmental concern or patriotism) decreases price sensitivity and increases variance on the willingness to pay function, compared to (experimental) instrumental cues alone" (Guber 2003).

Perhaps an appeal to altruism through design features would serve not only to decrease price sensitivity but also to demonstrate that self-interest and altruism are not diametrically opposed. Consider the exaggerated example of an altruistic car designed to keep people other than its passengers safe: external airbags, a crush-zone for pedestrian collisions, deer-whistles to avoid hitting animals, external warning lights alerting others of when you are changing radio stations or answering your cell phone, a speeding monitor, an external indicator light that shows when the brakes and other crucial safety components of the car are in disrepair, an ignition activated by breathalyzer test, and tires that control for external road noise. Environmentally friendliness in such a car would not seem out of place in the slightest, because many other features are included in the car out of genuine altruistic concerns.

Responsibility, complex decision-making, heuristics, trust, cognitive dissonance, guilt, motivation, and altruism all affect and inform green product decisions. If any one of these cognitive intermediaries is touched upon during customer preference elicitation in the design process for a green product, the intermediary may have an effect on the data collected. For example, it is likely that someone will feel an individual sense of responsibility when asked for help with designing a green product, but not necessarily when considering purchasing that product in the market. Within the confines of a controlled data collection, decisions are less complex than they are in the marketplace. Heuristics play an important role in design interactions because customers do not necessarily have all of the knowledge they would require in the market to form judgments, and therefore they make inferences, as discussed in Chapter 7. People may trust designers more than they do the associated business or product; additionally, less trust is required in this context to begin with, as the "customer" does not pay for the products in a design-process interaction. Cognitive dissonance can affect preferences reported during design interactions, and is one of the potential explanations for the findings of Chapter 4. Guilt and altruism are related to social desirability bias, which is difficult to overcome when collecting green product preferences. Motivation is difficult to reproduce during design interactions, as the customer is typically not asked to do anything that requires the level of effort involved in a real market situation, such as paying money or repeatedly using the product, and typically, the customer is externally motivated to participate in the data collection by monetary compensation. The consequences of these cognitive intermediaries in preference construction are in the background of the findings and methods presented in the remainder of this dissertation.

Chapter 3. Case study overview: Designing a green paper towel

3.1. Practically framing the main contributions

A case study in paper towels serves as a testing ground for the central contributions of this work. KermitCo Towel Company has purchased a paper towel manufacturing facility from a competitor and plans to introduce a new paper towel that has a recycled paper content somewhere in between 0 and 100%. In introducing a new towel, KermitCo must also consider the most important attributes in a paper towel purchase other than recycled paper content: absorbency, strength, and softness (Consumer Reports 1998, Atkins 2004a, Bottiglieri 2005, Hollmark, Ampulski 2004). They seek to understand and model the engineering relationship between these attributes and recycled paper content; it is not necessarily the case that including recycled paper content decreases the towel's other desirable properties. Pricing is another important consideration.

KermitCo has some concerns in introducing this new towel. They are skeptical of survey respondent data that indicate that a good portion of their potential customers are interested in buying towels that contain recycled paper content, because they know that people frequently say they are interested in buying green products, but fail to do so in the marketplace. The psychological underpinnings of this behavior were addressed in Chapter 2, and the theoretical and practical manifestations will be addressed formally in Chapters 4 and 6.

Believing that some customers say one thing and do another when it comes to green products, that other customers do not care about recycled paper content at all, and that still others have a slight prejudice against it, KermitCo must design a towel that captures as much market share as possible, by varying recycled paper content and price. Chapter 6 details two optimization approaches to the design of KermitCo's towel. The company must decide how much recycled paper content to include in their towel. To aid in this decision, they must model the engineering relationship between recycled paper content and strength, softness, and absorbency. Chapter 5 explains towel manufacturing processes and builds an engineering model of towel properties.

Given the findings of Chapter 6, which indicate that controlling construction of preference will lead to increased appeal of KermitCo's product, it seems worthwhile for KermitCo to invest in the design of towel features that control construction of preference for their towels, *and potentially other towel*s in the market, such that their towel is preferred in the marketplace. Also, they are concerned that people have a perception of towels that include recycled paper content as being less strong, soft and absorbent than competitors. Chapter 7 gives an illustration of triggering preference through design that KermitCo will find useful in working the design details of its towel for triggering preference construction. Chapter 7 also finds no evidence that people equate recycled paper content with low quality in towels and discusses why these findings are not conclusive.

3.2. Assumptions in the case study

3.2.1. Engineering Assumptions

The case study makes the assumption that including recycled paper content in a towel is environmentally beneficial or "green." Any real-world applications of this work should take this assumption into serious consideration with a life-cycle analysis. Depending on factors such as the amount of CO_2 produced during transportation of recycled pulp versus the amount of CO_2 sequestered in the growth of new trees, it may or may not actually be the green choice to make a towel using recycled paper pulp. However, it is very likely that a green paper towel needs to include some recycled paper content in order to conform to the likely green heuristic of assessing environmental impact based on recycled paper content, as will be discussed later.

KermitCo has seven competitors: Bounty, Brawny, Scott, Viva, Sparkle, Green Forest, and Seventh Generation. This fabricated market gives a reasonable representation of the real market, but does not include every towel brand. These towels have a variety of strength, softness, absorbency, and price levels. Of these competitors, Green Forest and Seventh Generation have 100% recycled content, and the rest have 0% recycled content, as verified by calling the customer service departments and/or visiting the websites of the various manufacturers. Table 3.1 reports towel purchases in the U.S. by the percentage of survey respondents who have used the brand of towel (n =23,740) (Mintel Oxygen 2006). Paper towel FMD (Food, Drug, Mass) sales were $2,180 million in 2006 (excluding Wal-Mart) (Mintel Oxygen 2006). Although 35% of adults did use store brand towels, it was not possible to include them in the engineering model and resulting optimization due to unknown status of the store brand towels' strength, softness, absorbency, and recycled paper content.

Table 3.1 Brands of paper towels used, January – September 2005. Base: 23,750 adults aged 18+ whose household uses paper towels.

Brand	**Percentage who have used**	**Brand**	**Percentage who have used**
Bounty	65 %	Hi-Dri	11 %
Brawny	36 %	Kleenex Viva	9 %
Scott Towels	29 %	Coronet	6 %
Sparkle	23 %	Marcal	5 %
Mardi Gras	17 %	Green Forest	2 %
Other brands	15 %	Store brand	35 %

For this case study, it is assumed that the costs of using recycled paper pulp and virgin pulp are identical. This assumption is not unrealistic, given that recycled pulp may have a lower purchase price than virgin pulp but causes more manufacturing down-time due to cleaning away stickies from the equipment (see Chapter 5) and thus is less efficient. It is assumed that KermitCo has bought a factory from a competitor and is not interested in upgrading the factory at this time. They will make minor adjustments to the equipment to accommodate the differences between recycled pulp and virgin pulp, but they will strive to keep factory conditions as constant as possible in the new production. Therefore, the only manufacturing variable they will change in designing their new towel is the percentage of recycled pulp in the pulp slurry at the beginning of the manufacturing process. Chapter 5 explains the need for this simplification, which is basically due to the complex relationship between manufacturing processes and final towel properties. This complex relationship also dictates the need for an empirical engineering model of the relationship between recycled paper content and strength, softness, and absorbency.

KermitCo does not have access to pilot paper equipment that can make consumer-grade towels. Therefore, it must make its engineering model from commercial-grade towels that have the general quality of towels found in public bathrooms. It is assumed that a scaled version of this model will apply to consumer grade towels. The limits placed on scaling this model to consumer grade towels, described in Section 6.3, represent the least justified assumption of the case study. In order to make the results of the study useful to industry, it would be best to replace the assumption and model with a new model created empirically from consumer-grade towel samples. For the illustrative purpose of the case study, the assumption holds merit; it is discussed further in Section 6.3. The above condition, where assessments about final design must be made from less-than perfect prototypes, is not unusual in engineering design.

3.2.2. User assumption

It is assumed that people equate recycled paper content with green paper towels. The survey used in the case study did not directly evaluate the strength of this link in order to minimize respondent “priming” for thinking about the environment during the survey. The survey intentionally never mentioned the word “environment,” as this could strengthen social desirability bias. It did not ask respondents for the relative importance of recycled paper content as compared to other attributes in eco-friendly paper towels at the end of the survey, as the large amount of exposure to this attribute during the survey would bias their answers. Guagnano uses a model of moral norm activation to predict willingness to pay for recycled paper towels and finds that a feeling of personal responsibility is a predictor variable. The results were presented as evidence of environmental behavior (Guagnano 2001). With respect to the perceived importance of recycled paper content versus other potential eco-friendly attributes, respondents did not care as much about packaging in their product choices as they did about recycled paper content. Previous choice analysis research on toilet paper found that the average respondent was not willing to pay more for unbleached paper alone, but was willing to pay more for recycled paper alone (Bennett, Blamey 2001). With respect to the perceived importance of buying products made from recycled materials versus other eco-friendly actions, Guber states that environmentalists and non-environmentalists alike are more likely to “buy products made from recycled materials whenever possible” than “buy a product because the label or advertising said it was environmentally safe or biodegradable” or “avoid purchasing products made by a company that pollutes the environment” (Guber 2003).

3.3. Case study survey design

The case study involves a six-part survey about paper towels that took a total of 30 minutes to complete. Analysis of this survey is discussed in Chapters 4, 6, and 7. For the sake of brevity, the survey will be described in its entirety only here and referenced throughout the remaining chapters. Table 3.2 gives an overview of the six part survey, and Table 3.3 gives more detail. First, the survey investigated consumer choice for product attributes of paper towels in two orthogonally designed choice-based-conjoint (CBC) surveys. Next, it collected consumer perceptions of existing paper towel attributes across a number of brands through attribute ratings. Then it collected past purchase information. Finally, willingness to pay for specific scenarios and demographic information was collected.

Table 3.2 Case study survey instrument framework.

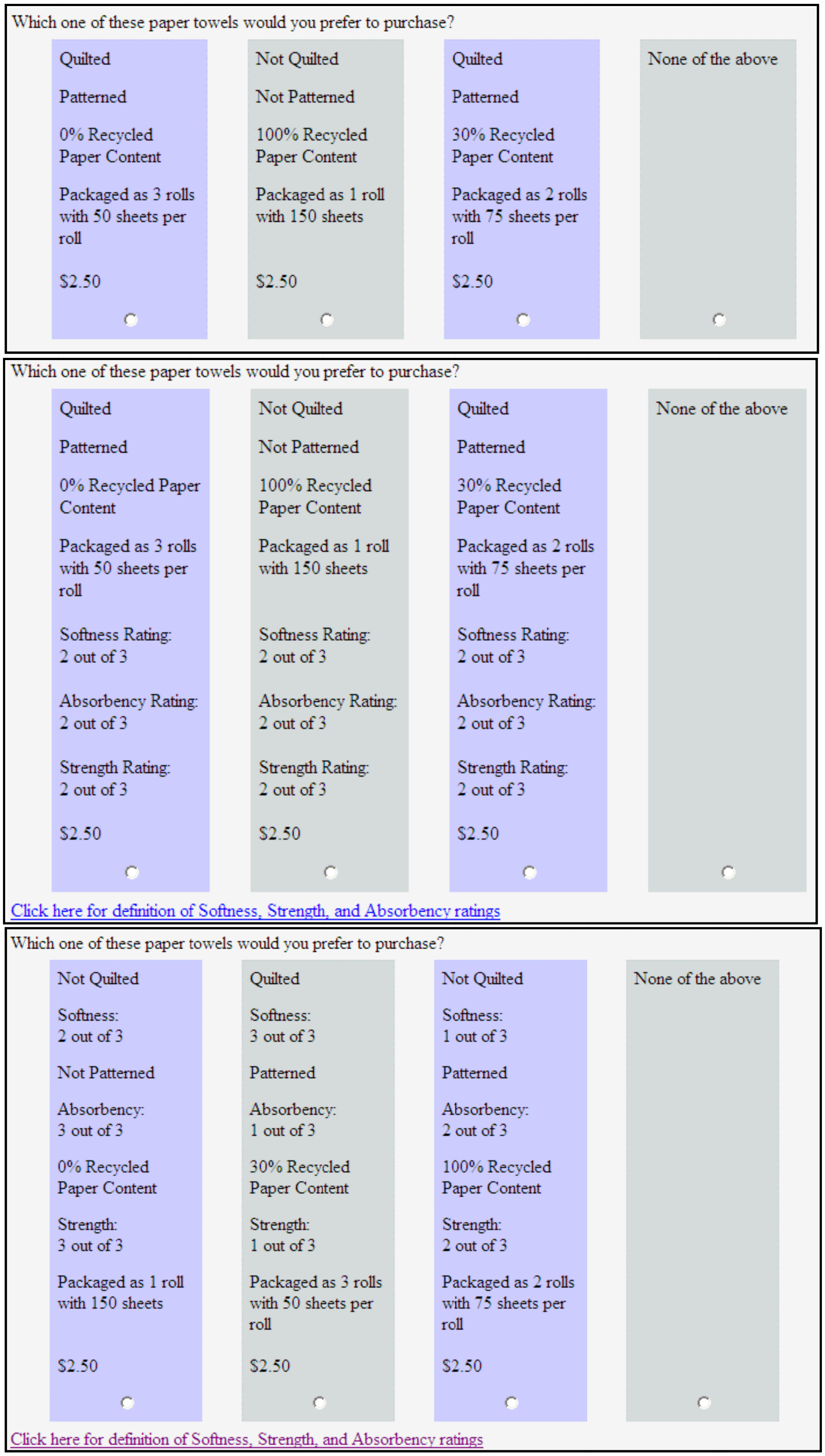
Part 1	**Part 2**	**Part 3**	**Part 4**	**Part 5**	**Part 6**
Discrete Choice I	Discrete Choice II	Rate Brand Performance	Past Purchase Information	Buy/Not Buy Scenarios	Demographics

The survey was designed using Sawtooth Software (Sawtooth Software 1999, Sawtooth Software 2005, Sawtooth Software Accessed 2007), and Luth Research (Luth Research Accessed 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 six months. 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.

Part 1 of the survey had three versions with ten multiple-choice questions about different paper towel configurations, as shown in Figure 3.1. Sawtooth's SSI Web interface varied towel configurations in the surveys in an orthogonal manner across the respondent population for eight out of ten questions. Two questions did not vary across respondents. 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. 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 in the following paragraph). 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. 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.

Table 3.3 Detailed description of case study survey.

	Version A "No Quality"	**Version B "Fixed Quality"**	**Version C "Quality as Attribute"**
Total Respondents	70	73	74
Part 1 Stated Preference Conjoint 10 Choice Tasks 8 Conjoint 2 Fixed NOA (None of the Above) option	Attributes: Quilting Pattern Packaging Recycled Paper Content	Attributes: Quilting Pattern Packaging Recycled Paper Content ** All paper towels given equal softness, strength, and absorbency ratings*	Attributes: Quilting Pattern Packaging Recycled Paper Content Softness Strength Absorbency
Part 2 Stated Preference Conjoint 6 Choice Tasks 4 Conjoint 2 Fixed No NOA option	Attributes: Price ($1.29, $2.39, $3.49, $4.59) Strength (1/3, 2/3, 3/3) Softness (1/3, 2/3, 3/3) Absorbency (1/3, 2/3, 3/3) Recycled Paper Content (0%, 30%, 60%, 100%)		
Part 3 Rating of Attributes	Rate across brand: Price, Strength, Softness, Absorbency, Environmental Responsibility, Quilting, Pattern, Packaging (above average, average, below average, don't know) Rate across brand: Recycled Paper Content (0%, 30%, 60%, 100%)		
Part 4 Past Purchase Information	Report Paper towel last purchased: Price, Brand, Packaging, Quilting, Pattern		
Part 5 Buy/Not Buy Scenarios	Report Willingness to Pay for Three Product Scenarios: (if not willing to pay, explain why not) (wtp1) Quilted, Not Patterned, 100% Recycled Paper Content, 2 rolls (wtp2) Quilted, Patterned, 0% Recycled Paper Content, 2 rolls (wtp3) Quilted, Not Patterned, 60% Recycled Paper Content, 2 rolls		
Part 6 Demographic Info	Gender, Age , Income, Where usually shop for paper towels, Zip Code Ethnicity, Education Level		



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	Packaged as 2 rolls with 75 sheets per roll	
$2.50	$2.50	$2.50	

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	Packaged as 2 rolls with 75 sheets per roll	
Softness Rating: 2 out of 3	Softness Rating: 2 out of 3	Softness Rating: 2 out of 3	
Absorbency Rating: 2 out of 3	Absorbency Rating: 2 out of 3	Absorbency Rating: 2 out of 3	
Strength Rating: 2 out of 3	Strength Rating: 2 out of 3	Strength Rating: 2 out of 3	
$2.50	$2.50	$2.50	

Click here for definition of Softness, Strength, and Absorbency ratings

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

Not Quilted	Quilted	Not Quilted	None of the above
Softness: 2 out of 3	Softness: 3 out of 3	Softness: 1 out of 3	
Not Patterned	Patterned	Patterned	
Absorbency: 3 out of 3	Absorbency: 1 out of 3	Absorbency: 2 out of 3	
0% Recycled Paper Content	30% Recycled Paper Content	100% Recycled Paper Content	
Strength: 3 out of 3	Strength: 1 out of 3	Strength: 2 out of 3	
Packaged as 1 roll with 150 sheets	Packaged as 3 rolls with 50 sheets per roll	Packaged as 2 rolls with 75 sheets per roll	
$2.50	$2.50	$2.50	

Click here for definition of Softness, Strength, and Absorbency ratings

Figure 3.1 Screen shots of survey Part 1, versions A, B, and C.

In Versions B and C of Part 1, and also in Part 2, detailed descriptions of the attributes and levels of strength, softness, and absorbency were presented at the beginning of the questions and also available as a pop-up window throughout the questions:

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.

Part 2 of the survey asked six choice questions with three multiple-choice answers available per question, as shown in Figure 3.2. Respondents could choose paper towels based on different levels of price, recycled paper content, and ratings of strength, softness, and absorbency, described in Table 3.3. Two of the questions were fixed across respondents, and the others varied as described for Part 1. Part 2 did not include a "none of the above" option, as people typically choose among available towel options at the store instead of waiting to find a preferred paper towel elsewhere, and in Part 1 this option was rarely selected. The survey instructed respondents to "imagine you are at a store, you need paper towels, and the three choices presented to you in each question are the only paper towels available at the store, and that you don't have time to go to another store."

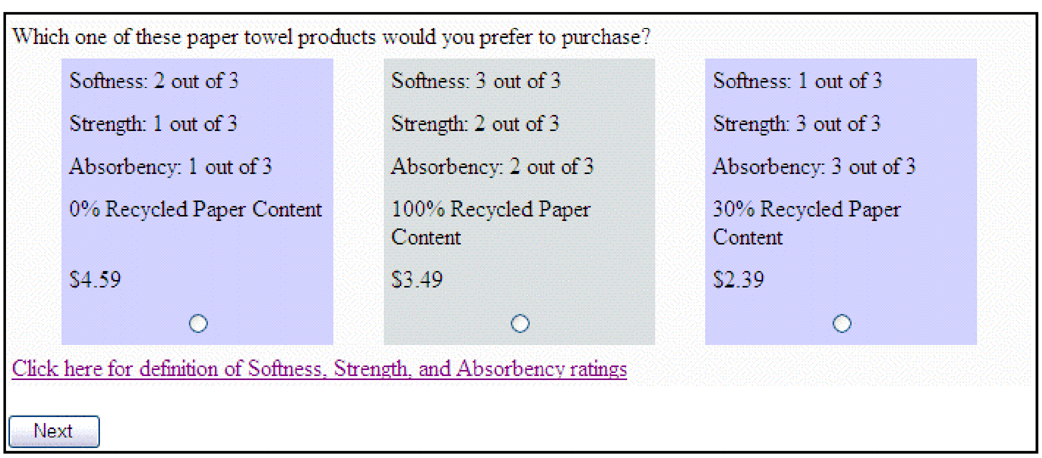


Figure 3.2 Screen shot of one of six multiple choice questions from survey Part 2.

Part 3 of the survey asked respondents to rate the paper towel brands Bounty, Brawny, Seventh Generation, Green Forest, Store Brand, Sparkle, Viva, and Scott on the product attributes of strength; absorbency; softness; environmental responsibility; affordability; and prints, colors and styles. The ratings “1 = Below Average,” “2 = Average,” “3 = Above Average,” and “Don't Know” were presented as options in a drop-down list within a 48-cell grid. The brands were the randomly-ordered rows of the grid, and the product attributes were the columns. After completing this grid, respondents were presented with a bubble-grid question that asked them to identify the recycled paper content of the eight brands as “0%”, “30%”, “60%”, “100%”, or “Don’t Know.” For this question, the brands were presented in randomly ordered rows.

Part 4 asked respondents for information about their last paper towel purchase, including brand (drop down of brands above plus “other” write-in response), store (write-in), print (yes/no/don’t know), quilting (yes/no/don’t know), packaging (write-in), and price (write-in). It also asked how sure they were about the price they reported within 50 cents (“Not at all sure,” “Somewhat sure,” “Very Sure,” “This is the exact price I paid”). Part 5 presented three paper towel “scenarios” individually, described Table 3.3 and Table 4.4, and asked respondents whether or not they would purchase the towels. If a respondent replied that they would purchase the described towel, they were asked to state how much they would pay. If they would not purchase the towel, they were asked to explain why. Part 6 asked respondents for their gender, age, household income, usual shopping locale for paper towels, zip code, ethnicity, and level of education.

3.4. Case study survey descriptive results summary

The survey had 317 attempted responses, including 39 disqualifications, 16 research opt-outs, and 45 incomplete surveys. Survey respondents were disqualified if they were below the age of eighteen or did not purchase paper towels in the last six months. The 217 complete responses that elected to participate in the study were analyzed, and will be referred to as “respondents.” Forty percent of respondents were male. The average respondent age was 50, with an age range of 18 to 83. Forty-three percent of respondents reported a household income between $35,000 and $74,999. Eighty-six percent of respondents completed at least a high school education, with 59% completing an undergraduate degree. Eighty-nine percent of respondents stated their ethnicity was “White or Caucasian.” As the usual shopping location question allowed multiple responses, 123 respondents reported they shopped for towels in supermarkets, 50 in warehouses, 97 in department stores, and small numbers (<8) in the other locales.

Responses to the choice questions in Part 1 will be analyzed with a multinomial logit model in Chapter 7. Responses to the four choice questions that varied in Part 2 will be analyzed with a latent class multinomial logit model in Chapter 4. Responses to the two fixed questions in Part 2 are reported in Table 3.5. Eighty-eight percent of respondents elected to purchase the paper towel with average strength, softness, and absorbency and 100% Recycled Paper Content for $2.39, the second lowest price point, with only 13% choosing a more expensive towel. When the $2.39 towel does not have recycled paper content but is the same otherwise, 44% of respondents choose a more expensive towel, stating a willingness to pay for recycled paper content.

A summary of rating responses to Part 3 is reported in Table 3.4, revealing that Bounty is the best-known and best-rated brand, with the fewest number of “Don’t Know” and blank responses and the highest overall rating of 2.4. Table 3.4 indicates that respondents were not confident in assessing environmental responsibility, as this category received far more "Don't Know" responses. Not many respondents rated the environmentally-friendly brands “Seventh Generation” and “Green Forest,” but those who did rate them rated them overall as better than average, and their "environmental responsibility" average ratings were the highest of any towel. Only two out of eight brands had overall ratings that were less than the “average” rating of 2 out of 3.

An unusually large number of affordability ratings were left blank. It may have been that on some computer screens the affordability grid column was neatly cut off in the active survey window and only visible by scrolling to the right. As responses were not required on this page, some respondents must not have been aware of the existence of this column and therefore left it blank. Responses to the affordability question will not be included in the subsequent analysis. Respondents had very little knowledge of the recycled paper content of their towels, as reported in Table 3.6. Green Forest had the most correct ratings, with 33 out of 217 respondents recognizing it had 100% recycled paper content. Most respondents did not know that the most well-known brands have 0% recycled paper content, and some respondents thought they had 100% recycled paper content.

Table 3.4 Respondents ratings of strength, softness, absorbency, prints (colors & style), environmental responsibility, and affordability.

	Bounty						**Brawny**					
	1	2	3	Don't Know	Blank	Mean	1	2	3	Don't Know	Blank	Mean
Strength	2	51	146	13	5	2.7	8	49	119	31	10	2.6
Softness	1	53	145	11	7	2.7	12	69	93	31	12	2.5
Absorbency	9	103	88	11	6	2.4	15	113	48	29	12	2.2
Prints, C&S	7	102	72	28	8	2.4	19	101	38	47	12	2.1
Env. Resp.	4	57	32	115	9	2.3	10	48	18	128	13	2.1
Affordability	22	95	38	18	44	2.1	25	82	32	31	47	2.1
	Seventh Generation						**Green Forest**					
	1	2	3	Don't Know	Blank	Mean	1	2	3	Don't Know	Blank	Mean
Strength	6	16	8	172	15	2.1	13	20	6	163	15	1.8
Softness	7	18	8	167	17	2.0	10	23	7	160	17	1.9
Absorbency	11	14	10	165	17	2.0	10	23	3	164	17	1.8
Prints, C&S	11	16	7	165	18	1.9	10	21	5	163	18	1.9
Env. Resp.	7	8	19	165	18	2.4	4	15	21	157	20	2.4
Affordability	5	16	5	140	51	2.0	9	24	4	128	52	1.9
	Scott						**Store Brand**					
	1	2	3	Don't Know	Blank	Mean	1	2	3	Don't Know	Blank	Mean
Strength	16	105	49	38	9	2.2	78	69	6	54	10	1.5
Softness	19	107	42	38	11	2.1	74	72	6	53	12	1.6
Absorbency	35	98	36	37	11	2.0	95	53	4	53	12	1.4
Prints, C&S	16	109	30	51	11	2.1	55	84	8	57	13	1.7
Env. Resp.	7	57	16	124	13	2.1	34	33	5	130	15	1.6
Affordability	13	93	25	41	45	2.1	33	43	51	42	48	2.1
	Viva						**Sparkle**					
	1	2	3	Don't Know	Blank	Mean	1	2	3	Don't Know	Blank	Mean
Strength	9	89	60	46	13	2.3	42	80	14	69	12	1.8
Softness	9	95	55	43	15	2.3	40	83	12	67	15	1.8
Absorbency	8	91	56	47	15	2.3	51	74	10	65	17	1.7
Prints, C&S	9	102	39	52	15	2.2	22	82	24	75	14	2.0
Env. Resp.	7	48	17	129	16	2.1	13	34	8	147	15	1.9
Affordability	15	75	27	50	50	2.1	19	61	26	62	49	2.1

Table 3.5 Responses to the fixed questions in survey Part 2 show a willingness to pay for recycled paper content.

Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 100% Recycled Paper Content $4.59	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 60% Recycled Paper Content $3.49	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 0% Recycled Paper Content $2.39
30 (14%)	67 (31%)	120 (55%)
Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 0% Recycled Paper Content $4.59	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 60% Recycled Paper Content $3.49	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 100% Recycled Paper Content $2.39
6 (3%)	21 (10)%	190 (88%)

Table 3.6 Few respondents have accurate knowledge of recycled paper content in major towel brands.

	Respondent Rating					**% Correct Rating**
	0	**30%**	**60%**	**100%**	**Don't Know**	
Bounty	18	37	25	11	126	8%
Brawny	16	40	22	8	131	7%
Scott	15	38	23	6	135	7%
Viva	9	36	23	3	146	4%
Sparkle	12	34	21	4	146	6%
Store Brand	23	16	19	13	146	unknown
Green Forest	2	6	21	33	155	15%
Seventh Generation	1	5	16	16	179	7%

Survey Part 4 revealed that 42% of respondents purchased Bounty the last time they went shopping. Other purchases were: Brawny (9%), Scott (9%), Seventh Generation (1%), Sparkle (9%), Store Brand (13%), Viva (8%), and Other (6%), with 3% of respondents selecting “don’t know.” No one purchased Green Forest. Ninety-three respondents purchased a printed towel and 117 purchased a non-printed towel (7 did not know); 110 purchased a quilted towel and 83 purchased a non-quilted towel (24 did not know). From responses about their last towel purchase that included total price, total rolls, and number of sheets per roll, the average price paid for the past purchase was calculated to be $0.013 per sheet with a standard deviation of 0.021, with 21 price responses eliminated due to typos and/or missing data. 53 respondents were “not at all sure” of the total price they reported, 98 were “somewhat sure,” 40 were “very sure," and 26 felt that “this is the exact price I paid.”

The results for Part 5 of the survey are summarized in Table 3.7. Three, two, and three values that were typos were left out of the calculations for average price in each of the scenarios, respectively. Note the significantly larger portion of the respondent population that would not purchase the towel with 0% recycled paper content, presented in Scenario 2. Sixty of these respondents, or 27% of the total population, stated specifically that the reason they would not purchase this paper towel was because it lacked recycled paper content (classified by explanations that indicated preference for "recycled" or "environment"). The average price for Scenario 2 is less than the other two scenarios, suggesting that among those who would pay, they were willing to pay slightly less for the towel because it did not have recycled paper content.

Table 3.7 Buy/Not buy questions in Part 5 reveal strong preference for recycled paper content.

N = 217	**Scenario 1**	**Scenario 2**	**Scenario 3**
	Quilted Not Patterned 100% Rec. Paper Content 2 rolls w/ 75 sheets per roll Softness: 3 out of 3 Absorbency: 3 out of 3 Strength: 3 out of 3	Quilted Patterned 0% Rec. Paper Content 2 rolls w/ 75 sheets per roll Softness: 2 out of 3 Absorbency: 2 out of 3 Strength: 2 out of 3	Quilted Not Patterned 60% Rec. Paper Content 2 rolls w/ 75 sheets per roll Softness: 2 out of 3 Absorbency: 2 out of 3 Strength: 2 out of 3
Would Buy	196	129	186
Average Purchase Price	$2.29	$1.95	$2.05
Variance	0.77	0.78	0.71
Would not buy	21	88	31
Top reason for not purchase (# of Responses)	No pattern (4)	No recycled Content (60)	No pattern (7)

The above results will be referenced throughout Chapter 4, Chapter 6, and Chapter 7.

Chapter 4. Preference heterogeneity, inconsistency, and heterogeneous inconsistency

This chapter discusses the difference between preference heterogeneity (the difference in preference between people or groups of people), inconsistency (the difference in preference for one person between two different decision contexts), and heterogeneous inconsistency (the difference in inconsistency between different groups of people). It provides a framework for designers to analyze preference construction and identify inconsistencies. The case study survey is investigated, supporting KermitCo's intuition that a group of customers say they are interested in protecting the environment, yet their past purchases say otherwise. KermitCo's customer base is analyzed, first using heterogeneity to separate different groups of customers, and then looking for preference inconsistency within these groups. The chapter gives advice on when designers should look for preference heterogeneity, inconsistency, or both. The results of this chapter are used in Chapter 6 to optimize a towel for inconsistent green preference.

4.1. A framework for the identification of preference inconsistencies

Psychologists may see the construction of preference as an interesting human trait for psychological study, and economists may see it as an unfortunate modeling inaccuracy, but for businesses, designers, and marketers, construction of preference is an important reality that can lead to success or failure in the marketplace. Designers draw many of their constraints from customer input, and the fact that these constraints are dependent on the context in which they are elicited is a daunting hurdle to overcome in the product design process. Researchers in fields outside of engineering design have used a number of different approaches to identify construction of preference and related psychological effects. In an attempt to incorporate construction of preference as a practical tool in the product design process, we have created a framework to understand the different manners in which preference construction inconsistencies are typically identified in marketing, economics, and psychology studies.

Assuming that every person is capable of making a decision between two or more choices, what might cause two separate individuals to make the same decision? It is possible that they share the same outlook on the choice, identify and value the factors in the decision similarly, and therefore make the same choice. It is also possible that they value completely different factors, identify them differently, and have an entirely different outlook but still make the same choice. Most models of decision theory start with the fundamental premise that if two different people make the same decision, they share some fundamental value in the decision, related to a predictable *psychological effect.* With every other consideration of the separate deciders expressed as error, the *psychological effect* can predict the outcome of the decision.

A simple model of a psychological effect is:

$$Y = X \cdot G + \varepsilon \tag{4.1}$$

$$X = (x_1, x_2, \dots, x_n) \tag{4.2}$$

$$G = (g_1, g_2, \dots, g_n) \tag{4.3}$$

where Y is the dependent variable (the decision outcome), G are the estimated predictor parameters associated with independent variables X (the observed effect), and ε is the error in the prediction (the unobserved effect). This model is for demonstration purposes—not all decision models take this form, and not all are modeled as linear and the predictor parameters can be either deterministic or stochastic. Typically, when decisions are modeled, the decision model is estimated for data from a group of subjects, Π, with individual subjects $\pi_1, \pi_2, \dots \pi_n$. Later, we will discuss two groups of subjects Π and Ξ.

The framework discussed below takes an inclusive view of the sometimes-nebulously-used term decision context, D. Every aspect of a subject's being at the time of decision is defined as part of the decision context *except* for the (almost) universally human ability to physically select one option over another. Even the manner in which this physical selection occurs is part of D. Every experience and thought the subject has ever had is assumed to be part of the decision context. The independent variable(s), X, are always based on the observed portion of decision context, D_o, such that $X(D_o)$. Observed decision context via the independent variables is thought to have a non-random impact on the dependent variable Y. It may also influence the decision in a random manner, and thus is also included in the error term ε. From the broad definition of decision context, it follows that most of a decision's context is thought to either not affect the decision outcome or have a random affect on the decision outcome. This portion of decision context is termed *unobserved decision context*, D_u. This term includes context that does not impact the decision because when this model is applied at the group level, there are some elements of context that will have random effects for some people and no effects for others. When a decision Y is modeled based on X, the predictor parameters G

and the error term ε are estimated using a statistical approach such that they best predict Y for a group of subjects. Construction of preference must be involved in estimation of G and ε because every choice that is not entirely random involves a preference for one choice outcome over the other(s). Therefore, we know that G and ε are estimated in the presence of decision context D, thus context is included as a superscript, G^D and ε^D, to indicate the influence of decision context and construction of preference on the estimation of the model's predictor parameters and error term. With decision context in consideration, Equation (4.1) becomes:

$$Y = X(D_o) \cdot G^D + \varepsilon^D \tag{4.4}$$

$$D = D_{\text{o}} \cup D_{\text{u}} \tag{4.5}$$

Typically, inconsistent construction of preference across subjects is estimated in the error term of the decision model as a random variable and a result of unobserved decision context, thus it is assumed that predictor parameters G are isolated from the effects of unobserved decisions context D_u.

$$Y = X(D_o) \cdot G^{D_o} + \varepsilon^D \tag{4.6}$$

This approach to modeling construction of preference accounts for *random preference inconsistency*. Any decision maker can be exposed to a number of mitigating context-dependent circumstances during decision making, such as their mood or the time available to make the decision. These circumstances are modeled as randomly affecting decision outcome, and are considered part of the unobserved context of the decision.

Random preference inconsistency, the inconsistency due to context found in the error term, "draws the box" around the experimental portion of decision context. The portion of context found inside the box is assumed to be accounted for in the predictor parameters of the experimental model; in this case, $G^{D_{\text{o}}}$. Any part of context outside of the box is assumed to be unobserved and typically represented by a random variable. However, there may be a portion unobserved context, D_u , affecting the dependent variable(s) Y in a non-random manner.

Below is a specific example in which estimation of G is influenced by a portion of unobserved decision context:

$$D = (d_1, d_2, d_3, d_4, d_5\ \ldots) \tag{4.7}$$

$$D_o = (d_1, d_2) \tag{4.8}$$

$$D_u = (d_3, d_4, d_5\ \ldots) \tag{4.9}$$

$$Y = X(d_1, d_2) \cdot G^{d_1, d_2, d_3} + \varepsilon^D \tag{4.10}$$

If a decision model repeatedly fails to accurately predict choice outcome, then it has failed to capture all non-random elements of the decision in the independent variables X. Therefore, some portion of the unobserved context must be incorporated into the observed portion of the model. In Equation (4.10) in the example above, this portion of context is d_3. It is this premise that supports the work of psychologists and economists in invalidating many typical assumptions of decision models, such as rationality, invariance, and independence of irrelevant alternatives. Experimenters create two or more decisions that are described differently but have an identical underlying framework in terms of the decision model. Because the underlying frameworks are identical, choice outcomes should be exactly identical in both decisions. When they are not, the experimenters can conclude that there is component of the decision context that should be incorporated into the observed decision context associated with the predictor parameters in the model.

Here, this is termed a *non-random preference inconsistency.* To tease out the formal manner of incorporation into the non-random portion of the model, the experimenters perform manipulations on the decision framework components in question to see how changing them changes the final decision. This approach is quite efficient for identifying important portions of decision context that would be difficult to identify otherwise. For example, in Equation (4.10), assume that the amount of time that someone has to consider the decision before making their choice is d_3. Instead of trying to measure the effect of time on survey answers by recording survey completion time as an independent variable, a researcher can dictate a variety of interaction times to different groups, (d_3', d_3'', d_3''') and evaluate the effect on Y. This approach is termed a *context manipulation,* and here context manipulation is indicated as a superscript; d_3' implies $D': D' = (d_1, d_2, d_3', d_4, d_5 \ \ldots)$.

If enough information is learned about the context manipulation such that its effect on the dependent variable(s) can be estimated, it can be considered as observed decision context and incorporated into the non-random portion of the model, perhaps along with the addition of another parameter or parameters:

$$Y = X(d_1, d_2) \cdot G^{d_1, d_2} + Z(d_3) \cdot R^{d_3} + \varepsilon^D \tag{4.11}$$

In his literature review of the construction of preferences, Slovic references many preference inconsistency experiments, some of which have associated model improvements, and some of which do not (Slovic 1995). A famous example of a model improvement resulting from preference inconsistency tests is prospect theory (Kahneman, Tversky 1979). Kahneman and Tversky performed a number of preference inconsistency choice experiments, such as:

Decision context 1: gain \$5000, probability 0.001 *versus* gain \$5

Decision context 2: lose \$5000, probability = 0.001 *versus* lose \$5

where context manipulation was framing the decision as a gain or a loss. Previous economic models predicted that subjects would choose the same option, regardless of the manipulation. Kahneman and Tversky not only demonstrated that the loss/gain context manipulation made a dramatic difference in the option people selected, but were also able to manipulate context to predict the shape of a "value" function, as shown in Figure 4.1, which differed from the original model for decisions framed as losses (shown as red vs. blue), but the same for gains (shown as purple). Contingent weighting (Tversky, Satan & Slovic 1988) is another example of using context manipulation to generate a more-detailed model of a decision.

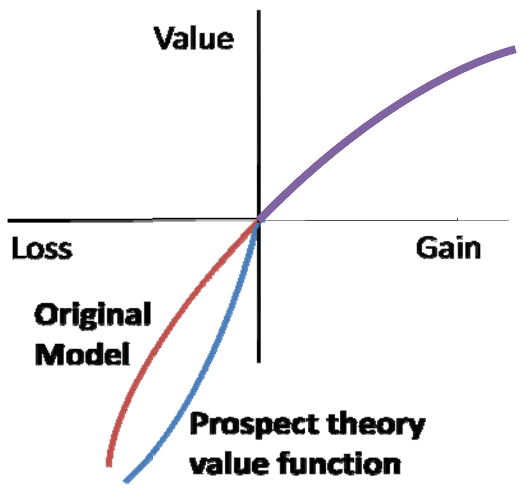


Figure 4.1 Kahneman and Tversky used preference inconsistency tests to develop a new value function model.

Note that the context manipulation could have a non-random, estimable effect on the model without necessarily adding an independent variable and/or predictor parameter. It could have a parametric effect on the size of the error term and predict the amount of variance in the subjects' choices.

$$Y = X(d_1, d_2) \cdot G^{d_1, d_2} + R^{d_3} \cdot \varepsilon^D \quad (4.12)$$

Experiments in the literature that attempt to point out the inadequacies of existing decision models use the concept of context manipulation to do so; they vary some portion of the decision context in order to invalidate the predictability of the model or a set of models.

Psychologists and marketers sometimes call a non-random preference inconsistency due to context manipulation a "context effect" (Kagel, Roth 1995, Sudman, Bradburn & Schwarz 1996). *A well-constructed context effect experiment can show what specifically about the context manipulation invalidates the model. A truly insightful experiment incorporates the context manipulation into the non-random portion of the model, adding to or correcting the model's predictive power.* The experiment(s) may test context manipulation through different approaches. Three approaches that are commonly used are termed c*omparative, external,* and *internal*. All three approaches use multiple subjects to prove that a portion of decision context thought to have no or a random effect on decision outcome impacts the outcome predictably. The three types of experimental constructs can also point out inconsistencies in people's decisions without a formal decision model structure, but here they are presented in terms of a decision model. The experiment uses two or more different configurations of decision context to test for preference inconsistency. A manipulation is performed on a portion of decision context that should have a random effect and therefore be included in the error term. This manipulation is not part of D_o. The experiment wishes to find that the manipulation, (D', D''), affects the estimated predictor parameters in the model. A preference inconsistency due to a context effect is said to occur when:

$$X(D_o) \cdot G^{D'} + \varepsilon^{D'} \neq X(D_o) \cdot G^{D''} + \varepsilon^{D''} \tag{4.13}$$

because

$$G^{D'} \neq G^{D''} \tag{4.14}$$

In order to perform the experimental test of the decision, one of three experimental designs is chosen corresponding to *comparative, external, and internal non-random preference inconsistency tests*. In the comparative preference inconsistency test, two sets of subjects form the basis for the two sides of Equation (4.14), subject groups Π and Ξ, and thus the typical between-subjects testing assumptions are made. Each subject π in the group Π has some elements of D that are same as others in the group, such as the description of the choices. Also, some elements of D are different amongst subjects, such as their ages or their level of hunger when they participate in the experiment. The subjects Π decision contexts' are termed D_Π. In the comparative test, two groups of subjects' decision contexts are purposefully manipulated so that some portion of D differs between the groups, for example, the description of the decision choices as losses or gains.

$$X_\Pi(D_{o,\Pi}) \cdot G^{D'_\Pi} + \varepsilon^{D'_\Pi} \neq X_\Xi(D_{o,\Xi}) \cdot G^{D''_\Xi} + \varepsilon^{D''_\Xi} \quad (4.15)$$

If it is an exceptional experiment, the researchers will be able to incorporate the context manipulation into one or more additional parameter(s) in the model, following, for example, Equations (4.11) or (4.12), thus learning more about how decision context influences the decision at hand.

Comparative preference inconsistency experiments have a carefully designed context manipulation such that the versions of the manipulation represent seemingly equivalent decisions; for instance, they are equivalent mathematically as the loss/gain manipulation mentioned previously. Either the decision or choice phrasing may change, or both. Various statistical tests such as ANOVA can be used to test the significance of the effects of the context manipulation.

Preference inconsistencies can also be tested using a within-subjects experimental design. In this case, the experiment wishes to find:

$$X_\Pi(D_{o,\Pi}) \cdot G^{D'_\Pi} + \varepsilon^{D'_\Pi} \neq X_\Pi(D_{o,\Pi}) \cdot G^{D''_\Pi} + \varepsilon^{D''_\Pi} \quad (4.16)$$

dropping the Π subscript because the subjects are the same:

$$\mathrm{X}(D_o) \cdot G^{D'} + \varepsilon^{D'} \neq X(D_o) \cdot G^{D''} + \varepsilon^{D''} \quad (4.17)$$

There are different ways to manipulate decision context in Equation (4.17). Two common approaches in the literature are given particular names here, so that designers can easily identify, use, and discuss them. In one of the approaches, termed an *external* inconsistency test, the context manipulation is deciding in an experimental framework *versus* deciding in the real world. Preference elicited in an experiment is sometimes referred to as stated preference, and real-world preference is sometimes referred to as revealed preference. The concept of context manipulation in comparing a real-world decision context to an experimental decision context is akin to the concept of ecological validity from behavioral psychology, which assesses the differences between conditions in a psychology experiment and real-world conditions and asks if these differences could influence the important findings of the experiment (Bem 1979).

Another frequently encountered realization of Equation (4.17), termed an *internal* inconsistency test, manipulates decision context in two (or more) different fashions in decision instances within the same survey instrument. It requires careful planning to implement an internal inconsistency experiment successfully. Consider a simple internal test, such as asking the same subjects a mathematically identical question in two different phrasings, one after the other. Subjects may suspect the intention of the experiment, which will affect results. Subjects' responses to one decision may bias their choices in others. The experiment must be designed carefully (for example, it may use distraction tasks) in order to minimize unwanted effects.

A comparative preference inconsistency test is frequently easier to implement in experimentation than external or internal tests, because it does not require careful avoidance of the effects mentioned above or the monitoring of real-world decisions. However, between-subject tests face the problem of mistaking preference heterogeneity for preference inconsistency because the inconsistency cannot be corroborated at the individual level. This inadequacy is extensively examined by Hutchinson et al. (Hutchinson, Wagner & Lynch 2000) and also discussed below in Section 4.2. Without the ability to compare subjects' responses in the two conditions directly on a case-by-case basis, researchers can never know if the conclusions they draw hold at the individual level, but they may use demographic or other information to draw inferences about similar groups of subjects, informing them on the nature of the context effect. External and internal preference inconsistency tests can test at the individual subject level for inconsistency because the experiment's subjects make decisions under the decision context manipulations. There is no set rule as to how many individuals must experience the inconsistency to validate the group-level finding.

The weakness of the external consistency test is that there is typically little to no knowledge of the specific differences between decision choices elicited during the experiment and those revealed in real-world decisions. Although any preference inconsistency discovered at the group level can be checked at the individual level, the researcher may never be able to specify why the preference inconsistencies exist between the two situations or may find misleading explanations. The internal preference inconsistency test is the strongest of the three because the context manipulation is known and specific, and preference inconsistency can be verified at the individual subject level.

4.2. Heterogeneity

It is a potentially large assumption to think that preferences can be estimated at the group level. When this assumption is relaxed to allow for individual or group differences in preferences, decision models typically show a much better fit to the data, as expected because the model will include more parameters. This is called allowing for heterogeneity, and it has been addressed in many different forms in decision models, in two broad categories (that can also be used in combination): discrete heterogeneity, in which groups of individuals have different preferences; and continuous heterogeneity, in which each individual has different preferences (Train 2003). A basic decision model of the type described in Equation (4.1) already has some continuous heterogeneity included in the random variable error term, which typically takes a distribution such as a normal distribution. It may also already have some discrete heterogeneity incorporated, such as allowing for individual differences by linking specific parameters to specific demographic characteristics of the subject pool—in other words, identifying demographic information as part of observed decision context.

Instead of estimating heterogeneity through pre-defined demographic information, it can be estimated as a set of parameters in the decision model. This can be accomplished using discrete heterogeneity, continuous heterogeneity, or a combination of the two. With continuous heterogeneity, some or all estimated model parameters are represented by a random variable, such as one with a normal distribution. With "latent class" discrete heterogeneity, the modeler assumes that there are different estimated parameters for different groups of subjects, but the subjects in each group are not predetermined. Instead, the "subject classification probability" of being a member of each group is estimated in the model at the individual-subject level. With a combination of discrete and continuous heterogeneity, the group-level parameters each take a distribution, with each subject having a probability of belonging to that group.

Hutchinson et al. (Hutchinson, Wagner & Lynch 2000) use discrete heterogeneity to question the findings of important internal preference inconsistency tests. Their main demonstration piece is an investigation of an internal inconsistency test of the compromise effect, a test that was created to invalidate the assumption of independence of irrelevant alternatives. They show that introducing heterogeneity into the model could explain the previous findings without preference inconsistencies. Applying their approach to our demonstration model, it may be possible to find:

$$\mathrm{X}(D_o) \cdot G^{D'} + \varepsilon^{D'} \neq X(D_o) \cdot G^{D''} + \varepsilon^{D''} \tag{4.18}$$

without finding preference inconsistency. For example, using discrete heterogeneity in the model, a researcher may to identify two subgroups, Π and Ξ such that:

$$X_\Pi(D_{o,\Pi}) \cdot G^{D'_\Pi} + \varepsilon^{D'_\Pi} = X_\Pi(D_{o,\Pi}) \cdot G^{D''_\Pi} + \varepsilon^{D''_\Pi} \tag{4.19}$$

$$X_\Xi(D_{o,\Xi}) \cdot G^{D'_\Xi} + \varepsilon^{D'_\Xi} = X_\Xi(D_{o,\Xi}) \cdot G^{D''_\Xi} + \varepsilon^{D''_\Xi} \tag{4.20}$$

thus finding no preference inconsistency at the subgroup level.

The finding of consistent preferences for the two (or more) subgroups can occur for one of two reasons:

(1) The context manipulation has no effect on the non-random portion of the split model, and thus remains in the error term. This may occur due to statistical analysis reasons.
(2) The context manipulation has different effects for the two subgroups, and these effects cause what looks like a preference inconsistency at the group level, but cause no violations at the subgroup level. The context manipulation should be incorporated into the non-random portion of the model in a different way for each of the two subgroups.

Consider KermitCo: if a researcher came to them having found that two groups reacted differently to a change in the decision phrasing regarding an environmental towel purchase, as in the example above, the designers would be interested to learn more—in particular, *why* this happened. Unless the researcher can examine groups Π and Ξ to determine a cause for the difference in preference based on context manipulation, the information can only inform design decisions as a market estimation tool; it will not give designers a better understanding of their customers in any deep sense. What was said for preference inconsistency experiments can be said as well for alternate explanations through the modeling of heterogeneity: a somewhat fruitful heterogeneity investigation can show that groups react differently to a context manipulation, providing a better fit to collected data; a more thoroughly effective heterogeneity investigation will indicate why the reaction is different for the two groups and potentially lead to the formation of a better model with added parameters to address the effects of the context manipulation (and any related context change).

Note that the presence of heterogeneity does not necessarily predicate the elimination of all preference inconsistencies. Identifying subgroups may be an efficient way to determine the reason that the context manipulation causes inconsistencies in the model's predictions. An investigation of heterogeneity may reveal that:

$$X_\Pi\left(D_{o,\Pi}\right) \cdot G^{D'_\Pi} + \varepsilon^{D'_\Pi} = X_\Pi\left(D_{o,\Pi}\right) \cdot G^{D''_\Pi} + \varepsilon^{D''_\Pi} \tag{4.21}$$

$$X_\Xi\left(D_{o,\Xi}\right) \cdot G^{D'_\Xi} + \varepsilon^{D'_\Xi} \neq X_\Xi\left(D_{o,\Xi}\right) \cdot G^{D''_\Xi} + \varepsilon^{D''_\Xi} \tag{4.22}$$

as in the findings below.

4.3. Practical application of preference heterogeneity and inconsistencies

When designers investigate preference inconsistency and/or heterogeneity, the goal is to determine it exists in response to decision context manipulation, and how to incorporate it into a model of product decisions: specifically, preference for one product over another. While psychologists and economists debate the theoretical implications of incorporating the effects of context manipulation as heterogeneity versus inconsistency, designers must concern themselves with practicalities. In general, we seek incorporation into the model that allows us to learn the most about our customers' relationship with the product. In the following case study of KermitCo's customer base, we explore two different instances of context manipulations for recycled paper content preference within the customer survey described in Section 3.3: (1) homogeneity versus heterogeneity in explaining model data (survey Part 2) and (2) discrete choice *and* willingness to pay versus market behavior, as an external preference inconsistency test (Parts 2 and 5 vs. Part 4).

4.3.1. Homogeneous and heterogeneous multinomial logit models of survey Part 2

Two multinomial logit models of product utility were fit to the multiple choice responses of survey Part 2, described in Section 3.3. 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). In terms of the discussion above, the product descriptions and their prices in the survey (the choices) as described in Table 3.2 and shown in Figure 3.1 and Figure 3.2 represent the observed portion of decision context in the decisions that survey respondents make.

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

$$U_j = v_j + \varepsilon_j \tag{4.23}$$

To estimate v_j, we 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 (Louviere, Hensher & Swait 2000). 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 modeled so that it receives the highest utility, described in Equation (4.24) as the probability that product j has the highest utility U_j of all available products.

$$P_j = \mathrm{P}\left[U_j > U_{j'} \text{for all } j' \neq j\right] \tag{4.24}$$

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 (4.25) 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; for example, the product attribute "color" can only be configured as red or green, not both. Each attribute/level combination has its own discrete utility or "partworth," signified as $\beta_{\zeta\omega}$. Summing the part-worths of a particular product j gives the measurable portion of utility. In Equation (4.25), $x_{j\zeta\omega}$ 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 (4.26) (Louviere, Hensher & Swait 2000).

$$v_j = \sum_{\zeta}\sum_{\omega}\beta_{\zeta\omega}x_{j\zeta\omega} \tag{4.25}$$

$$P_j = \frac{e^{v_j}}{\sum_{j'} e^{v_{j'}}} \tag{4.26}$$

In terms of decision context, it is assumed that only the observed portion of context impacts the estimated part-worths, and the unobserved portion is assumed to impact only the variance of the part-worths (not shown).

$$v_j^{D_o} = \sum_{\zeta}\sum_{\omega}\beta_{\zeta\omega}x_{j\zeta\omega}(D_o) \tag{4.27}$$

Equation (4.26) is reached by assuming homogeneous preferences across respondents. Note the lack of an error term in the equation. In this author's interpretation, the assumption coupled with the lack of an error term is equivalent to saying that everyone has exactly the same decision context, and that any deviation from this assumption is captured in the variation of the estimated part-worths. A latent class model relaxes this assumption to account for latent class heterogeneity, in which groups of survey respondents have homogeneous preferences. Let L equal the number of latent classes, l. Each $\beta_{\zeta\omega}$ can now take L different values, one for each latent class, with probability g_l that $\beta_{\zeta\omega} = \beta_{\zeta\omega l}$ (Train 2003). The model estimates the probability of each survey respondent n choosing product j:

$$P_{nj} = \sum_{l=1}^{L} g_{nl} \left(\frac{e^{\boldsymbol{\beta}_{\zeta\omega l} \boldsymbol{x}_{j\zeta\omega}}}{\sum_{j'} e^{\boldsymbol{\beta}_{\zeta\omega l} \boldsymbol{x}_{j'\zeta\omega}}} \right) \tag{4.28}$$

In discussing the results of a latent class analysis, researchers typically assign respondents to the class to which they have the highest probability of belonging.

A homogeneous multinomial model and a latent class multinomial mixture model were fit to the data from survey Part 2. The fixed questions were not included in the analysis. The multinomial model results are reported in Table 4.1, and shown graphically in Figure 4.2. In the figure, part-worths that will later be modeled as continuous variables in Chapter 6, recycled paper content and price, are shown with lines connecting the estimated data points. Those that will be modeled as discrete parameters are shown as discrete points. Price is the most influential factor in choice, and the lowest price point, $1.29, is the most preferred.

Table 4.1 Estimated part-worths for homogeneous mnl model of survey Part 2.

Attribute (ζ)	**Level (ω)**	**Level in Figures**	**Part-worth ($\boldsymbol{\beta}_{\zeta\omega}$)**	**St. Err**
Softness	1:3	1	-0.34	0.061
	2:3	2	0.14	0.057
	3:3	3	0.20	0.056
Strength	1:3	1	-0.62	0.066
	2:3	2	0.19	0.057
	3:3	3	0.42	0.057
Absorbency	1:3	1	-0.78	0.069
	2:3	2	0.24	0.058
	3:3	3	0.54	0.056
RPC	0%	1	-0.50	0.083
	30%	2	0.02	0.075
	60%	3	0.17	0.073
	100%	4	0.32	0.073
Price	$1.29	1	0.82	0.073
	$2.39	2	0.50	0.072
	$3.49	3	-0.06	0.075
	$4.59	4	-1.26	0.104

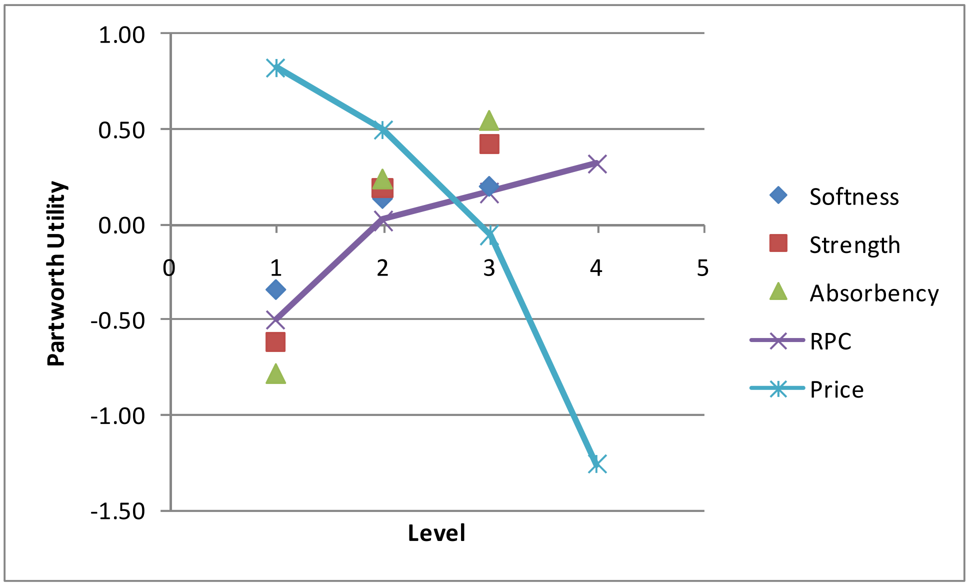


Figure 4.2 Estimated part-worths for homogeneous mnl model of survey Part 2.

Table 4.2 Responses to fixed questions in survey Part 2 indicate potential heterogeneity in preference for price and recycled paper content.

Fixed Question 1		
Choice A	Choice B	Choice C
Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 100% Recycled Paper Content $4.59	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 60% Recycled Paper Content $3.49	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 0% Recycled Paper Content $2.39
30 respondents (14%)	67 respondents (31%)	120 respondents (55%)
Fixed Question 2		
Choice A	Choice B	Choice C
Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 0% Recycled Paper Content $4.59	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 60% Recycled Paper Content $3.49	Softness: 2 out of 3 Strength: 2 out of 3 Absorbency: 2 out of 3 100% Recycled Paper Content $2.39
6 respondents (3%)	21 respondents (10)%	190 respondents (88%)

The fixed questions from survey Part 2 indicate there may be reason to estimate a heterogeneous model. Fixed question 1 is configured such that the most expensive towel has 100% recycled paper content, and the least expensive has 0% recycled paper content. Fixed question 2 is configured in the opposite manner. Comparing the number of respondents that chose each selection for these two questions in Table 4.2 above, it seems that some respondents do not trade off recycled paper content and price, as the homogenous model would suggest, as they pick the lowest price towel regardless of recycled paper content. Other respondents are willing to pay a price premium for recycled paper content.

Noting this potential difference in preference, a latent class model was also fit to the data. Models with 2 to 8 latent classes were explored. A class structure of 3 groups will be described here, as it provided the best-fitting model. To determine which model was best, the Consistent Akaike Information Criterion (CAIC) was compared between models, with groups of 2 and 3 providing the lowest (and thus best) CAIC values (Sawtooth Software 2004). Although the 3-group model had a slightly higher (1529.56) CAIC than the 2-group model (1484.54), we selected the 3-group model because: (i) the idealist group fell out statistically, as we had predicted, (ii) the pooled standard error on the parameter estimates was lower in the 3-group model than the 2-group one, and (iii) the 3-group model "added" a large third group that was highly sensitive to absorbency measures, thus providing additional explanatory value to the model. As Sawtooth recommends for selecting the best model, "[w]hen choosing among solutions, one also has access to other information, such as their patterns of utilities and estimated group sizes" (Sawtooth Software 2004).

Table 4.3 Estimated part-worths and pooled standard errors for latent class multinomial logit model of survey Part 2 with three classes.

Attribute (ζ)	**Level** (ω)	**Level in Figures**	**PickUps n = 45 Part-worth** ($\beta_{\zeta\omega l}$)	**Traders n = 120 Part-worth** ($\beta_{\zeta\omega l}$)	**Savers n =52 Part-worth** ($\beta_{\zeta\omega l}$)	**Pooled St. Err**
Softness	1:3	1	-1.19	-0.40	-0.26	0.18
	2:3	2	1.67	0.04	0.05	0.19
	3:3	3	-0.48	0.36	0.21	0.19
Strength	1:3	1	-3.31	-0.59	-0.62	0.21
	2:3	2	2.44	0.07	-0.36	0.20
	3:3	3	0.87	0.52	0.97	0.22
Absorbency	1:3	1	-10.69	-0.63	-0.65	0.20
	2:3	2	5.34	0.03	0.21	0.20
	3:3	3	5.35	0.60	0.45	0.19
RPC	0%	1	-0.58	-1.10	1.18	0.28
	30%	2	0.47	0.14	-0.60	0.27
	60%	3	-0.81	0.46	-0.22	0.24
	100%	4	0.92	0.50	-0.36	0.26
Price	$1.29	1	0.89	0.55	5.16	11.78
	$2.39	2	2.36	0.39	3.49	11.78
	$3.49	3	0.65	0.13	0.79	11.78
	$4.59	4	-3.90	-1.07	-9.44	35.33

The estimated part-worth utilities for attribute levels are reported in Table 4.3 and shown in Figure 4.3, where the graphs have been visually normalized to compare the groups. This normalization is legitimate, as utility comparisons on a numerical scale can only be made within groups, not between groups. For example, a price of $4.59 has a utility of -1.07 to the traders and -9.44 to the price-driven group. This does not mean that the traders get 8.37 more utility out of a $4.59 price than the price-driven group does. It can be concluded, though, that all three groups prefer a price of $3.49 to $4.59, as $3.49 has a higher utility in all groups. Due to formulation of the latent class model, only pooled standard error can be reported, and this is not comparable to the standard error reported for the homogenous model as reported in Table 4.1. It is suspected that the pooled standard error on the attribute Price is so large because respondents in some latent classes did not choose the high price options in the survey. Figure 4.3 clearly illustrates a group of survey respondents, termed the “Traders” (120 respondents), who value recycled paper content as much as price in their decisions, and trade off all attributes in their decisions; and another group, the "Savers" (52 respondents), who choose almost solely based on price considerations. The third group, the "PickUps" (45 respondents), choose mainly according to absorbency level.

The Traders exhibit a compensatory decision structure in which they make trade-offs in their decisions among levels of all attributes; thus there is more variance in this group’s estimated parameters, and the scale their part-worths is smaller. Note that price and recycled paper content are both most important features for this group, with a price of $4.59 and 0% recycled paper content both strongly disliked.

Because the heterogeneous model introduces information that is useful to towel designers, it tentatively seems like the better choice of model when pursuing new towel designs. However, with either estimation, there is a problem for KermitCo's designers. Both models indicate a preference for recycled paper content in towels in at least the majority of survey respondents. In the current paper towel market, only a tiny percentage of towels sold have recycled paper content, a percentage so small that the towels fall into the "other" category in Table 3.1. The predictive power of both models is clearly limited in terms of predicting what people currently purchase. This presents an important distinction between using marketing models for design work and marketing work. Marketers need their preference models to be accurate at predicting market behavior. However, knowing of the phenomenon of construction

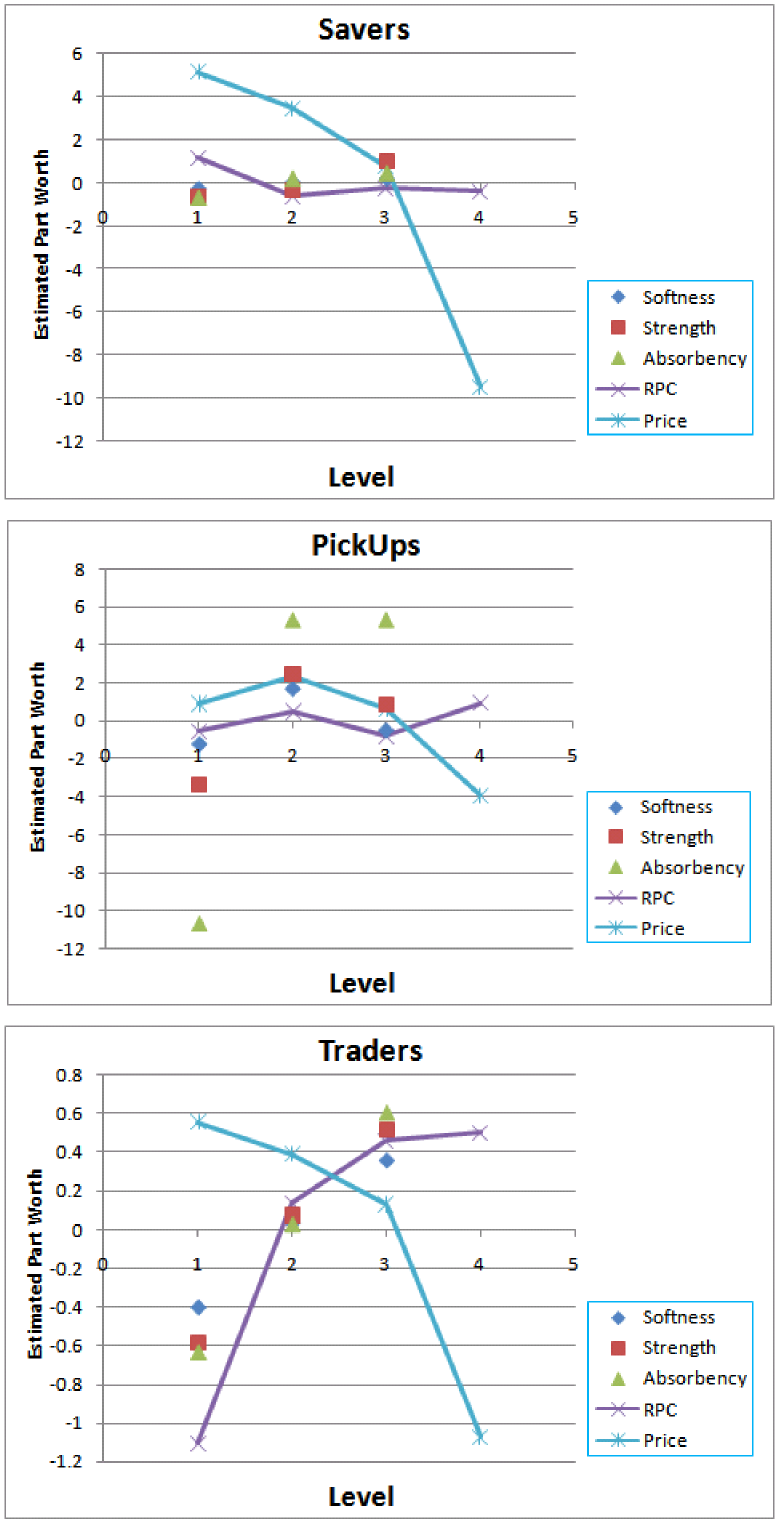


Figure 4.3 Latent class part-worth estimations for Savers (52 respondents), Traders (120 respondents), and PickUps (45 respondents) groups.

of preferences, designers can choose to look at this data and see not inaccuracy but instead design opportunity. If people can construct preferences in one manner while answering a survey, it is not beyond the realm of possibility that the construction could be similar at the point of purchase, even though that is currently not the case. In the heterogeneous model, it seems that only one latent class, the Traders, exhibits this inaccuracy in recycled paper content preference. In the next section, we learn more about this group using two external preference inconsistency tests. We learn that the respondents classified as Traders have the most potential to change to green consumers, perhaps using some of the approaches suggested in Chapter 2.

4.3.2. Discrete choice and buy/not buy versus market behavior: an external preference inconsistency

The Buy/Not Buy questions in survey Part 5 first described a towel product, and then asked respondents if they would purchase the towel. If a respondent replied that they would purchase the product, they were asked to state how much they would pay. If they would not purchase the product, they were asked to explain why. Descriptions of the three towel products described and responses are reported in Table 4.4. Scenario 2 asks what price respondents would pay for a paper towel with average strength, softness, and absorbency, and 0% recycled paper content. Sixty out of 217 users stated that they would not buy the towel due to lack of recycled paper content and/or concerns for the environment.

Table 4.4 Description of buy/not buy scenario.

N = 217	**Scenario 1**	**Scenario 2**	**Scenario 3**
	Quilted Not Patterned 100% RPC 2 rolls w/ 75 sheets per roll Softness: 3 out of 3 Absorbency: 3 out of 3 Strength: 3 out of 3	Quilted Patterned 0% RPC 2 rolls w/ 75 sheets per roll Softness: 2 out of 3 Absorbency: 2 out of 3 Strength: 2 out of 3	Quilted Not Patterned 60% RPC 2 rolls w/ 75 sheets per roll Softness: 2 out of 3 Absorbency: 2 out of 3 Strength: 2 out of 3
Would Buy	196	129	186
Average Purchase Price	$2.29	$1.95	$2.05
Variance	0.77	0.78	0.71
Would not Purchase	21	88	31
Top reason for not purchase (# of Responses)	No pattern (4)	No recycled content/ environment (60)	No pattern (7)

An external preference inconsistency is identified through analyzing the "revealed preference," or past purchase, data for these respondents collected in survey Part 4, and reported at a high level in Section 3.4. Fifty-two out of 60 of these respondents reported buying a towel brand that has 0% recycled paper content the last time they went shopping. This external preference inconsistency can be partially explained by the fact that only three of the 52 users gave a correct rating of 0% recycled paper content for their brand of towel in survey Part 3. We term these 52 users Idealists, as they are both idealistic in their own preferences and the configurations of the products they purchase. Note that, as a whole, all respondents did a poor job of correctly identifying the recycled paper content of the towels, as described in 6.

Returning to the latent class model estimated in Section 4.3.1, one would guess that the Idealists, a group of respondents that find recycled paper content very important in survey Part 5, may also find it important in other parts of the survey, such as survey Part 2, which provided the data for the latent class model. Subjects were assigned to the latent classification to which they had the highest probability of belonging according to the model estimation described in Section 4.3.1. Forty-eight of the 52 idealists were classified as Traders, comprising 31% of the total group. The heterogeneous model has provided a solid advantage over the homogeneous model: it has isolated a preference inconsistency to only one portion of the model. A thorough analysis of preferences for the Savers and PickUps with other information collected from the members of these groups indicated no worrisome preference inconsistencies for these groups.

4.4. Discussion of results

From investigating the other survey answers of the Traders and Idealists, we learn that they are either uneducated as to the recycled paper content of the towels they currently use, or in denial of their recycled paper content within the confines of the survey, due perhaps to a resolution of cognitive dissonance, as discussed in Section 2.3. Social desirability bias, in which a survey respondent answers a survey in a manner deemed socially acceptable, may also be a factor (Bennett, Blamey 2001). It is also possible that the preference inconsistency between stated and revealed preferences is due to the availability of brands containing recycled paper content at the Idealists' usual point of purchase. But this explanation cannot account for the more troubling inconsistency of the Idealists’ lack of knowledge regarding the recycled paper content of the towels they previously purchased. If recycled paper content is actually an important attribute in the Idealists' purchase decisions, Idealists should know that the towels they last purchased contain 0% recycled paper content.

Whatever the reason for the misinformation, the external inconsistency represents a large market share opportunity for eco-friendly paper towels with the "activation" of the stated preferences of the idealists, possibly accomplished by educating them as to the recycled paper content of the towels they currently buy and of eco-friendly alternatives. If a survey can make Idealists prefer recycled paper content, then it must be possible for other decision contexts to produce similar results. In terms of the case study, if the 60 out of 217 respondents that declined to buy a towel because it had no recycled paper content could be encouraged to exhibit this preference structure in their marketplace decisions, KermitCo could potentially stand to take a large portion of the towel market with a well-positioned green paper towel.

The Idealists' preferences could be pseudo-sacred. Thompson and Gonzalez (Thompson, Gonzalez 1997) speak about pseudo-sacred values in terms of environmental dispute negotiations, but the logic can be applied more broadly to other types of values and preferences. In terms of purchase decisions, some people may have a value for decreasing waste through the recycling of materials as sacred. For these people, this value would prohibit, for example, the purchase of paper towels without any recycled paper content. In some purchase contexts, however, these people may trade off this sacred value—for example, in situations where they cannot tell the recycled content of the towels available for purchase, or when shopping in a market that does not offer towels with recycled paper content. Thompson and Gonzalez mention that depending on the interaction, a value can be either sacred or pseudo-sacred. When the value is viewed as sacred by an individual, their behaviors conform to the value. When the value is pseudo-sacred, this value can be negotiated and therefore may be unrepresented in the behavior (Thompson, Gonzalez 1997).

The Idealists' responses to Scenario 2 in survey Part 5 indicate that they would not consider purchasing a towel with no recycled paper content *at any price of their choosing*, but they trade off this belief in their own purchases and are not educated about the attribute's configuration in the product they last purchased. This is the true challenge of eco-design: to design product that can educate the customer about its own configuration of attributes while *also* informing the customer about the competitions' attribute configurations. These survey results suggest that it is not enough for a design to communicate "our product is green"; the design must also inoffensively communicate "and the product you currently buy is not green."

Thinking back to the consequences of cognitive dissonance described in Section 2.3, this is a precarious position for a company to take. An assertion of this type may cause in a change in attitude towards the environment, a decreased willingness to pay to support those attitudes in product purchases, a feeling of general mistrust of company claims, or any variety of responses.

In our latent class model, we found three groups of consumers with different preferences. When respondents are classified by their estimated latent class probabilities, 55% of respondents traded off price, strength, softness, and absorbency with recycled paper content. We identified 58 respondents (28%) that held a pseudo-sacred value for the environment, and only 2 respondents (1%) that actually made environmentally-driven product choices.

Preference inconsistencies for eco-friendly product attributes can be addressed proactively in design by, for example, including design details to “activate” consumers to construct a set of preferences that lead to a large market share shift. Preference inconsistency can also be addressed reactively, by designing an eco-friendly paper towel that is preferred in the market over a variety of preference constructions. A new methodology for proactive and reactive incorporation of an inconsistent preference model in a design optimization framework is introduced in Chapter 6.

The case study highlights a potential disadvantage of solely using revealed (previous purchase activity) preference data to assess preference for products that are similar to existing products, but cannot yet be purchased in a particular configuration or have attributes that are unfamiliar to the survey respondents (such as a towel with 60% recycled paper content). While such data can be helpful for identifying potential preference trade-offs and testing for preference inconsistencies, they can create unnecessary limitations on design possibilities when evaluated in isolation. For instance, in this study, assessing only revealed preferences for towels would have neither distinguished three different types of paper towel users nor indicated the potential for market share change.

4.5. Conclusions

Preference inconsistency cannot be neglected by designers because it is the purpose of good design to guide and inform preferences. Perhaps in the past, the purpose of design was simply to satisfy functional needs through the creation of a product. Now, in the design lexicon, the word "need" has outstretched its usual definition. When designers speak of customer needs, they mention in the same breath customer delight and paradigm shifting. Designers focus as well on satisfying "latent needs," product attributes (or products) that the customer never even knew they needed. This represents a manipulation in decision context accompanied by a shift in preference structure.

This chapter offers a framework for understanding preference inconsistency experiments as they exist in the current literature, and it discusses the potential limitations of different experimental approaches. The framework includes classifications of *random* and three types of *non-random* preference inconsistency: *comparative, external*, and *internal*. In random preference inconsistency, a person may construct preferences with dependence on, for example, mood or amount of time available to interact with the preference elicitation tool. In non-random inconsistency, a group of users is inconsistent in their preferences in a similar, overt manner. The framework serves to help design researchers integrate the construction of preference into engineering design. It is here asserted that internal preference inconsistency tests, which manipulate a portion of decision context within a single decision experiment using one subject group, can provide the most information to designers.

A discussion of heterogeneity, outlined in terms of decision context, details how a preference inconsistency may also be explained by groups of subjects with different preferences. It is also asserted that a truly insightful preference inconsistency experiment, or alternatively, a heterogeneous model, can offer an explanation regarding the relationship between the inconsistency (or heterogeneity) and the context manipulation, and ideally incorporate this explanation into an improved decision model.

To demonstrate these principles, the discussion of heterogeneity and preference inconsistency is here applied to the KermitCo case study, identifying heterogeneity that was confirmed through a separate internal test of preference consistency. The analysis discovers that one group of survey respondents, the group potentially most interested in KermitCo's new green product, is also the only group with noticeably inconsistent preference for recycled paper content. Design strategies that address this inconsistency will be offered in Chapter 6.

Chapter 5. A model of strength, softness and absorbency as a function of recycled paper content in paper towels

Chapter 4 establishes that there may be a market opportunity for a towel with recycled paper content. If KermitCo wishes to secure this market opportunity, they must consider the engineering feasibility of creating green towels that also have satisfactory levels of strength, softness, absorbency; in addition, they may perhaps be able to identify design "triumphs" in which some amount of recycled paper content improves strength, softness, and absorbency. In order to evaluate the engineering feasibility of hypothetical towel designs, KermitCo must create a model that relates the towel's strength, softness, and absorbency to recycled paper content.

This chapter discusses various metrics of strength, softness, and absorbency; reviews the towel manufacture process; and explains the many potential engineering variables that impact final towel properties. Empirical data on the relationship between recycled paper content and strength, softness, and absorbency is used to create the engineering model for the design optimization in Chapter 6. As discussed in Section 3.2, the case study contains the assumption that KermitCo has a set manufacturing configuration in a plant purchased from a competitor, and wishes to vary only the fraction of recycled paper content that enters into their manufacturing process, with some slight adjustments to equipment and chemicals as necessary. This chapter explains why this assumption is necessary. It also explains why the study uses an empirical engineering model of towel properties rather than a theoretical model.

Published towel-recycled-content research is sparse due to fierce competition in the industry. Some of the research included in this chapter, such as research on recycled pulp, centers on paper for printed materials. A wide variety of sources are cited, including dissertations on towel and paper properties, expert opinions, industry association videos, and papers from a variety of fields.

5.1. Towel properties: metrics and measurement devices

A towel is a carefully-controlled tangle of wood fibers, water and various additives. Because a particular towel derives its properties of loft and flexibility from the random and kinked nature of this network, the mechanical properties of a towel are challenging to represent—both empirically and theoretically. Measuring even the most straight-forward of a towel's physical properties, such as caliper (thickness), is not straightforward, in this case due to the sensitivity of the sheet to applied pressure. A number of caliper measurement methods are in use, including one that involves immersing the towel in resin and then letting it harden before attempting to measure thickness and density (Ramasubramanian 2002). In the testing presented later in this chapter, a micrometer measurement procedure was used.

5.1.1. Measuring strength

Strength consists of two components: fiber strength and strength of the bonds between fibers. A basic test of strength is the tensile test. In a towel tensile test, a strip of towel is stretched between two clamps that move slowly apart. The test records the force required to move the clamps apart, and the deflection (length increase) of the towel, as it stretches, begins to fracture (tear), and finally reaches ultimate fracture. It computes a stress/strain curve, which compares force per unit area of the towel to an associated strain: the ratio of the sample length under the applied force to the original sample length. Because the fiber/additive matrix in towel is a composite (as is wood pulp itself), the stress-strain curve exhibits non-traditional properties. In the elastic region of the tensile test, towels recover their original length after being pulled. In the plastic region of the tensile test, where permanent deformation to the towel occurs during pulling, the stress/strain curve is rough, as it is the breaking of inter-fiber bonds that causes ultimate fracture, not the breaking of fibers (Ramasubramanian 2002).

Relatively standard tensile test procedures can be used to measure towel tensile strength (Ramasubramanian 2002). However, towel tensile measurements exhibit unwanted dependency on the gauge (sample) length, clamping procedure, and the direction of pulling. Therefore, like most mechanical tests for towels, achieving a standardized result is challenging. Furthermore, a towel is unlikely to fail in simple tension in use and thus the results of the standard tensile test have limited meaning in evaluating strength. Another measurement of strength is burst strength, where water pressure is applied to the paper that is held in an embroidery-hoop-like brace. The water forms a blister under the towel's surface that grows until it bursts. For a set fiber network configuration in writing paper, burst strength relates to tensile strength/strain to failure by a pulp-specific constant (El-Hosseiny, Anderson 1999). Many towel property tests are similar to fabric tests. A common test of fabric strength is the tear test, where a tear or rip is purposefully induced and propagated through a sample to measure strength. This is the type of test used in the empirical model for both wet and dry tear tests, and it is discussed in detail in Section 5.3.

5.1.2. Softness

Softness is a customer-specific term, and a large number of measurement techniques attempt to emulate the customer's perception of softness. Softness has been linked to measurable properties of "bulk softness" such as compressibility, flexibility, elastic modulus, resiliency (sponginess), density, specific volume, and pliancy, as well as properties of "surface softness" such as texture and friction (Hollmark 1983, Hollmark, Ampulski 2004, Liu 2004, Ray 1965). Terms in this list are not mutually exclusive. The nature of the specific relationships between physical properties and softness remains nebulous, although models do exist (Hollmark 1983, Liu 2004). Several tests exist to measure flexural rigidity and bending modulus, both related to flexibility. Surface structure measurements, to gauge texture, can be acquired using a profilometer, an interferometer, and/or a surface friction measurement device (Liu 2004, Ramasubramanian 2002). Free fiber ends sticking up from the surface can also be counted to gauge softness. Human subject tactile response is also used.

Researchers create special softness terms to articulate what customers cannot, such as "total flexibility," a stiffness measurement, and "sponginess," the total work required to compress the surfaces of a single ply sheet toward each other under a specific unit load. Because the tissue industry is particularly competitive in softness, most tissue makers have secret and proprietary testing methods (Bottiglieri 2002). Hollmark provides a thorough literature review on known measurement techniques (Hollmark, Ampulski 2004) . Special testers, such as the Kawabata tensile tester and the Handle-O-Meter, exist, but not all researchers agree on the usefulness of these tests (Liu 2004, Ramasubramanian 2002, Ray 1965). Also, ultrasonic fiber measurements can provide a softness metric (Pan, Habeger & Biasca 1989, Ramasubramanian 2002). The empirical model uses the Handle-O-Meter test, which is described in more detail in Section 5.3.

5.1.3. Absorption

Absorbency refers to the transport of liquid through a porous material or material system. A towel's absorption properties relate to its fiber network configuration, which controls porosity, surface properties of the final towel, and chemical characteristics. Absorbency may be the most difficult of all towel properties to model theoretically, as this is a model of capillary flow kinetics through a porous inhomogeneous solid. Model considerations are described in a number of publications, but no comprehensive model exists (Hollmark, Ampulski 2004, Liu 2004, Zaveri 2004). Absorption *rate*, or speed of water transport, and *capacity*, or amount of water absorbed, are both important in toweling.

Rate is more important in most towel uses, such as quickly stopping spills and wiping hands. Rate of absorption is highest at first contact with water, and decreases with time due to (1) liquid friction: flow resistance increases as more liquid is absorbed; (2) gravity: liquids are typically absorbed up into the towel from a surface, and the height of the liquid is inversely proportional to absorption; and (3) spreading: as liquid spreads out in the towel, its velocity decreases. Methods for measuring absorption rate in toweling are varied and tailored to specific applications – for more detail refer to Hollmark (1984). A towel's porosity, or cavities in between fibers, is most important in determining absorption capacity and rate. Porosity can be inferred from the towels' *grammage*, a measurement of area divided by mass, assuming thickness is held constant. This is the measurement commonly used when discussing density of the fiber network in the toweling industry. Confusingly, *density* can sometimes refer to *bulk,* or the grammage divided by the caliper. The empirical model uses a capillary rise method to test absorption rate, and a measure of grammage to assess porosity, as will be discussed further in Section 5.3. Hollmark states that capillary rise methods, particularly in testing one-ply toweling such as paper towels, "provide a simple and reliable way of characterizing the absorbency."

5.2. Tree to towel: Manufacturing's influence on metrics

Only a century ago, paper was not made from wood, but rather other fibrous, cellulosic sources. Today, with the exception of some designer papers, the entire market of paper products begins in the forest. A lumber company grows and harvests trees. Pulp manufacturers may purchase the trees, or they may purchase the scraps produced when the trees are turned into lumber. Pulp manufacturers then make pulp, a network of tree fiber in aqueous solution. They dry the pulp into card-stock-like paper material and sell it to paper manufacturers such as

KermitCo. Towel manufactures re-immerse the pulp in water, add some chemicals, and run it through their manufacturing equipment in order to form a specifically-bonded network of pulp fibers. One company can do all three steps—harvesting, pulping, and towel manufacture—but it is most common to have a supplier relationship between the three steps.

Figure 5.1 shows properties at each step in manufacture that influence final towel properties (Paavilainen 2002). Wood fiber properties are determined during tree growth and harvesting conditions, pulp properties during pulping, and fiber network properties during towel manufacture. Unfamiliar terms will be covered in the following sections, which review the manufacturing stages and the mechanical and chemical processes that interact with inherent fiber properties during manufacturing stages.

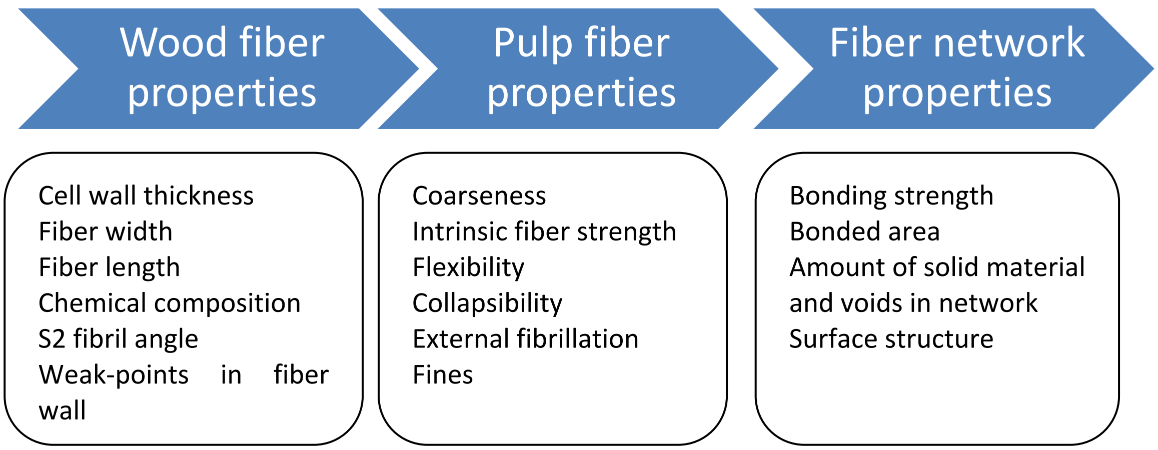


Figure 5.1 Properties of towels are acquired at different stages in processing (Paavilainen 2002).

5.2.1. Tree and wood fiber properties

Paper can be made from both softwood and hardwood trees. The virgin wood fiber used in towels comes from softwood trees, such as the Nordic fir, hemlock, larch, douglas fir, spruce, and pine. As a rule of thumb, a sheet of regular writing or printing paper is about ten wood fibers thick, and the ratio of fiber length to thickness is about 100:1 (Alava, Niskanen 2006). Fiber properties vary with species, genetics, age of the fiber (rings), and placement of the fiber along the tree's length. Combining raw wood from different trees in order to make pulp is a science of its own. For a detailed description of different fiber types and images of fibers, refer to the *Handbook of Physical Testing of Paper* and Liu's dissertation (Liu 2004, Paavilainen 2002). Also, *The Preparation and Treatment of Wood* Pulp provides much background information on fiber, including physical properties, although some of the information is dated (Stephenson 1950).

Three polymers—cellulose, hemicelluloses, and lignin—create the network of fibers in wood, and thus the fundamental structure of paper. These polymers have hydrophilic and hydrophobic regions, as well as crystalline and amorphous regions. Fibers include specific chemical components besides their polymers, such as tannins. As these polymeric regions and chemicals interact and bond in the paper-making process, they contribute to a particular paper's properties. Figure 5.2, taken directly from Paavilainen, details the cellular and lamellar structure of a wood fiber. A wood fiber is basically an organization of cellulosic *fibrils* in a matrix of hemicelluloses and lignin. Basic fibrils group together to form microfibrils which are visible on an electric microscope. Microfibrils, in turn, form the lamellae shown in Figure 5.2. The S2 layer, a right-handed helix of microfibrils, determines the strength and stiffness of the fibers through variation in layer thickness and angle of the microfibrils (Paavilainen 2002).

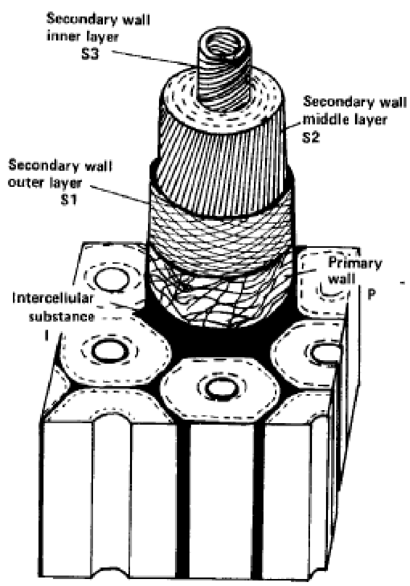


Figure 5.2 The angle and thickness of the microfibril layer S2 determines the wood fiber's mechanical properties (Paavilainen 2002).

Figure 5.3 repeats Figure 5.1 with arrows to indicate relationships between wood fiber properties and final towel properties. Some relationships are taken directly from Paavilainen, and some were added by the author based on the conclusions of other references. The relationships shown are merely highlights of the interrelated process properties. This figure will reoccur in this chapter for different processing stages. The figure will not be used to build the model; it serves to illustrate the complex nature of towel properties and the detailed relationship to processing steps. Note that fiber length has a direct impact on final strength, softness, and absorbency. Dimensions, mechanical properties, and chemical properties of original wood fibers may shape absorbency (Hollmark 1984).

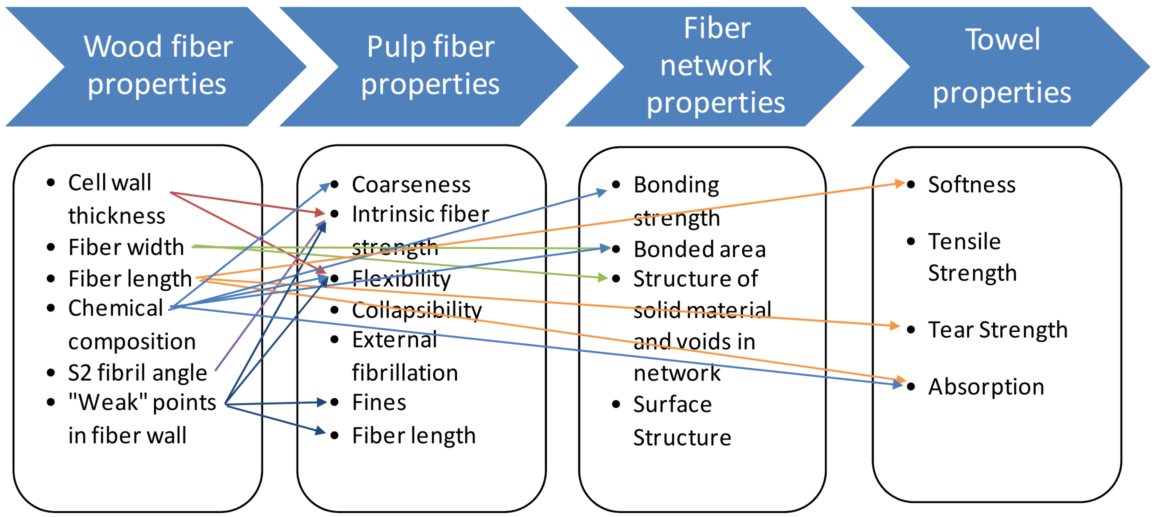


Figure 5.3 Influence of wood fiber properties on subsequent material properties in towel manufacturing stages.

5.2.2. Pulp processing

Virgin pulp

Pulp begins as lumber and, after processing, is sold to towel manufacturers as a thick sheet of coarse, card-stock-like paper. The pulping process strives to maintain the inherent strength of the raw wood fibers while separating the fibers from one another and conditioning them for further processing. Different woods result in different pulps, with different properties and percent yields (Biermann 1993). Fibers are separated using mechanical processes such as grinding between stones (pressure groundwood, stone groundwood), and/or cutting with metal disks (thermomechanical pulp, refiner mechanical pulp). Both cutting and grinding may be done at atmospheric conditions, or in the presence of steam. Towel and tissue pulping typically involves a particular type of chemical pulping, known as kraft pulping, which uses sodium sulfide and sodium hydroxide to remove the lignin from pulp. These chemicals can be completely recovered and reused. Removal of lignin, the least flexible wood fiber polymer, makes the pulp easier to wash and improves its strength (Liu 2004). Pulp may be bleached, or other chemical processes may occur during pulping (Biermann 1993). Each sub-process in the pulping process influences final paper properties, as will be discussed.

Recycled pulp

Recycled pulp can be a combination of softwood and hardwood fibers, and has properties quite different from virgin pulp, only some of which are desirable for paper towels. Recycled paper pulp can come from pre-consumer paper, such as scraps from the paper processing industry and unpurchased newspapers, and/or post-consumer paper, such as office paper and home-recycled newspaper. Recycling pulp involves both mechanical and chemical processes. One important mechanical step in recycling is called beating, a process that blends the reclaimed paper products together with water and chemicals in a large vat that resembles a dull-bladed giant food processor. A common chemical process at this stage is de-inking, in which colored paper scraps are turned into white pulp. For a review of mechanical and chemical improvements to recycled pulp, refer to Wistara and Young (1999).

Many references suggest that towel and other paper manufacturers carefully test the properties of recycled pulp before purchase because recycled pulp has quality control and consistency problems, and it is impossible to control the exact composition of the pulp. For example, it contains *stickies* such as latex from coatings, foil laminants, adhesives, bindings, release oils, defoamers, and starches (Novotny 1988). Stickies can clog and begrime towel manufacturing equipment and cause stops in manufacturing for belt cleaning. Recycled pulp manufacturers or towel manufacturers can address stickies by washing them away with large quantities of water before manufacture, or allow them to build up on equipment with intermittent cleaning. Manufacturers can add chemical surfactants that make the stickies hydrophilic so that they remove themselves from the pulp, or they may add cationic polymers that trap them inside the towel sheet (Novotny 1988)).

Fines, or comparatively small fiber pieces present in pulp, come from two sources: routine processing steps of virgin pulp, and the beating process used in recycling. Therefore, recycled pulp contains more fines than virgin pulp. Fines have different characteristics from fibers: they have a high surface area that improves drainage of water from pulp, increases bonding between fibers, and improves opacity (important in printing paper, but not towels) (Wistara, Young 1999). Secondary fines, when paired with long fibers, can improve overall pulp strength because they are quite stiff (Wistara, Young 1999). Fines, in moderation, can improve towel properties, as the empirical model demonstrates in Section 5.3. However, too many fines lead to a weak towel with a poorly-bonded fiber network. Beating consistency plays a role in determining the number of fines present in recycled pulp, but repeated beating does not change the number of fines significantly. Repeated recycling has a greater detrimental effect on mechanical properties of short fibers, like fines, than the long fibers (Abubakr, Scott & Klungness 1995).

Properties of recycled fiber depend on the type of fiber included, the number of times it has been processed, and the different manners of processing (Woodward 1996). The ratio of amorphous to crystalline region in fibers and fines changes with recycling, and this change seems to explain some of the property changes, along with other factors; for more information, refer to Wistara et al. (Wistara, Zhang & Young 1999). Figure 5.4 shows how pulp properties change with the number of chemically processed recycles (Woodward 1996).

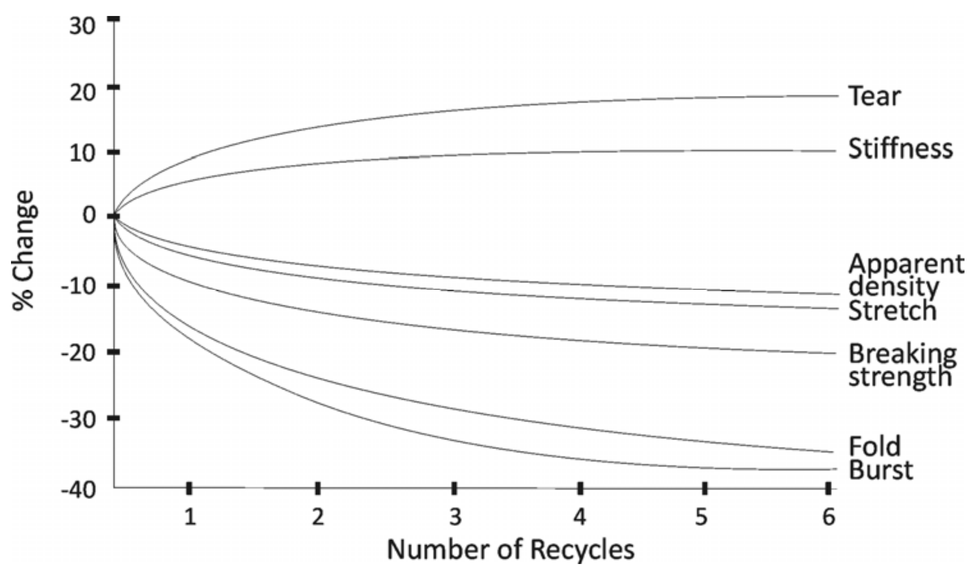


Figure 5.4. Mechanical properties change in chemical pulp with the number of times the pulp is recycled (Woodward 1996).

There is some scientific disagreement regarding the changes of properties over multiple rounds of recycling (Wistara, Young 1999), but Figure 5.4 does demonstrate an important and seemingly universal property of recycled paper pulp: although mechanical properties change over the first six or seven recycles, they do not change noticeably after that. The property changes shown in the figure are interrelated. For example, Cao found that the reason for a decrease in strength in recycled hemlock pulp, a softwood, is due to decreased wet-fiber flexibility in recycled fibers, which decreases inter-fiber bonding ability (as opposed to a decrease in intrinsic fiber strength) (Cao, Tschirner & Ramaswamy 1999). Decreased wet-fiber flexibility is also related to increased stiffness.

Progress has been made in improving the quality of recycled paper pulp. As mentioned previously, Abubakr found that responsibility for degradation of desirable pulp properties in recycled pulp lay with the short fibers in the pulp, and furthermore, that fractionation, or separating the fibers by length, could be used to improve the properties of recycled pulp. Continuing this research, Wonrosli et al. (Wanrosli, Zainuddin & Roslan 2005) discovered that adding only a small amount of palm fiber soda pulp, a non-wood pulp, dramatically improved the properties of recycled pulp (Wanrosli, Zainuddin & Roslan 2005) Wanrosli et al. provided only empirical evidence for this improvement. The properties of different types of paper depend on processing methods and pulp mixture, which is practically impossible to replicate across recycling conditions, so comparison of results between studies can only be high-level and therefore only useful in the case study to compare and contrast findings.

Combining virgin and recycled pulp

The author has spoken with Jim Atkins, a consultant to the paper industry; Dr. Said Abubakr and Dr. Peter Parker, professors in the Department of Paper Engineering, Chemical Engineering, and Imaging at Western Michigan University; and Mark Lewis, Program Manager at the University of Washington's College of Forest Resources. All agreed that though the paper towel industry does research on towel property changes as a function of virgin and recycled pulp mixture, the industry has yet to share its models in a published work for proprietary reasons. In summary, Figure 5.5 shows the important relationships between pulp properties and final towel properties. Some elements play a larger role for virgin pulp, such as intrinsic fiber strength, and some play a larger role for recycled pulp, such as fines. Note that flexibility and fines influence fiber network properties, while all pulp properties influence final towel properties directly in some respect. Not shown below, the ratio of crystalline to amorphous regions in pulp affects the absorbency of the pulp, and thus the towel (Zaveri 2004), and Ph level of pulp influences absorbency (Hollmark 1984).

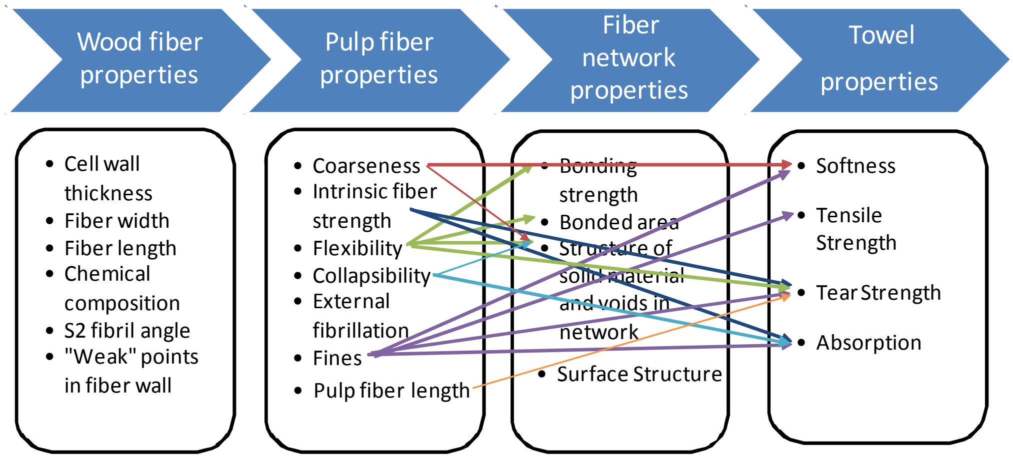


Figure 5.5 Influence of pulp fiber properties on final towel properties.

5.2.3. At the factory

In order to make a roll of paper towels, the manufacturing process blends pulp with water and chemicals, feeds the pulp into a continuous strip, removes as much liquid as possible from the strip, dries the strip, and performs finishing steps. There are two general manufacturing processes: conventional wet press and through air drying (TAD). The towels produced for the empirical model in the case study were manufactured on a conventional wet press, and it is assumed that KermitCo also owns a conventional press, so the discussion will focus here only on this process. In a conventional wet press manufacturing process, four stages of processing occur, as detailed in TAPPI's (Technical Association of the Pulp and Paper Industry) video module on Towel and Tissue making (Atkins accessed 2008): forming, pressing, drying, and finishing. The pulp is first soaked in water and chemicals to loosen the fibers and prepare it for processing. During *forming*, the wet pulp is shaped into the approximate width of the final paper towel and a pre-determined thickness using a *gaproll former.* The gaproll former feeds the pulp into a small gap between two wire meshes, or a wire mesh paired with a felt belt, that move in conveyer- fashion around a configuration of barrels. Water will drip from the pulp as it rolls along between the wire meshes. Gaproll formers come in a variety of configurations for different factory settings and water removal needs (Atkins 2004a).

Next, a series of suction cups transfers the formed pulp, still approximately 85% liquid, from the wire mesh to a solid belt. A wide and gentle force *presses* against the pulp on the solid belt, removing water without excessively decreasing towel *bulk*. Bulk is the thickness of the still-pulpy towel, called a "wet low basis weight sheet." When bulk decreases, the porosity of the resulting towel decreases, thus decreasing absorbency properties. Although pressing does reduce bulk, it removes enough water to bring the material to 35 – 45% solid with much less energy than needed to thermally dry the towel. Thus, there is a trade-off between bulk reduction and manufacturing cost (Atkins 2004a).

The strength of the paper results, in large part, from the surface tensions generated during water removal processes that improve the fiber networks' bonds (Liu 2004). As water is removed, a surface tension force is created in the direction normal to the fiber surface keeping the length and width of the towel relatively constant while thickness decreases by up to 200%. The layout of fines and fibers in the fiber network, set during forming and pressing, is related to strength, softness, and absorbency. The absorbency of the towel is determined, in part, during forming by the distances between fiber bonds and strength of inter-fiber bonds. Note that long distances between fiber bonds and weaker interfiber bonds increase absorbency while decreasing tensile strength of the towel, as loosely and poorly bonded fibers will separate from each other long before they reach their own point of fracture.

The "wet low basis weight sheet" transfers from the belt to the exterior of a large cylindrical hollow drum called a *Yankee dryer* that is covered in adhesive (Ramasubramanian 2002). The adhesive sticks the towel securely to the dryer, assists in creping as described below, and also acts as protective coating on the cast iron drum, keeping it from being nicked and worn away by the creping blade. Yankee dryers are typically twelve to eighteen feet in diameter, and up to 300 feet wide (the length of the cylindrical hollow drum)(Atkins 2004b, Liu 2004). The towel and dryer spin in unison, while steam emits through the many holes on its surface, helping to dry the towel. Hot jets of air, directed at the exterior surface of the drum, also help dry the towel.

During *finishing,* a creping blade cuts the towel from the Yankee dryer. Creping puts tiny fold-like structures into the towel, as shown in Figure 5.6, that make the towel softer and more flexible. The crepe wavelength is determined by the frequency of these folds, which in turn is determined by a number of factors such as the crepe blade angle, the percent solid during creping, the use of release agents, the glue used to attached the towel to the Yankee dryer, and the basis weight of the towel (Ramasubramanian 2002). The creping process decreases density, stiffness, and strength, and increases the stretch and absorbency of the towel, depending on crepe wavelength. Creping causes fiber axial microcompressions that aid in absorbency (Ramasubramanian 2002); it increases absorbency in the cross-machine direction, and in practical cases, absorption rate increases with increasing blade crepe angle (Hollmark 1984).

Creping can occur at various points in the drying process, and the dryness of the towel at creping is related to stiffness, softness, and stretch (Ramasubramanian 2002). During finishing steps just prior to rolling, a towel may be *embossed*, also known as quilted, to add absorbency and surface texture, but this significantly decreases strength (Liang, Suhling 1997). Calendering, or making a change in the surface roughness of the towel by rubbing, can increase smoothness, which is related to softness, but decreases bulk (Novotny 1988, Atkins accessed 2008). The tiny folds introduced in creping shorten the length of the towel, causing the final process, rolling, to run ten to twenty percent slower than the previous processes.

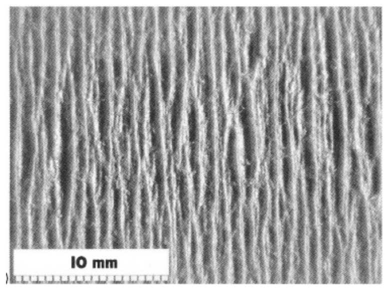


Figure 5.6 Creping wavelength effects towel properties. Micrograph from (Ramasubramanian 2002).

The physical and mechanical properties of toweling are more dependent on manufacturing processes than are those of other, denser grades of paper (Ramasubramanian 2002). Novotny provides an excellent review of the close relationship between manufacturing processes and final properties (Novotny 1988), and some highlights are summarized in

Figure 5.7 below. Chemical additives aid in the manufacturing process, and each additive has an effect on towel properties (Liu 2004, Novotny 1988). For example, surfactants are used to increase surface softness (Novotny 1988). Non-traditional mechanical processing and chemical additives can also aid in absorbency, including surfactants that lower surface tension (Liu 2004, Novotny 1988, Shepherd, Xiao 1999). Wistara and Young review strength-increasing chemical processes (Wistara, Young 1999).

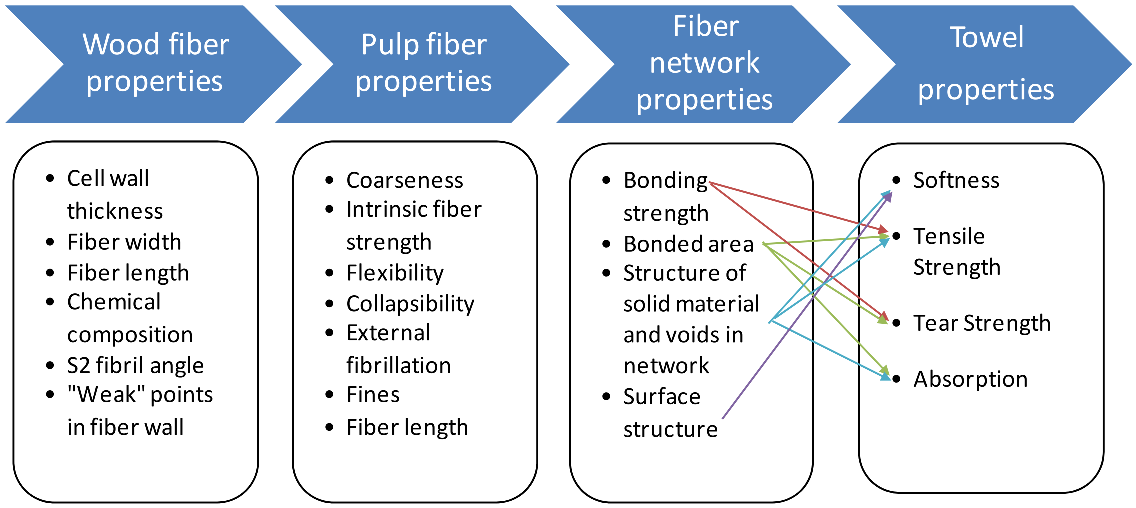


Figure 5.7 Fiber network properties, established during towel manufacturing, determine many of the towel's final properties.

In conclusion, the mechanical properties of the paper towel are intricately dependent on both the raw materials and the entire processing route. Our goal is to create a model of these mechanical properties. Although theory-based models have been built informed by fiber properties (Alava, Niskanen 2006, Bever 1986, Hollmark, Andersson & Perkins 1978), these models will not serve our purposes because: (1) they include too many assumptions about fiber shape and homogeneity; (2) when they are specific, they are for paper, and not for toweling, which has a highly inhomogeneous structure (Bever 1986); (3) they do not include recycled paper pulp, which has inherently different properties than non-recycled pulp; and (4) they study mechanical properties in isolation from specific manufacturing techniques, yet the two are related. Thus, an empirical model was built for the case study.

5.3. Building the empirical model

5.3.1. Paper towel manufacture and testing

Based on the above research and also the advice of professors and consultants who are experts in paper towel manufacturing, the case study models the relationship between recycled/virgin ratio and strength, softness, and absorbency using empirical data. The University of Washington College for Forest Resources Pulp and Paper Laboratory manufactured commercial-grade paper towels with different recycled/virgin ratios on their pilot paper towel machine, shown in Figure 5.8. The photo identifies the former, Yankee dryer, and caliper. The pilot equipment can make commercial-grade towels, such as those found in public restrooms, but not consumer-grade towels, such as those found in the supermarket. The empirical model will compensate for this. The recycled pulp was leftover stock from a project with Kimberly-Clark and is post-consumer. The virgin pulp was a mixture of the softwoods western hemlock and douglas fir.

As days on the pilot facility machinery are quite expensive, the project's budget limit made it possible to run only a limited number of levels of recycled paper content through the pilot machine. Based on the paper lab's advice and the need for samples in configurations for future testing (not discussed in this thesis), the lab produced towels with 0, 12.5, 25, 37.5, 50, 75 and 100% recycled paper content. Smaller testing intervals at the lower levels of recycled paper content were selected based on the belief that there would be greater variation in properties at these levels, and the data adhere to this belief. Table 5.1 displays data collected on the samples. Note that data were collected from a different set of samples for each measurement type, represented in the table by a double line break between columns.

Figure 5.8 Dryer (left) and former (right), both without belts at the University of Washington.

As previously discussed, both absorbency rate and capacity indicate absorption, but in the short lifetime of a towel, the more important measurement of absorption is the amount of water that can be transported to the pores during wiping, or rate of absorption, as will be demonstrated in Section 6.2. However, the lab performed a test for rate and provided an indication of capacity, so the study explores both as indicators of preference before concluding that rate is the better measurement. For capacity: grammage measures the density of a paper, which in turn represents porosity for a given towel caliper. Grammage was calculated by the lab as the mass of an eight-inch-square towel sample divided by its area. Caliper was measured using TAPPI test T411 (micrometer measurement). Figure 5.9 shows the grammage for the towel samples. The spline curves through the points on this plot, and the plots in Figure 5.10 and Figure 5.12 will be addressed later. Levels of 25% and 100% recycled paper content show the lowest grammage, and thus potentially the highest porosity.

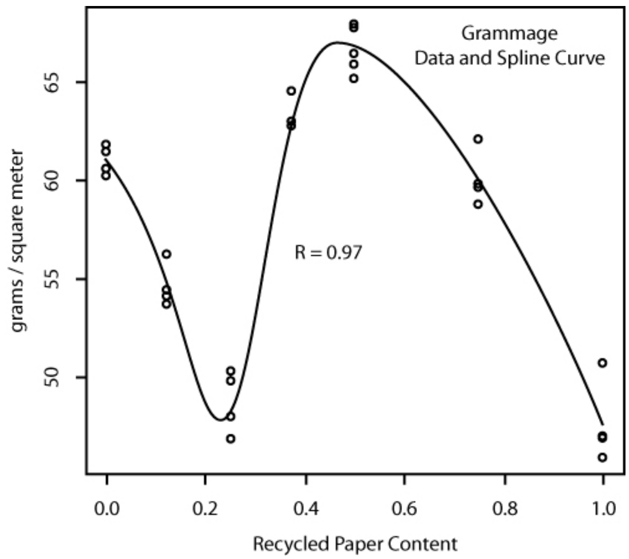


Figure 5.9 Grammage indicates favorable density properties at 25% and 100% recycled paper content.

To measure absorbency rate, the lab used TAPPI test T 432 om-94. First, towel specimens are cut into 100 x 100 ml samples. Then the samples are placed flat on a horizontal holder with a 40 mm diameter hole in the center. A pipette filled with 0.1 milliliter of water is placed vertically over the sample at the center of the 40 mm hole in the holder. A bright light is shown at the water level in the pipette, making it easier to see, while being careful not to heat the sample or the water. The pipette is touched lightly to the surface of the towel, and the time required for the towel to draw all of the water out of the pipette is recorded, marked by the disappearance of the water level line from inside the pipette. The lab performed five tests on five separate samples per recycled/virgin ratio, instead of the recommended ten in the TAPPI procedure. Figure 5.10 displays the collected data for absorbency rate. The data indicate that, as with grammage, there is a synergistic effect between the two pulps at a level of 25% recycled pulp. The synergistic effects exist only for this 25% combination, and this "batch" of towels is certainly not an outlier, as grammage, caliper, and tear-testing data are well within the range of the measurements recorded across other sample levels. Figure 5.11 demonstrates that the caliper of the 25% samples are not outlier data, although there is the largest amount of variation in caliper measurement at this level of recycled paper content, suggesting these samples have a different macrostructure than samples with other levels of recycled paper content.

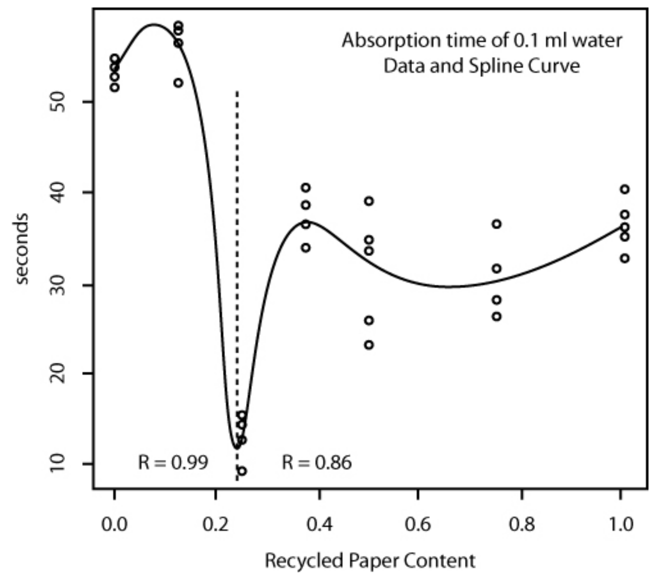


Figure 5.10 Absorption rate is best at 25% recycled paper content.

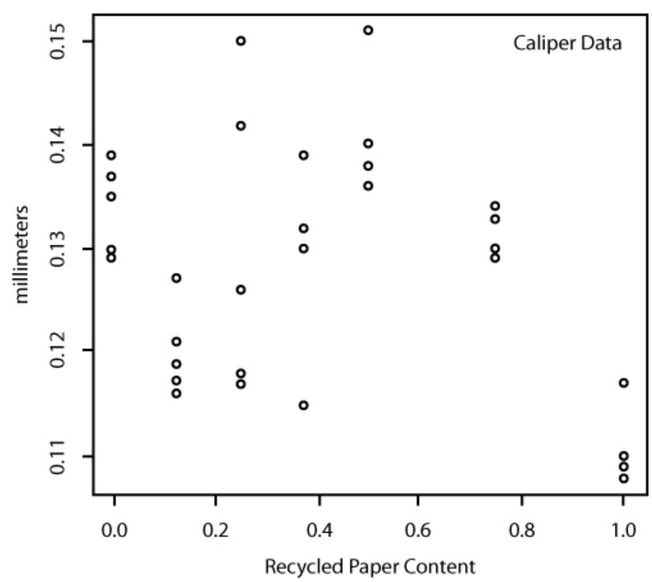


Figure 5.11 Caliper measurements reveal 25% recycled paper content as the most variable thickness across measured samples, but no individual measurement is an outlier.

The lab measured tear strength using TAPPI test T 414 om-98 under two-ply 200 gram-force (pendulum type 1/4A (E)) testing conditions. In this test, two sheets (two-ply) of sample were "torn together through a fixed distance by means of the pendulum of an Elmendorf-type tearing tester. The work done in tearing is measured by the loss in potential energy of the pendulum." A picture of an Elmendorf tear tester is shown in Figure 5.12 at right. First, the two-ply sample is clamped into place horizontally and pre-notched using the Elmendorf tester. Then, the technician raises the pendulum with a blade at the end of it to a specific height, sets the pointer that will indicate force exerted, and releases the pendulum. The pendulum hits the paper and tears it in half. The technician catches the pendulum on the upswing before it can disturb the pointer. The variations in testing equipment, such as the sample clamping mechanism and specific pendulum, make it difficult to compare the results received here to other studies that measure tear strength directly. The plot in Figure 5.12 shows that tear strength was quite variable across samples that contained some amount of virgin pulp, but dropped considerably with 100% recycled paper. Note that, in the case of tear strength, 25% recycled paper content shows no synergistic effects, and 37.5% has a larger range of measurements than the other levels.

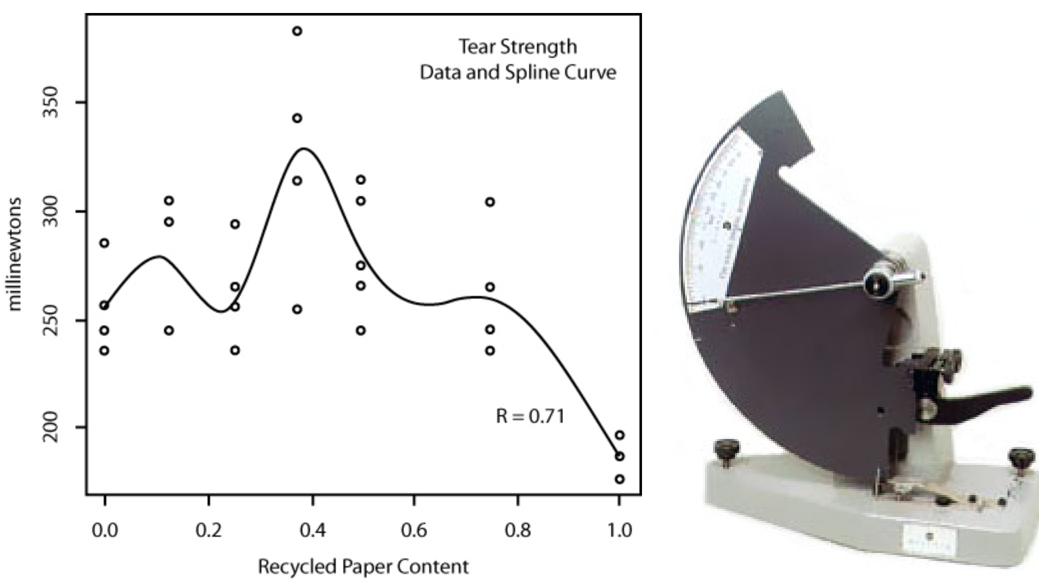


Figure 5.12 Elmendorf tear test results reveal that a recycled paper content of 37.5% has the highest tear strength and variability in measurement. An Elmendorf tear tester is shown at right, Image from (Testing Machines accessed 2007).

Table 5.1 Grammage, caliper, absorbency, and tear strength data from commercial-grade paper towel samples (Double line break indicates separate samples).

RPC	Grammage	Caliper	Absorbency Rate	Tear Strength	Softness
Percent	grams/meter^2	millimeters	seconds	Millinewtons	gram meters
100	50.68	0.117	35.06	176.58	14.4
100	46.93	0.108	40.20	196.20	13.1
100	46.80	0.110	37.47	186.39	11.6
100	45.90	0.109	36.07	186.39	12.4
100	46.90	0.110	32.74	186.39	11.6
75	59.76	0.129	26.54	264.87	27.2
75	59.73	0.130	31.60	304.11	29.5
75	62.02	0.129	31.50	245.25	30.6
75	58.73	0.133	28.34	235.44	25.1
75	59.80	0.134	36.36	245.25	28.1
50	67.80	0.136	33.57	313.92	35.0
50	66.46	0.140	38.87	245.25	33.8
50	65.88	0.138	34.67	304.11	37.7
50	65.10	0.136	23.33	264.87	34.5
50	67.95	0.151	26.00	274.68	43.4
37.5	62.93	0.132	36.24	382.59	32.8
37.5	62.80	0.130	36.30	313.92	27.5
37.5	64.51	0.139	38.57	343.35	33.5
37.5	62.78	0.115	40.45	255.06	31.5
37.5	62.90	0.130	33.97	343.35	31.5
25	49.76	0.142	14.74	255.06	11.2
25	50.27	0.150	9.46	235.44	13.0
25	47.93	0.117	15.60	235.44	13.0
25	46.68	0.126	14.47	264.87	14.9
25	46.80	0.118	12.76	294.30	12.5
12.5	54.02	0.117	52.06	245.25	23.1
12.5	54.12	0.119	57.52	304.11	15.5
12.5	56.15	0.127	56.24	294.30	19.9
12.5	53.68	0.116	58.02	294.30	27.7
12.5	54.49	0.121	56.06	245.25	19.1
0	60.24	0.139	52.50	255.06	28.9
0	61.61	0.137	53.74	235.44	33.5
0	61.88	0.135	53.73	245.25	30.8
0	61.39	0.130	54.64	284.49	33.7
0	60.63	0.129	51.37	255.06	31.4

Softness was tested at a Weyerhauser facility near Seattle, Washington using a Thwing Albert Handle-O-Meter that measures "handle," a combination of surface friction and flexibility. The data are shown in Figure 5.13. Twenty-five percent and 100% recycled paper content have the lowest values and thus the highest softness by this measurement system. The spline fitted to the data has a shape very similar to the curve for grammage in Figure 5.9.

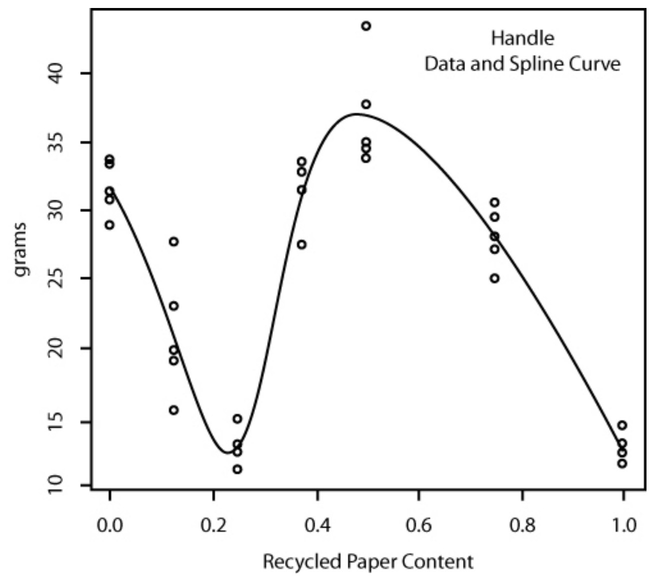


Figure 5.13 Thwing Albert Handle-O-Meter data indicate that recycled paper contents of 25% and 100% produce the softest towels (the lower the value, the better).

5.3.2. Models using spline curves of data

As shown in Figure 5.9, Figure 5.10, and Figure 5.12, cubic spline curves were fit to the data collected using a linear model. Splines are piecewise polynomial curves that share common proprieties of their derivates at their "knots." The natural spline (ns) function in the [[R]] Spline package provided a good fit for all three curves. Absorbency required two separate spline curves to get a good fit, with R-squared values of 0.99 and 0.86. Grammage had an R-squared of 0.97, and Tear Strength of 0.71. The knots and piecewise polynomial coefficients are shown in Table 5.2, Table 5.3, and Table 5.4. These splines will be used in Chapter 6 as the basis for the engineering portion of the paper towel optimization model.

Table 5.2 Expression of spline for absorbency rate.

Knot	Intercept	Linear	Quadratic	Cubic
0	53.20	106.93	0.00	-6.91E+03
0.0625	58.19	25.93	-1295.90	5.04E+03
0.1250	55.98	-77.03	-351.60	-4.01E+04
0.1875	40.00	-590.88	-7869.94	1.68E+05
0.2500	13.41	397.01	23676.14	-8.63E+06
0.2510	13.82	418.48	-2206.62	2.11E+03
0.3045	30.21	200.49	-1867.90	4.64E+03
0.3580	36.30	40.50	-1122.61	4.82E+03
0.4115	36.00	-38.26	-349.49	3.43E+03
0.4650	33.47	-46.22	200.78	-5.64E+02
0.5185	31.49	-29.58	110.23	4.02E+01
0.5720	30.23	-17.44	116.69	-1.22E+02
0.6255	29.61	-6.00	97.15	-7.83E+01
0.6790	29.56	3.73	84.58	-9.00E+01
0.7325	29.98	12.00	70.14	-8.68E+01
0.7860	30.81	18.76	56.20	-8.77E+01
0.8395	31.96	24.02	42.13	-8.75E+01
0.8930	33.36	27.78	28.09	-8.75E+01
0.9465	34.91	30.03	14.04	-8.75E+01
1	36.54	30.78	0.00	0.00E+00

Table 5.3 Expression of spline for tear strength.

Knot	Intercept	Linear	Quadratic	Cubic
0	255.1	331.56	0	-10170
0.125	276.6	-145.15	-3814	29753
0.250	257.0	296.12	7344	-41539
0.375	327.7	184.95	-8233	29919
0.500	280.6	-470.87	2987	-5794
0.750	259.0	-63.91	-1359	1812
1	186.4	-403.61	0	0

Table 5.4 Expression of spline for softness.

Knot	Intercept	Linear	Quadratic	Cubic
0	31.66	-73.14	0	-746.26
0.125	21.06	-108.12	-279.8	4990.8
0.25	12.92	55.86	1591.7	-6867.5
0.375	31.36	131.87	-983.6	2255.3
0.5	36.88	-8.31	-137.9	122.59
0.75	28.1	-54.26	-45.932	61.242
1	12.62	-65.75	0	0

5.4. Discussion

Properties of strength, softness, and absorbency in towels depend on the entire process of towel manufacturing and also on intrinsic wood properties. Towels are a complex composite-within-composite—on one level it is a tangle of wood fiber and chemical additives; on another, within the fibers, it is a matrix of different polymers and other chemicals. Each manufacturing step has fundamental impacts on both levels of this composite. In creating an engineering model of strength, softness, and absorbency, the complex nature of these properties relays the need for many assumptions in the model, be it theoretical or empirical. The empirical model presented above thus far avoids the needs for many assumptions; however, it will require many more for integration into our case study. For example, the relationship between commercial-grade and consumer-grade towels must be assumed to have a particular form, because no research discusses this relationship. Likewise, there is no research to directly corroborate our finding of the synergistic effect of 25% recycled paper content on absorbency and softness properties. It is likely this combination of the two types of pulp, virgin and recycled, receives the benefits of plenty of flexible virgin pulp fibers with a favorable mixture of stiff recycled fibers and just enough fines to improve capillary intake and surface softness without yet sacrificing bulk and pliability. Substantiating the models presented here would require further production of towels on the University of Washington pilot equipment, to test that the results are repeatable. The results should also be expanded to other manufacturing processes. For the purposes of the case study, however, we assume that the findings are valid and repeatable.

Chapter 6. Proactive and reactive incorporation of construction of preference in design optimization

6.1. Introduction

Design optimization for consumer products frequently includes parameters derived from an assessment of user preference for potential product attribute configurations. When this assessment is estimated directly from users' choices, as is the case with utility estimates from discrete choice surveys (conjoint analysis), the decision context in which the users' choices are made implicitly influences product optimization. User preference parameters deserve special treatment in multidisciplinary design optimization, as they have properties that are different than those of engineering or cost parameters. They are not tangible, measurable parameters, but instead they are estimates of an abstract, dimensionless concept (the utility) that has been proven dependent on conditions not captured in the typical design optimization framework, namely, decision context.

As previously discussed in Chapter 4, inconsistent preference can manifest in estimates of utility as random or non-random inconsistency (MacDonald, Gonzalez & Papalambros 2007). Random preference inconsistency appears in the error term and variance of a utility estimate. Like an uncertain engineering parameter, a user preference estimated with a utility parameter and a known variance can be modeled as a random-variable parameter in design optimization, an approach taken by Besharati et al. (Besharati et al. 2006). Non-random preference inconsistencies are predictable across a group of subjects, in response to manipulation of a certain element of decision context. This chapter focuses on the incorporation of non-random preference inconsistency in design optimization. Two scenarios are considered: (1) it is known that decision context causes preference inconsistency, but the results of the inconsistency are not entirely predictable; and (2) it is known that decision context causes preference inconsistency, and it is possible to control preference construction through a careful manipulation of context (at the time of purchase). Both scenarios are explored; in the first, termed a *reactive* approach, preference inconsistency is modeled as a parameter with unknown distribution; in the second, termed a *proactive* approach, preference inconsistency is added as a deterministic variable in the model.

KermitCo wants to create a towel that secures the largest share of the market possible by introducing a green product that they predict will be highly preferred by their customers. Given the assumption that the manufacturing process is constant and pre-determined, this business goal can be written as an optimization problem dependent on the configuration of the recycled paper content and price of KermitCo's towels. As seen in Chapter 4, a significant percentage of KermitCo's customers have inconsistent construction of preference for the level of recycled paper content in towels. Here, the construction of preference for recycled paper content in towels is addressed in the two manners described above: reactively and proactively. In reactive optimization, KermitCo takes the approach that it does not know how the customers will assess or prefer recycled paper content, because their preferences are highly inconsistent. Therefore, customer assessment and preference for recycled paper content are modeled as random variables in the optimization. KermitCo then assumes it can control assessment of recycled paper content and level of preference, and thus preference is treated as a variable in the proactive optimization.

Before this optimization can occur, multiple sources of data must be integrated: consumer towel lab measurements; commercial towel lab measurements; and survey respondent (customer) ratings and preference estimates for consumer towels, as shown on the following page in Figure 6.1. Survey respondents did not have the opportunity to test actual towels, and it is pointless to ask a consumer if they prefer a towel with an absorbency rate of 5 seconds or 7 seconds, so the classifications of 1, 2, and 3 out of 3 were used. These subjective assessments must be linked in engineering assessments and variables. There have been some sophisticated approaches to dealing with subjective customer measurements (Kumar et al. 2007, Luo, Kannan & Ratchford (in press)); however, they do not address one-to-one comparisons of individual attributes assessed on two different (engineering and subjective) scales. Section 6.2 explains our approach. It was not possible to build a first-principles or empirical model of consumer towel properties. Section 6.3 explains how an empirical model of commercial towel properties is adjusted for use in the case study.

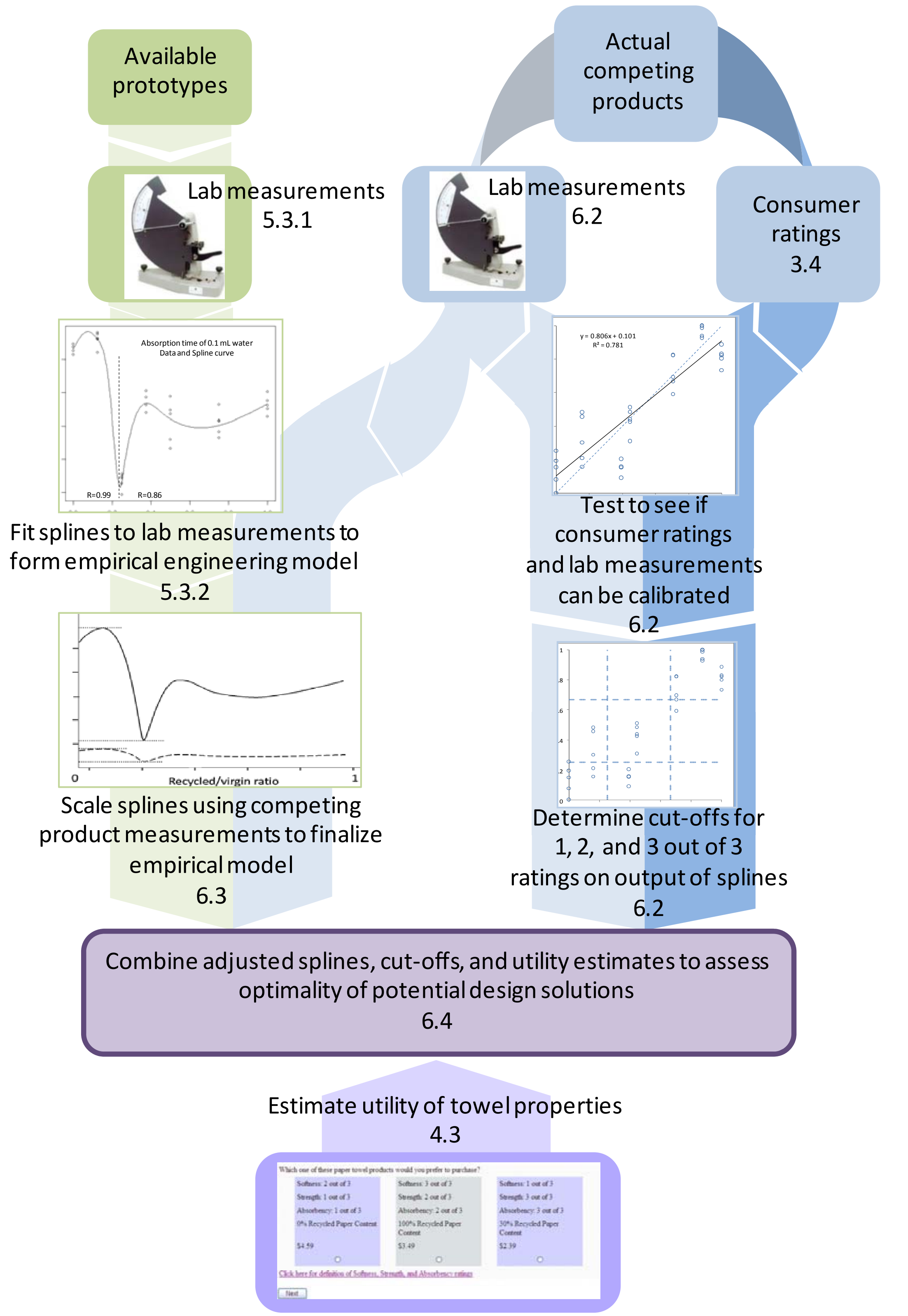


Figure 6.1 Overview of linked empirical, market, and customer model and related thesis section numbers.

6.2. Measurement calibration

6.2.1. Testing for correlation between lab and customer assessment of towel properties

As mentioned in Section 3.3, the survey's descriptions of towel strength, softness, and absorbency attributes were ratings of 1, 2, or 3 out of 3 within choice questions, with more detailed explanations given at the beginning of the survey and also available throughout as a pop-up window. The descriptions served to help respondents ground their preferences and trade-off decisions in reality, but were not scientifically based. Design optimization of KermitCo's towel requires quantitative scientific measurements of absorbency rate, grammage, and tear strength as a function of recycled paper content. This section investigates the correlation between survey respondents' ratings (1, 2, or 3 out of 3) of existing towels' properties of strength, softness, and absorbency and corresponding actual scientific measurements of strength, softness and absorbency. A good correlation is found only in the case of absorbency, leading to the decision to include only measured properties in design optimization, and not consumer assessments.

The University of Washington lab measured grammage, caliper, absorbency rate, tear strength, and softness for consumer towel samples from Bounty, Brawny, Scott, Viva, Sparkle, Green Forest, and Seventh Generation. Figure 6.2 shows the measurements of dry tear strength for consumer samples. Note that these tear strengths are significantly higher than those shown in Figure 5.12 for the prototype commercial-grade samples. Figure 6.3, Figure 6.4, Figure 6.5, and Figure 6.6 show the wet tear strength, absorbency rate, grammage, and softness of the consumer samples, respectively. Recall that for absorbency rate, lower is better and note that these rates are extremely low as compared to those of the commercial samples presented in Figure 5.10. The consumer towels have much higher calipers and thus much higher grammage measurements than the commercial towels. The softness of the consumer towels is also much better than that of commercial towels.

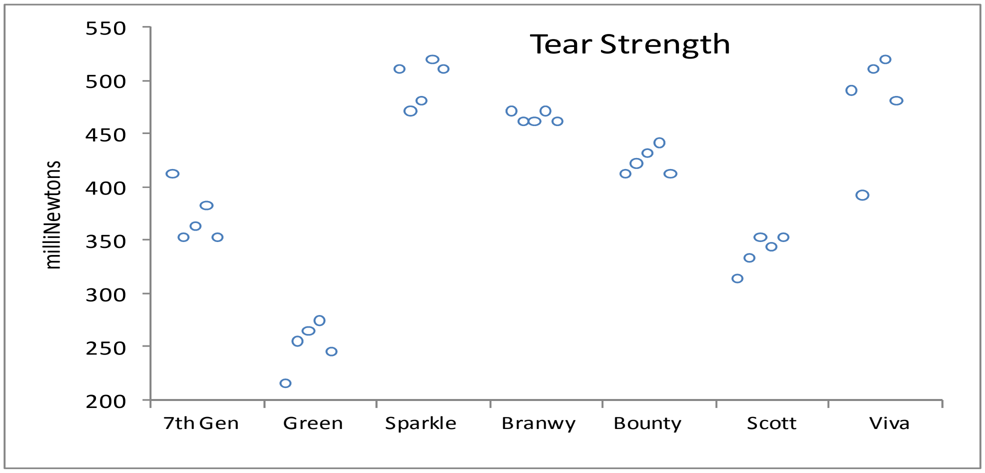


Figure 6.2 Dry tear strength for consumer-grade towels.

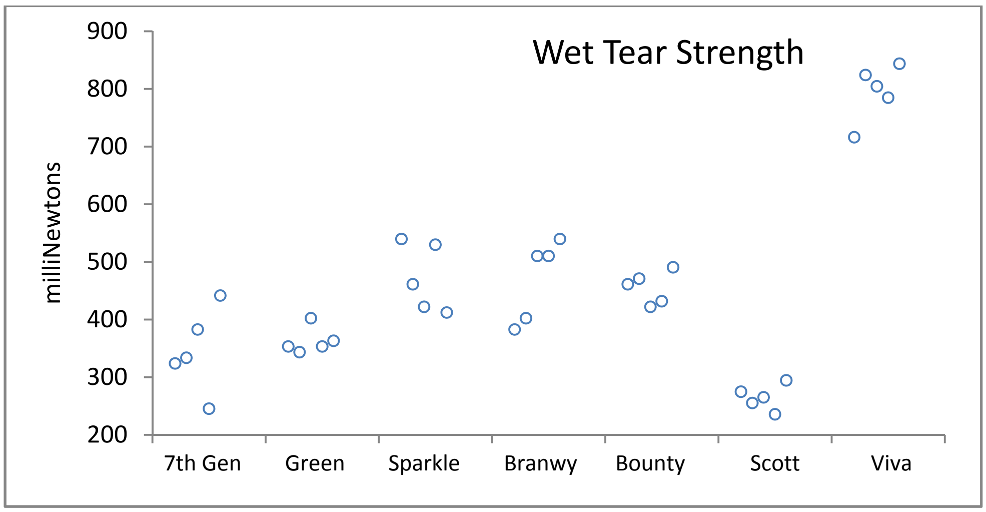


Figure 6.3 Wet tear strength for consumer-grade towels.

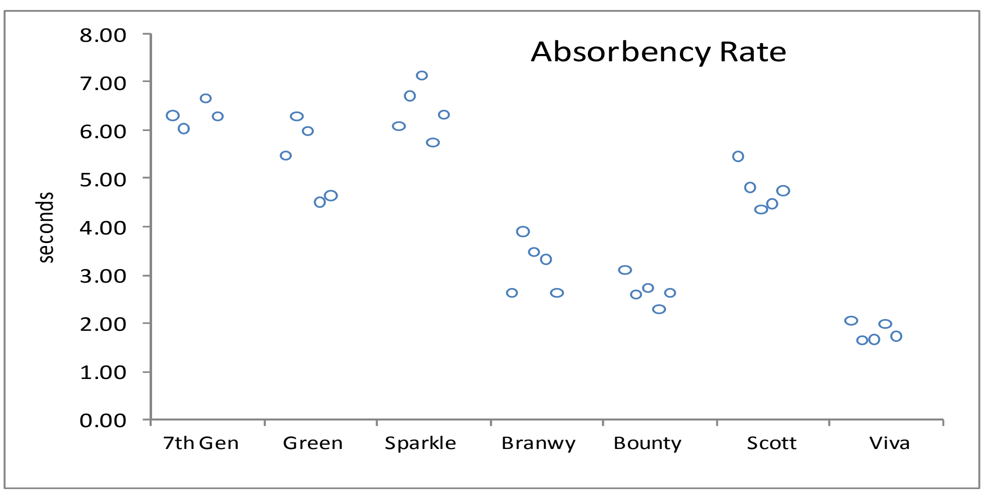


Figure 6.4 Absorbency rate for consumer-grade towels (the lower, the better).

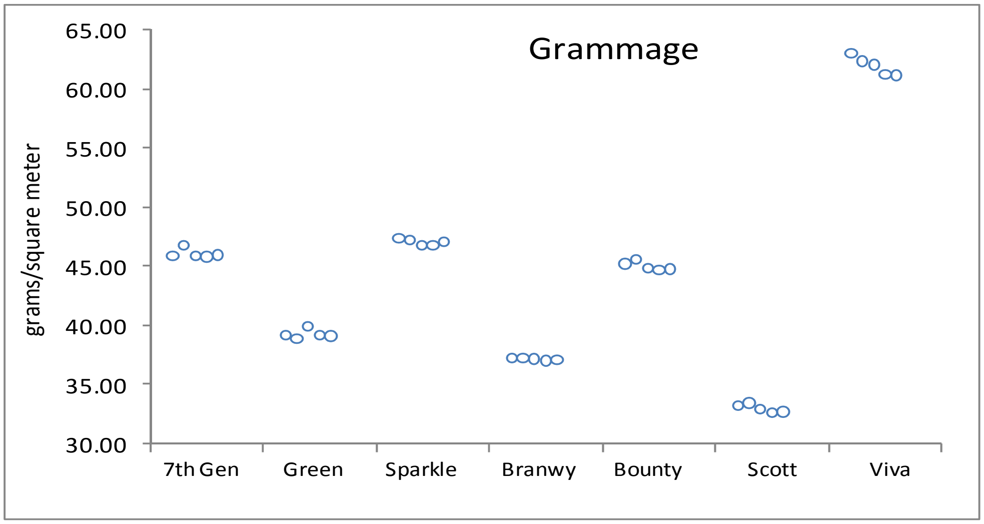


Figure 6.5 Grammage of consumer-grade towels.

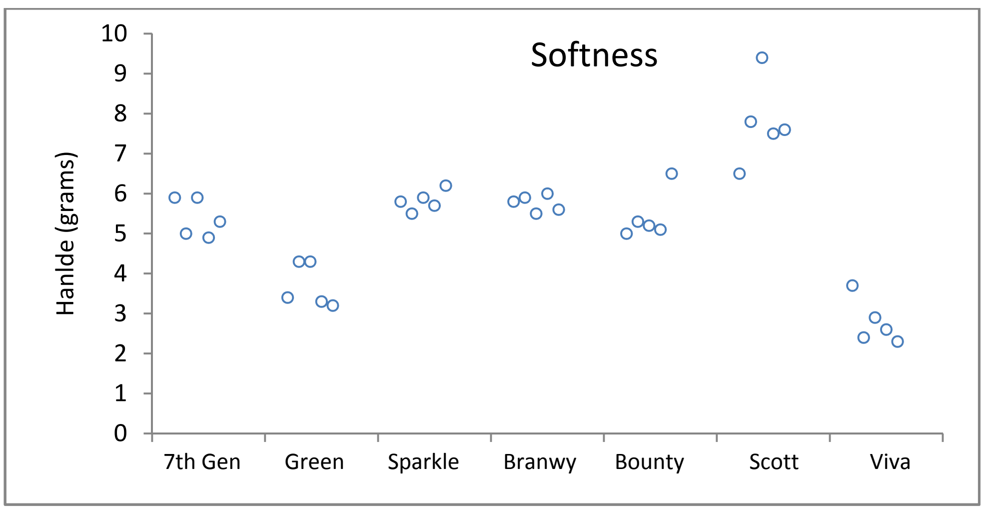


Figure 6.6 Softness of consumer-grade towels (the lower, the better).

Table 6.1 Grammage, caliper, absorbency, tear strength, and softness data from consumer-grade paper towel samples. All entries are from different towel samples.

Brand	RPC	Absorbency Rate	Dry Tear Strength	Wet Tear Strength	Softness
	%	seconds	Millinewtons	Millinewtons	grams
		η_a	η_t		η_s
Seventh Gen.	100	6.30	412.02	323.73	5.9
		6.03	353.16	333.54	5.0
		7.91	362.97	382.59	5.9
		6.65	382.59	245.25	4.9
		6.29	353.16	441.45	5.3
Green Forest	100	5.48	215.82	353.16	3.4
		6.28	255.06	343.35	4.3
		5.99	264.87	402.21	4.3
		4.50	274.68	353.16	3.3
		4.64	245.25	362.97	3.2
Sparkle	0	6.08	510.12	539.55	5.8
		6.71	470.88	461.07	5.5
		7.14	480.69	421.83	5.9
		5.75	519.93	529.74	5.7
		6.31	510.12	412.02	6.2
Brawny	0	2.62	470.88	382.59	5.8
		3.89	461.07	402.21	5.9
		3.47	461.07	510.12	5.5
		3.32	470.88	510.12	6.0
		2.61	461.07	539.55	5.6
Bounty	0	3.10	412.02	461.07	5.0
		2.58	421.83	470.88	5.3
		2.73	431.64	421.83	5.2
		2.27	441.45	431.64	5.1
		2.61	412.02	490.5	6.5
Scott	0	5.45	313.92	274.68	6.5
		4.81	333.54	255.06	7.8
		4.34	353.16	264.87	9.4
		4.47	343.35	235.44	7.5
		4.74	353.16	294.3	7.6
Viva	0	2.05	490.50	716.13	3.7
		1.64	392.40	824.04	2.4
		1.65	510.12	804.42	2.9
		1.97	519.93	784.8	2.6
		1.72	480.69	843.66	2.3

Preparing for design optimization, subjective consumer ratings and objective lab measurements are compared to see if a good correlation exists between how towels are perceived in the market and how they perform in the lab. Both consumer and lab assessments are normalized to 0 to 1 scales. The tear strength lab measurements are normalized from 0 to 1 using Equation (6.1) where 1 is the best measurement, c represents an individual consumer towel sample, and $\eta_{t,c}$ is an individual measurement.

$$\varphi_{t,c} = \frac{\eta_{t,c} - \min_{c}\{\eta_{t,c}\}}{\max_{c}\{\eta_{t,c}\} - \min_{c}\{\eta_{t,c}\}} \tag{6.1}$$

A low absorbency time should correlate to high ratings of absorbency by consumers. The normalization equations for absorbency are calculated such that 1 equals to the lowest measurements of absorbency a and grammage. A similar equation is used for softness.

$$\varphi_{a,c} = 1 - \frac{\eta_{a,c} - \min_{c}\{\eta_{a,c}\}}{\max_{c}\{\eta_{a,c}\} - \min_{c}\{\eta_{a,c}\}} \tag{6.2}$$

$$\varphi_{s,c} = 1 - \frac{\eta_{s,c} - \min_{c}\{\eta_{s,c}\}}{\max_{c}\{\eta_{s,c}\} - \min_{c}\{\eta_{s,c}\}} \tag{6.3}$$

As described in Section 3.3, respondents rated the strength, softness, and absorbency of consumer towels. Their average ratings, $\mu_{i,b}$ of brand $b =$ Bounty, Brawny, Sparkle, Seventh Generation, Green Forest, Scott and Viva for properties $i =$strength, softness, and absorbency as reported in Table 3.4 are considered here. These respondent ratings from the survey were normalized to vectors $\boldsymbol{\rho}_i$ following Equation (6.4).

$$\rho_{i,b} = \frac{\mu_{i,b} - \min_{b}\{\mu_{i,b}\}}{\max_{b}\{\mu_{i,b}\} - \min_{b}\{\mu_{i,b}\}} \tag{6.4}$$

Figure 6.7 reveals a good match between normalized lab measurements and consumer ratings of absorbency. The trendline of these ratings graphed against each other has a slope of 0.721 and an intercept of 0.190, with an R squared of 0.726. When one outlying lab measurement, an extremely low absorbency rate for one of the Seventh Generation lab measurements, is removed from the analysis, the trendline improves to a slope of 0.806 and an intercept of 0.101, with an R squared of 0.781, as shown in Figure 6.7.

Lab measurements of tear strength were normalized and compared to respondent ratings of strength. The relationship between the two was weak, as shown in Figure 6.8. The lab tested dry strength, and the respondents chose between towels with different "wet strengths" and then were asked to rate the "strength" of the brands of towels. It was thought that the poor correlation may be due to the wet vs. dry inconsistency, so the samples were tested again wet, but the results did not improve, as shown in the graph at right in Figure 6.8. Softness also exhibited no noticeable correlation between the two assessments.

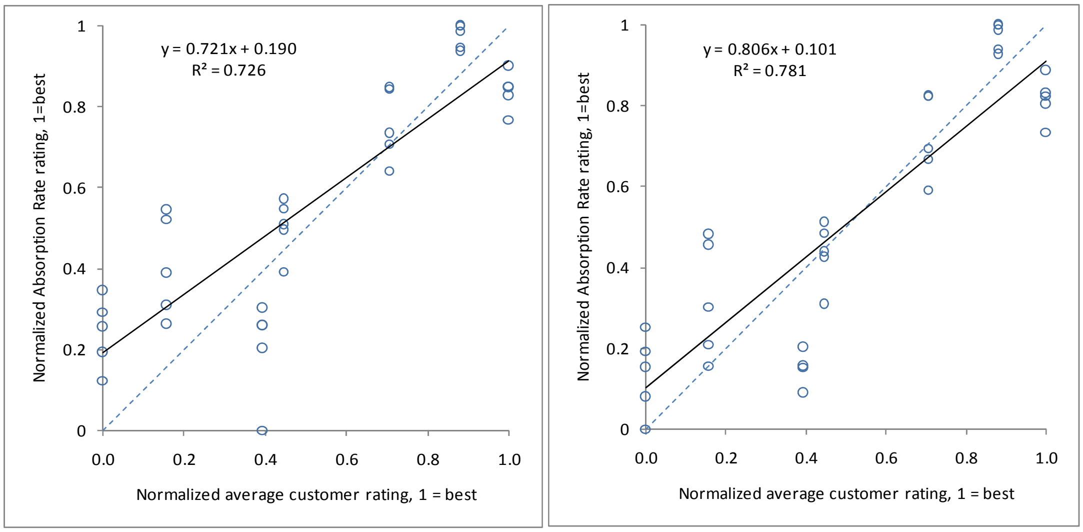


Figure 6.7 Subjective ratings and lab measurements of absorbency rate have a high correlation. Removing one outlying measurement improves the relationship (graph at right).

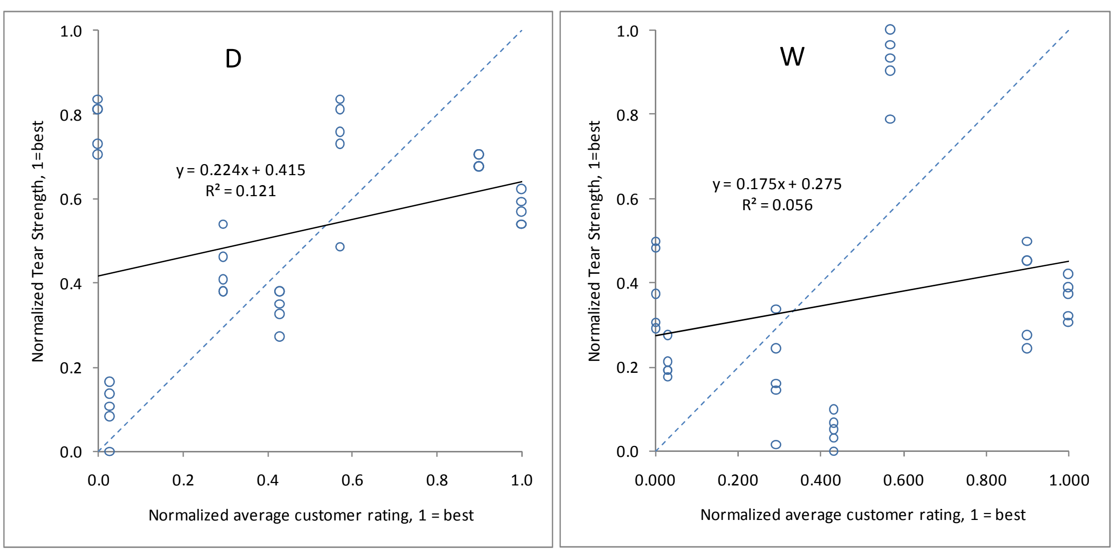


Figure 6.8 Normalized lab tear strengths (dry and wet) and consumer ratings are not correlated.

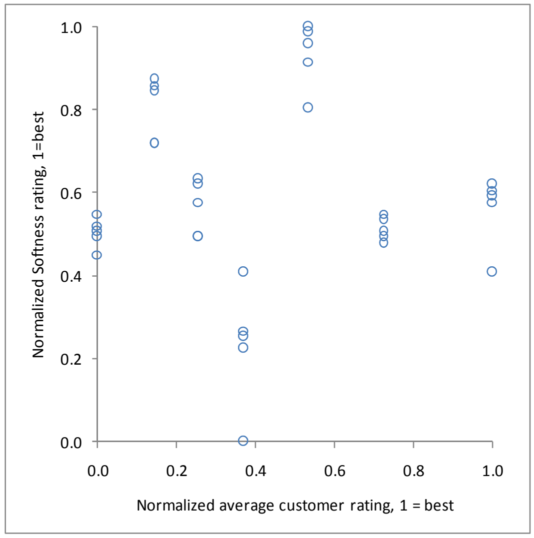


Figure 6.9 Assessments of softness between customer (X-axis) and lab (Y-axis) are not correlated.

In summary, while the two assessments, lab and consumer, were correlated for absorbency, they were not for tear strength and softness. Consumer assessments are likely influenced by factors other than unbiased scientific measurement, such as advertising, branding, and price. Perceptions of product attributes are important, and these results demonstrate that for a towel to be successful, it must not only have good engineering design, but also correlated consumer perceptions of this design. Chapter 7 offers a design method to identify perceptions that are linked to specific product attributes. As an assumption, the following design optimization disregards customer perception and relies on engineering configuration and testing to assess strength, softness and absorbency of the brands in the market, as well as the optimal configuration of KermitCo's product.

6.2.2. Determining cut-offs for 1, 2, and 3 out of 3 ratings based on lab measurements

Respondents made discrete choices among hypothetical towels with different levels of strength, softness, and absorbency of 1, 2 and 3 out of 3. These discrete choices formed the basis for the preference estimation in Chapter 4. In order for the preferences to be used along with the engineering model, they must be linked to engineering measurements. For example, what lab measurements correspond to a customer rating of, for example, 2 out of 3, in absorbency? These measurements shall be linked together using cut-offs to determine what normalized ratings of 0 to 1 represent 1 out of 3, 2 out of 3, and 3 out of 3 in *both* the lab measurements and consumer ratings.

The vectors of cut-offs $\boldsymbol{\theta}_\mathbf{i}$ $i =$ strength, softness, and absorbency were determined by splitting the brands into three groups: below average, average, and above average property characteristics, based on their lab measurements for i. The break-points between these classifications were selected as the cut-offs for determining 1, 2, and 3 out of 3 assessments, and they are shown in Table 6.2.

Table 6.2 Cut-offs for strength, softness, and absorbency classifications

Attribute	$\boldsymbol{\theta_{i,1}}$	$\boldsymbol{\theta_{i,2}}$
Absorbency a	5.48	2.73
Strength t	362.97	472.00
Softness s	5.821	4.900

6.3. Building the engineering model

As discussed in Section 5.3, the University of Washington lab created commercial towel samples with 0, 12.5, 25, 37.5, 50, 75 and 100% recycled paper content and measured their strength, softness, and absorbency in order to create an empirical model of these properties as a function of recycled paper content. This model will now be scaled to consumer towels and used as the engineering model in the design optimization.

This scaling is necessary due to differences in the range in property values between consumer and commercial towels. Absorbency rates in consumer towels had ranged from 1.64 seconds to 7.14 seconds. Absorbency rates in the commercial prototype towels with different levels of recycled paper content had a range of 48.6 seconds, with a minimum value of 9.46 seconds and a maximum value of 58.02 seconds. Consumer towels have a much faster absorbency rate than their commercial counterparts because their manufacturing process is configured to maximize bulk, whereas the commercial towel process is configured to minimize cost. Maximizing bulk is expensive, as the manufacturer cannot press the water out of the pulp to more than a small amount without decreasing bulk. Instead, they must use air drying to dry the towel, which is energy intensive and expensive. Commercial towels, however, are pressed flat to remove water from the pulp.

Precisely what type of variation in towel properties can one expect to see in consumer-grade towel as a function of recycled paper content? To answer this question, the design optimization includes an assumption: the consumer towel engineering model will have the same "shape" spline curve functions as the commercial towel empirical model, but scaled to the range of values found in the consumer towels test measurements, as illustrated in Figure 6.10.

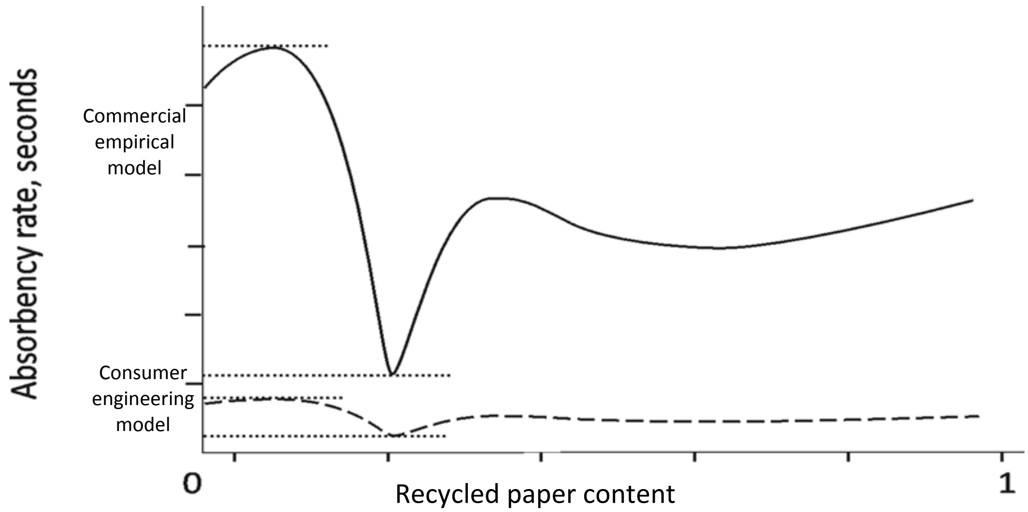


Figure 6.10 The consumer towel engineering model for absorbency is a scaled version of the empirical model from Section 5.3.2.

In the engineering model, the towel's absorbency a, strength t, and softness s for recycled paper content r are given by the spline functions $q_i(r)$:

$$For\ \delta_{i,z} < r \le \delta_{i,z+1}: \tag{6.5}$$

$$q_i(r) = \alpha_{i,\delta_{i,z}}(r-\delta_{i,z})^3 + \gamma_{i,\delta_{i,z}}(r-\delta_{i,z})^2 + \lambda_{i,\delta_{i,z}}(r-\delta_{i,z}) + \tau_{i,\delta_{i,z}}$$

where $(\delta_{i,z}, \delta_{i,z+1}, \delta_{i,z+2}, \dots)$ are the spline knots for towel property $i = a, t, s$

and $(\alpha_{i,\delta_{i,z}}, \gamma_{i,\delta_{i,z}}, \lambda_{i,\delta_{i,z}}, \tau_{i,\delta_{i,z}})$ are the spline coefficients from Tables 6.3, 6.4, and 6.5 below.

Table 6.3 Spline knots and coefficients for strength (mN).

z	Knot δ_t	Intercept τ_t	Linear λ_t	Quadratic γ_t	Cubic α_t
1	0	369.9003	708.3274	0.0000	-21726.1991
2	0.125	416.0072	-310.0882	-8147.3247	63563.5524
3	0.25	374.0918	632.6222	15689.0075	-88741.4064
4	0.375	524.9873	395.1206	-17589.0199	63918.7891
5	0.5	424.3903	-1005.9411	6380.5260	-12377.8908
6	0.75	378.2833	-136.5326	-2902.8921	3870.5228
7	1	223.1963	-862.2557	0.0000	0.0000

Table 6.4 Spline knots and coefficients for absorbency (s).

z	Knot δ_a	Intercept τ_a	Linear λ_a	Quadratic γ_a	Cubic α_a
1	7.1421	14.3561	0.0000	-927.9298	7.1421
2	7.8128	3.4820	-173.9868	676.1634	7.8128
3	7.5158	-10.3426	-47.2062	-5383.4957	7.5158
4	5.3707	-79.3312	-1056.6116	22588.5413	5.3707
5	1.7999	53.3018	3178.7399	-1158332.8904	1.7999
6	1.8552	56.1843	-296.2588	283.3423	1.8552
7	4.0565	26.9176	-250.7824	623.4396	4.0565
8	4.8742	5.4372	-150.7203	646.7140	4.8742
9	4.8328	-5.1367	-46.9227	460.3066	4.8328
10	4.4941	-6.2049	26.9565	-75.7437	4.4941
11	4.2277	-3.9710	14.7996	5.3994	4.2277
12	4.0585	-2.3411	15.6662	-16.3428	4.0585
13	3.9756	-0.8051	13.0432	-10.5170	3.9756
14	3.9682	0.5002	11.3552	-12.0780	3.9682
15	4.0256	1.6115	9.4167	-11.6598	4.0256
16	4.1370	2.5190	7.5453	-11.7718	4.1370
17	4.2916	3.2252	5.6559	-11.7418	4.2916
18	4.4785	3.7296	3.7714	-11.7498	4.4785
19	4.6870	4.0323	1.8855	-11.7478	4.6870
20	4.9064	4.1331	0.0000	0.0000	4.9064

Table 6.5 Spline knots and coefficients for softness (g).

z	Knot δ_s	Intercept τ_s	Linear λ_s	Quadratic γ_s	Cubic α_s
1	0	7.1972	-21.1316	0.0000	-215.6093
2	0.125	4.1347	-31.2383	-80.8535	1441.9482
3	0.25	1.7829	16.1397	459.8771	-1984.1731
4	0.375	7.1106	38.1008	-284.1878	651.6091
5	0.5	8.7054	-2.4019	-39.8344	35.4183
6	0.75	6.1687	-15.6782	-13.2706	17.6942
7	1	1.6962	-18.9959	0.0000	0.0000

6.4. Optimization of a green towel design

In this section we formulate a design optimization problem where the assumption of a priori user preference is relaxed; further, preference construction and the resulting inconsistencies in utility estimates are included in the problem formulation. We examine three scenarios: no accommodation for preference construction; reactive accommodation, and proactive accommodation of utility inconsistencies.

We create a linked engineering and marketing model to design the optimal market entry for KermitCo. At first, the only design variable is KermitCo's recycled paper content. Then, construction of preference is added as a second design variable κ. The objective is to maximize the choice share of KermitCo's towel as determined by a latent class (discrete heterogeneity) multinomial logit model of paper towel utility. The estimation of the parameters of this model is discussed in Section 4.3, the product attributes $\boldsymbol{\zeta}$ being recycled paper content r, absorbency a, strength t, softness s, and price p. These part-worth utilities for KermitCo's towel, indexed by k, and competing products, indexed by j, sum as described in Equations (6.7)and (6.8), respectively. The available levels $\boldsymbol{\omega}$ of these attributes are described in the paragraph below. The objective function is calculated using the marketing model

$$\max f(r_k) = \sum_{\mathbf{l}} \left(\frac{\mathrm{e}^{v_{k,l}(r_k)}}{\sum_{\mathbf{j} \in \mathbf{J}} \mathrm{e}^{v_{j,l}}} \right) \left(\frac{\sum_{\mathbf{n}} \mathrm{P}_{l,n}}{N} \right) \tag{6.6}$$

$$\text{subject to } r_k \leq 1$$

$$r_k \geq 0$$

$$v_{k,l}(r_k) = \sum_{\zeta = \mathrm{a,t,s}} \beta_{\zeta,\omega,l}(r_k) + h_l(\boldsymbol{\beta}_{p,l}, p_k) + m_l(\boldsymbol{\beta}_{r,l}, r_k) \tag{6.7}$$

$$v_{j,l}(r_j) = \sum_{\zeta = \mathrm{a,t,s}} \beta_{\zeta,\omega,l,j} + h_l(\boldsymbol{\beta}_{p,l}, p_j) + m_l(\boldsymbol{\beta}_{r,l}, r_j) \tag{6.8}$$

where r_k is the recycled paper content of KermitCo, $k \in J$, $\mathrm{P}_{l,n}$ is the probability that subject n is in latent-class l where ($l = PickUps$, $Traders$, $Savers$), and N is the total number of subjects ($N = 217$). Functions h and m are functions that calculate part-worth for a given recycled paper content and price, created by fitting polynomial curves to the part-worth estimates for price and recycled paper content in Table 4.3. Prices and recycled paper content of competing towels are listed in Table 6.6.

Table 6.6 Prices and recycled paper content of competing towels.

	Bounty	**Brawny**	**Scott**	**Sparkle**	**Viva**	**Green Forest**	**Seventh Generation**
Price	\$2.20	\$2.23	\$1.97	\$1.90	\$3.15	\$2.78	\$2.67
RPC	0%	0%	0%	0%	0%	100%	100%

Figure 6.11 depicts the linking of the engineering and marketing model: The engineering model is depicted on the left and estimated part-worth parameters for the three-class latent class utility model are presented on the right hand side of Figure 6.11 for the different ratings of strength, softness and absorbency. For KermitCo's towel, the levels of strength, softness, and

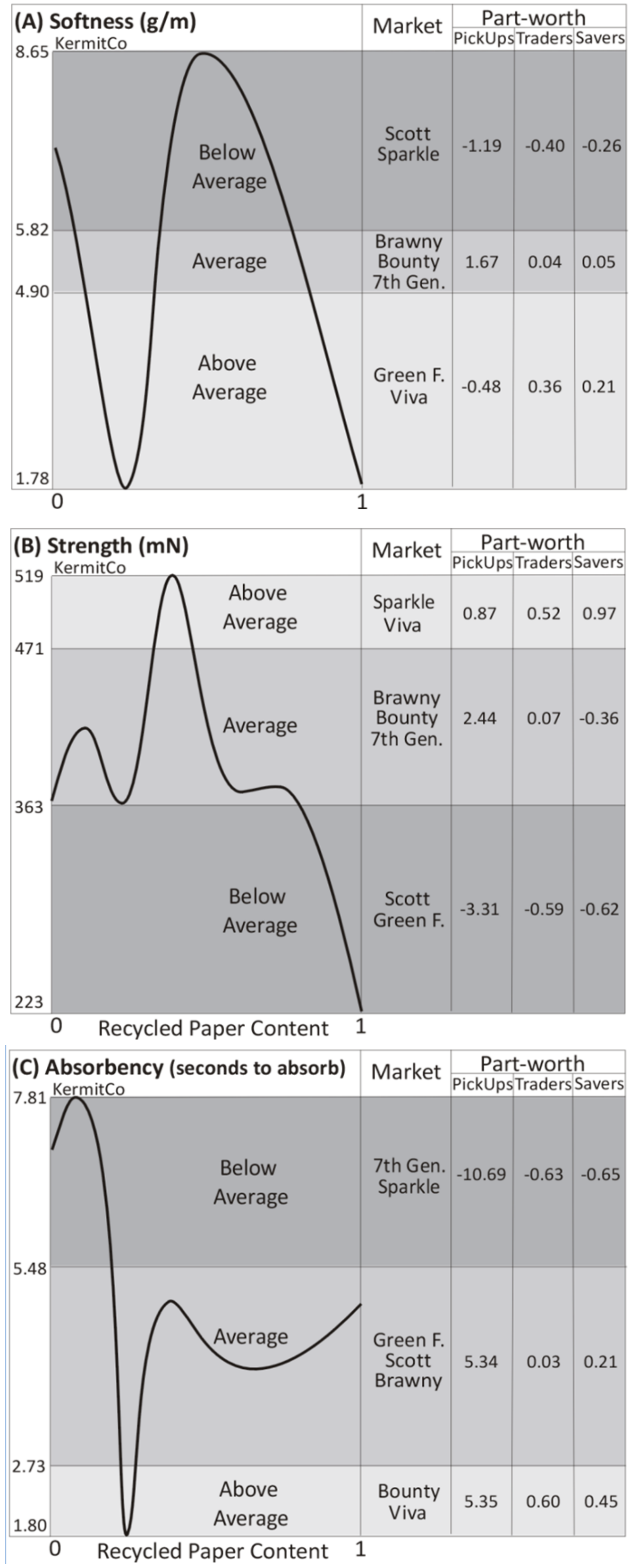


Figure 6.11 Engineering and marketing model.

absorbency are determined solely by the level of recycled paper content in the towel. The spline curves in Figure 6.11 respectively model the levels of softness, strength, and absorbency of KermitCo's towel for any given recycled content from 0 (0%) to 1 (100%).

The shaded regions in the spline curves represent category classifications that link the engineering and marketing models. As shown in the figure, for KermitCo's towel product k, the part-worths $\beta_{a,k,l}$, $\beta_{t,k,l}$ and $\beta_{s,k,l}$ are discrete values determined using $q_i(r)$ from equation (6.5) and the cut-offs $\boldsymbol{\theta}_i$ for absorbency, strength, and softness described in Table 6.2. For example:

$$\text{If } \theta_{t,1} \leq q_t(r) < \theta_{t,2} \text{, then}$$

$$\beta_{t,k,l}(q_t(r)) = \beta_{t,1,l} \tag{6.9}$$

Here $\beta_{a,1,l}$ is the part-worth for absorbency, 1 out of 3 (below average), for latent class l. These part-worths are shown in Figure 6.11. The part-worths $\beta_{a,j,l}$, $\beta_{t,j,l}$ and $\beta_{s,j,l}$ for the competitors are also shown in Figure 6.11 and were determined by categorizing the lab measurements of their strength, softness and absorbency listed in Table 6.1.

6.4.1. Reactive design for preference construction

Traders have inconsistent preference for recycled paper content between preference estimated in the discrete choice survey and their actual buying habits. In the reactive optimization approach, we assume that the reason for this inconsistency is that people do not know the recycled paper content of the towels, an assumption supported in part by other findings in the survey. Because the parameter that predicts the part-worth for recycled paper content is uncertain in the minds of the traders, the part-worth for recycled paper content, a function of this parameter, may also be uncertain. We address this uncertainty through an exploration of the design space over a range of part-worth parameters using κ as a scaling parameter on recycled paper content part-worth values for the Traders ranging from $\kappa = 0$ (past purchase self-reports indicate no preference for recycled paper content) to $\kappa = 1$ (preference estimates from discrete choice survey). For the latent class of Traders, equation (6.7) becomes:

$$v_{k,Traders}(r_k) = \sum_{\zeta=\mathrm{a,t,s}} \beta_{\zeta,\omega,Traders}(r_k) + h_{Traders}\big(\boldsymbol{\beta}_{p,Traders}, p_k\big) + \kappa m_{Traders}(\boldsymbol{\beta}_{r,Traders}, r_k) \tag{6.10}$$

and equation (6.8) is similarly modified.

6.4.2. Proactive design for preference construction

Having inaccurate information for environmental decisions may be indicative of missing a necessary intermediary between environmental attitude and behavior: the desire for environmental education about product decisions. A towel's design may be able to trigger this desire (or provide the desired information), resulting in product decisions where recycled paper content is known rather than merely guessed. In turn, this trigger may shift preference construction for environmentally friendly towels to one in which recycled paper content plays a dominant role in preference formation, as in the Trader's preference for recycled paper content in the discrete choice survey.

In the proactive optimization framework, it is assumed that recycled content education and/or preference construction can be controlled via design. Thus, preference construction is represented with a deterministic design variable κ. The optimization question changes to: what preference would KermitCo like the Traders to have for recycled paper content configurations, given all other preferences parameters remain the same? It is formulated as:

$$\max f(r_k, \kappa) = \sum_{\mathbf{l}} \left(\frac{e^{v_{k,l}(r_k)}}{\sum_{\mathbf{j} \in \mathbf{J}} e^{v_{j,l}}} \right) \left(\frac{\sum_{\mathbf{n}} P_{l,n}}{N} \right) \tag{6.11}$$

subject to $r_k \leq 1$

$r_k \geq 0$

$$v_{k,Traders}(r_k, \kappa) = \sum_{\zeta = a,t,s} \beta_{\zeta,\omega,Traders}(r_k) + h_{Traders}(\boldsymbol{\beta}_{p,Traders}, p_k) + \kappa m_{Traders}(\boldsymbol{\beta}_{r,Traders}, r_k) \tag{6.12}$$

$$v_{j,Traders}(r_j, \kappa) = \sum_{\zeta = a,t,s} \beta_{\zeta,\omega,Traders,j} + h_l(\boldsymbol{\beta}_{p,Traders}, p_j) + \kappa m_{Traders}(\boldsymbol{\beta}_{r,Traders}, r_j) \tag{6.13}$$

It is odd for marketers to think about selecting part-worths from a utility estimation and externally changing their scale. To frame the concept of κ in terms of marketing literature, it is like the concept of adjusting the scale parameter that Louviere et al. speak about (Louviere et al. 2002, Louviere, Hensher & Swait 2000). When combining two multinomial logit models, the part-worths of one model may be adjusted by a multiplicative scaling parameter in order to accommodate the size-effect in the part-worth coefficients caused by different levels of variance in the two models. Here, a scaling parameter is applied only to one attribute's part-worths, instead of applying the parameter to all part-worths in the model. There is no reason that the scale parameter must be thought of as constant across all attributes, because certainly some attributes have more impact on error terms in the models than others.

One realistic feature of this form of optimization is that the introduction of KermitCo's new product, in which it is assumed that careful design can trigger certain product preferences, also changes the preference for other products in the market. It also changes the relative preference between competitors: in this case, those that do and do not include recycled paper content.

6.4.3. Results

Optimization was performed using the standard evolutionary algorithm in Excel Solver (Frontline Systems accessed 2008) Evolutionary algorithms have the advantage of finding good, if not optimal, solutions for discontinuous search spaces (Eiben, Smith 2003)and were chosen for this study because of the many discontinuities created from including cutoffs in the modeling of user preference. The algorithm begins with an initial population of randomly generated designs and creates subsequent generations through a combination of mutations, crossovers, random local searches around the best members of the population, and elimination of the worst. This process terminates when 99% or more of the members of a generation have a relative difference of the objective less than the convergence tolerance. In each optimization run, an initial population of 150 members was used along with mutation rate of 5% and convergence tolerance of 0.00001. The combination of these parameters resulted in solutions that were repeatable and verified through perturbations as at least local optima. Results are examined for a number of price parameters for KermitCo's towel.

Results with no accommodation from construction of preference are reported in Table 6.7 for prices of $1.29, $2.20, and $3.00, corresponding to choice shares of 32%, 27%, and 23%, respectively. Price points of $3.00 and $2.20 share towel design due to the cut-off structure of the utility model.

Table 6.7 Optimization results without accommodation for preference construction.

Price	r_k	Choice Share	Softness (g/m)	Strength (mN)	Absorbency (s)
$1.29	0.33	32%	4.90	476	4.56
$2.20	0.27	27%	2.21	390	2.73
$3.00	0.27	23%	2.21	390	2.73

Reactive optimization was performed using three separate price points for the towels, and varying scale parameter in ten equal intervals from 0.0 to 1.0, corresponding respectively to the Traders' revealed and stated preferences. The results, plotted in Figure 6.12, indicate that the recycled paper content (RPC) solutions are not much influenced by when price is below the other firms in the market ($1.29) and dependent at mid-market and higher ($3.00) prices for parameter values between 0 and 0.4. At a price point of $2.20, if KermitCo were to design for and sell in a market where , they would lose 4.5% choice share versus designing for

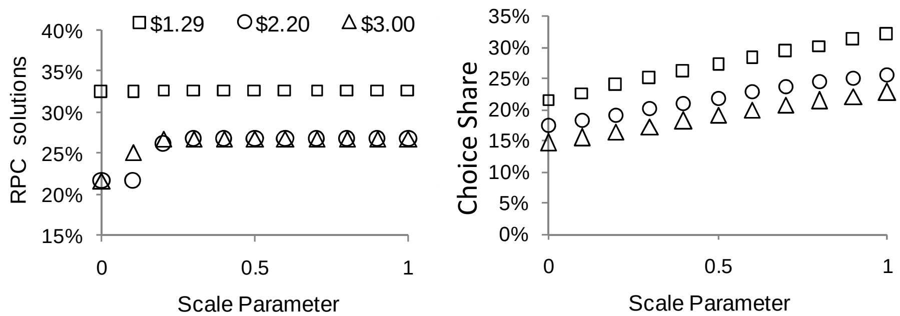


Figure 6.12 Reactive optimization results varying .

The choice shares with and without KermitCo at a price of $2.20 are shown in Figure 6.13 for low (0.0) and high (1.0) values of . As expected, the brands with some recycled paper content have larger choice shares when the scale parameter is high. Similar trends result from the other two price points.

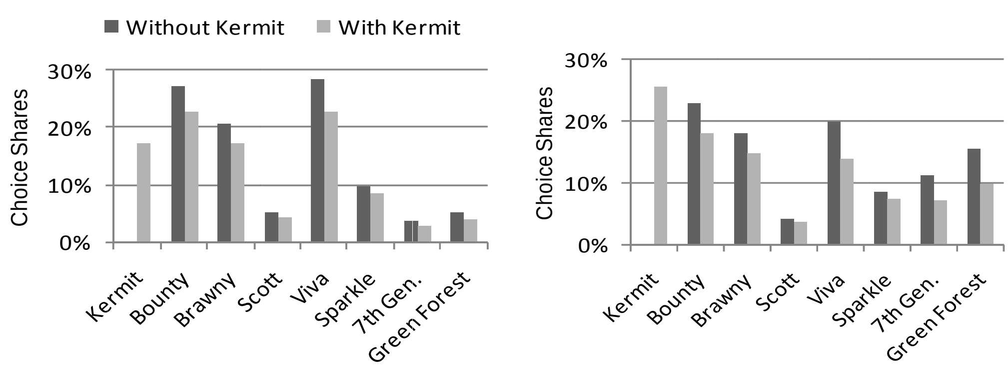


Figure 6.13 Choice shares from reactive optimization for scale parameters of 0.0 (left) and 1.0 (right).

The proactive optimization, which includes as a variable, was performed for multiple sets of bounds. Where is constrained between 0.0 and 1.0, the upper bound is active for all three price points; therefore, the solutions correspond to the right-most points in Figure 6.12. The upper bound was then relaxed to 5.0, representing a scenario where—through advertising or other means—the Traders' preference for recycled paper content could be increased beyond what was stated in the survey. For this scenario, an internal solution was found for each price point, as shown in Table 6.8.

Table 6.8 Proactive optimization solutions.

Price	κ	RPC	Choice Share	Softness (g)	Strength (mN)	Abs.(s)
$1.29	2.02	0.33	36%	4.90	477	4.56
$2.20	3.38	0.80	30%	5.28	363	4.19
$3.00	3.38	0.80	26%	5.28	363	4.19

6.5. Discussion

Out of the optimal points explored, KermitCo has the least choice share at $\kappa = 0$, where part-worth utility for recycled paper content is constant across the attribute's levels. This represents the status quo in the market: that users who indicate preference for towels with recycled paper content do not purchase them, nor do these users know the recycled paper content of the towels in the market. The results indicate that KermitCo will have a larger choice share if it proactively controls preference construction than if it designs without accommodation of construction of preference or reactively designs for inconsistent preference.

This research can be extended in a number of ways. The model can include the variance of the estimated user preference parameters. In the reactive approach, this would require addressing the propagation of uncertainty, because the value of the preference construction scale parameter κ is uncertain. In the proactive approach, the scale variable κ could be replaced with a more sophisticated expression or a quantitative model of the impact of advertising expenditures on preference construction. A more general model could also be applied, with κ as a random variable that applies differently to each parameter.

A life cycle analysis can be added to the case study to assess environmental impact, potentially introducing a trade-off between perceived eco-friendliness (recycled paper content) and actual environmental impact. The link between the engineering and marketing model could be improved with further exploration of the relationship between user and engineering assessment of strength, softness, and absorbency. The model uses categorizations for strength, softness, and absorbency (below average, average, and above average) in order to determine a towel's part-worth utilities for these attributes. Alternative expressions for these product attributes as continuous variables could be included once the link between user and engineering assessment is strengthened.

The results of the case study suggest that designers should attempt to control preference, or trigger specific preference constructions, for key product attributes that are prone to preference inconsistencies. When a design seeks to evoke a certain emotional state in emotional design (Norman 2004, Yoshimura, Papalambros 2004) the authors believe this emotional state enhances the preferences that align with the emotional state. For example, designing a car to look and sound sporty is likely to bring the associated product attribute of acceleration time to the foreground in purchase consideration. Using emotional design may help to trigger preferences for related product attributes.

For eco-friendly products, it is difficult to design towards an emotion without being accused of "greenwashing," presenting a product that has merely superficial environmentally friendly features. However, triggering preference for eco-friendly product attributes is different from "greenwashing," because the point of these triggers, or *product cues,* is to inspire users to investigate the environmental attributes of the product under consideration, and to construct their preferences in a manner similar to when they performed these explorations in the decision context of the design process. For example, a product attribute that could trigger a feeling of social obligation may trigger preferences similar to those exhibited during a survey.

Chapter 7 focuses on creating a design method that can identify such product cues for preference enhancement in green design, using a general approach that tests for relationships between product attributes. They will seek to identify product cues that inspire the user to call to mind their environmental concerns when constructing product preferences during purchase and use.

6.6. Conclusion

This chapter provides a framework for the integration of preference construction into linked engineering and marketing design optimization. Articulated here, through theoretical discussion and a specific example is the important distinction of customer preference parameters in engineering design: that they are dimensionless, estimated quantities, and subject to inconsistencies between design interactions and purchase decisions. These inconsistencies can be addressed with an uncertain parameter in the design optimization; or, as has been demonstrated, proactively attempting to eliminate the uncertainty with careful design could lead to a product that is more successful in the market. Hence the benefit was established of investigating the construction of preference as a design variable, and it is suggested that the design method in Chapter 7 can be used to identify relationships between product attributes that could trigger certain preference constructions.

Chapter 7. The Construction of preferences for crux and sentinel product attributes

7.1. Introduction

In Chapter 6, results from the proactive approach to incorporating the construction of preference in engineering design indicate that a green product design could benefit from a careful triggering of particular product preferences. One potential trigger may be the inclusion of design attributes can cause specific preference constructions for other design attributes. This chapter provides a general design method that could be used to identify such preference-triggering product attributes, and a brief discussion of how to apply the method is included in Section 7.6.3. However, the method is applied in this chapter to addressing a practical concern of this dissertation: is there a perception of low quality in green products, and particularly, in towels with recycled paper content? An attribute relationship termed *crux/sentinel* is rigorously defined to answer this question in the case study (and in future design studies). The results indicate that the answer is no, but they are not conclusive. The results in the chapter also reveal a perceived relationship between absorbency and quilting, which is important for KermitCo to keep in mind in future towel design iterations.

This chapter uses preference inconsistency tests with purposeful manipulation of the decision framework, an important aspect of decision context, to learn about the relationship between people and a product. The author believes that this is the true research potential of the construction of preference in design methods. While Chapter 6 demonstrates how relaxing the assumption of a priori customer preference in design optimization may lead to incrementally better product design, this chapter uses it as a new design tool. When people have trouble articulating their opinions on a sensitive design attribute that involves difficult trade-offs, such as safety or environmental issues, merely broaching the subject of these trade-offs with potential customers may be impossible. While they may not be able to express their preferences, or indicate the stability of their preferences, designers can use carefully constructed context experiments to tease out their feelings, concerns, and perceptions. A wide range of design methods can be developed from preference elicitation methods that use decision context.

It is duly noted that this approach bears a resemblance to experiments performed in human factors and ergonomics engineering, in which some small but important aspect of a human task is varied across an experimental design (for example, time to complete the task, weight of an object being lifted, or type of grip on a door handle). A researcher can use this approach to learn about the physical or perceptual relationship between humans and products. The experiment and method introduced in this chapter can be seen as an extension of this work, in that it investigates the effects on the human through decision context manipulation to learn about the cognitive relationship between humans and products.

This chapter demonstrates that even small modifications to a preference elicitation technique in a design process can cause large inconsistencies in customers' constructed preferences. One can elicit a variety of inconsistent constructed preferences by making small modifications to decision context, specifically in this chapter, a discrete choice question framework. This research 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 with small changes in decision context. The preference inconsistency is identified through the comparison of results from separate discrete choice surveys analyzed with multinomial logit analysis. Section 7.3 offers a new analysis technique, called the full factorial marketplace, for comparing results from separate mnl estimates.

This chapter develops a set of hypotheses expressed as inequalities between compared preference constructions that define the customer's conceptualized relationship between *crux* attributes, namely, product attributes that are important and complex; and *sentinel* attributes, namely, product attributes that have a perceived association with crux attributes but are less complex and often easier to evaluate in product purchase decisions. First, the chapter describes the terms crux and sentinel attributes, the relationship between them using five hypothesized inequalities, and the techniques used to explore these hypotheses. Next, these techniques are applied to an example product; following is a description of the survey method used, a report of the survey results, and an analysis of the hypotheses. The discussion section offers an explanation for the findings, a generalized 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.

7.2. Crux attributes influence preference construction

The terms crux and sentinel are intentionally new to designers, distancing 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.” Insofar as people perceive that a sentinel attribute “stands guard” for its crux attribute, which is a “chief problem” and “difficult to interpret,” the author submits this terminology as appropriate (Oxford English Dictionary accessed 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 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, airbags may appear very important to automobile customers, but what they really care about is avoiding injury during crash. Asking customers “How crashworthy would you like your car to be?” is pointless. Therefore, designers present crashworthiness as a bundle of 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.

It is postulated 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 behavioral literature has documented a related finding in judgments of frequency (Fischhoff, Slovic & Lichtenstein 1978). To study the crux-sentinel relationship in the context of consumer choice, 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 are investigated. Table 7.1 gives the general structure of the experiment and shows the relation of the three discrete choice question frameworks. In Table 7.1, 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 of 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. To put the approach in terms of the discussion in Section 4.1, Table 7.1 represents the manipulation of decisions context in the comparative preference inconsistency test. Hypotheses are stated in terms of the three scenarios in Table 7.1 to facilitate their description in the context of the present study.

Table 7.1 Overview of variation in preference elicitation technique.

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

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.

$$I_{Sentinel,A} > \max_{i=B,C}\{I_{Sentinel,i}\} \quad (7.1)$$

- In scenario A, where the sentinel attribute stands in for the crux attribute, the sentinel attribute should have high importance in choice. This importance should be at least as high as the importance of the crux attribute $Crux$ in scenario C. To easily test the statistical significance of the hypothesis, strict inequalities are used. Thus, the importance of a sentinel attribute in product choice scenario A is greater than the importance of the associated crux attribute in scenario C.

$$I_{Sentinel,A} > I_{Crux,C} \tag{7.2}$$

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

$$\max_{i=A,B,C}\{I_{Sentinel,i}\} - \min_{i=A,B,C}\{I_{Sentinel,i}\} > \max_{i=A,B,C}\{I_{Non-sentinel,i}\} - \min_{i=A,B,C}\{I_{Non-sentinel,i}\} \tag{7.3}$$

- 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.

$$I_{Sentinel,C} < I_{Crux,C} \tag{7.4}$$

- Equation (7.5) 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 is discussed in Section 4.3. In scenario A, the configuration of the sentinel attribute hypothesized 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.

$$\beta_{Sentinel\ configuration\ predicted\ to\ be\ most\ preferred,A} > \beta_{Other\ sentinel\ configurations,A} \tag{7.5}$$

These inequalities will be tested in the case study.

7.3. A new approach: full factorial marketplace analysis and importances

A multinomial logit (mnl) model of utility theory, explained in Section 4.3, is used to evaluate the above hypotheses. This type of model is commonly used in preference estimation, and frequently employed in recent integrated engineering marketing design studies. In order to test the hypotheses about preference construction and subsequent changes in attribute importance, the analysis must include comparison of results across survey versions. Utility is not estimated on an absolute scale, and therefore one cannot compare part-worths across survey versions directly when the parameters are estimated separately. However, one can normalize utilities to the same scale in the form of choice share per product using Equation (4.26). Typically, Equation (4.26) is used to predict the choice share of several competing products; this analysis technique diverges 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 colors (red, blue, green) is described in Table 7.2.

Table 7.2 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 (4.26) 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 versus other attribute/levels, the higher its part-worth utility will be, and the larger the choice share of the full factorial marketplace that 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 normalizing 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 (7.6), 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.

$$\hat{P}_{\zeta\omega} = \sum_{j} x_{j\zeta\omega} P_j \tag{7.6}$$

The full factorial marketplace is a new aggregate measurement technique used to investigate the effects of preference construction on the relative importance of attributes in product decisions. Importance in the full factorial marketplace is defined 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 (7.7) and (7.8).

$$\hat{P}_{\zeta 1} = \sum_j x_{j\zeta 1} P_j \tag{7.7}$$

$$\hat{P}_{\zeta 2} = \sum_j x_{j\zeta 2} P_j \tag{7.8}$$

For an attribute with levels not very important in predicting product choice, 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 the no-choice 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 (less than 0.1%) and was 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 (7.9).

$$I_\zeta = \sum_\omega \left(\hat{P}_{\zeta\omega} - n^{-1} \right)^2 \tag{7.9}$$

7.4. Survey instrument design and administration

Part 1 of the survey described in Section 3.3 was designed as a case study 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 2004a). The study 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 hypothesized 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 (RPC) 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 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 7.3 repeats Table 7.1 as applied to the towel study, in which three versions of a discrete choice survey, with ten multiple choice tasks each, were used as the three scenarios described in Table 7.1. The attribute/levels available for choice in the survey are presented in Table 3.3.

Table 7.3 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
Pattern (non-sentinel)	2 configurations	2 configurations	2 configurations
Packaging (non-sentinel)	3 configurations	3 configurations	3 configurations

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%

Respondents answered one of the three versions of Part 1 of the survey. 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, the price was fixed across conditions to allow respondents to focus on the other attributes of the scenarios.

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 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 respondents (Sawtooth Software 1999). 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, but all three towels were patterned and recycled paper content varied as 30%, 60%, and 100%. Responses to these fixed questions were not included in the preference estimation.

7.5. Survey results and analysis

The data for each survey version were fit with a hierarchical Bayesian (HB) estimation of the multinomial logit model, described in Section 4.3, using Software's CBCHB program (Sawtooth Software 2005). 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 7.4. The results were also estimated with Sawtooth's log likelihood (LL) maximization, a more "traditional" approach than HB estimation (Sawtooth Software 1999, Louviere, Hensher & Swait 2000). The relationships between attribute importances were the same using both estimation techniques, but only the HB estimate gave significance at the 0.05 level for most of the hypotheses, as detailed in the paragraph below. A HB approach produces estimates with better statistical properties than a LL maximization when there are a small number of data points. With only approximately 70 subjects in each group, and only 6 questions answered by each subject (plus 2 fixed questions that were not analyzed), the HB approach had much less variance in its estimated parameters.

Table 7.4 Part-worths (standard error) estimated in HB multinomial logit model.

Attribute	**Level**	**Version A**		**Version B**		**Version C**	
Quilting	Quilted	1.36	(0.038)	0.65	(0.038)	0.46	(0.068)
	Not Quilted	-1.36	(0.038)	-0.65	(0.038)	-0.46	(0.068)
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% RPC	-1.85	(0.150)	-1.65	(0.160)	-1.85	(0.239)
	30% RPC	-0.65	(0.074)	0.04	(0.076)	-0.39	(0.153)
	60% RPC	0.76	(0.056)	0.44	(0.065)	0.99	(0.123)
	100% RPC	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 7.5 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 (7.6). Table 7.5 reports importance metrics computed with Equation (7.9) and their standard errors, estimated using the δ method (Rice 1995). 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, although this value was not significantly different from that of absorbency in version C—refer to Equation (7.11) below.

The computed metrics satisfy the hypothesized inequalities, Equations (7.1) through (7.5), on the relationship between the sentinel attribute quilting and the crux attribute absorbency:

Equation (7.1):

$$I_{Quiling,A} = 0.38 > 0.16 = \max_{i=A,B,C}\{I_{Quilting,i}\} \text{ (p <0.05)} \qquad (7.10)$$

Equation (7.2):

$$I_{Quilting,A} = 0.38 > 0.34 = I_{Absorbency,C} \text{ (cannot reject hypothesis that these values are equal)} \qquad (7.11)$$

Equation (7.3) for the non-sentinel attribute packaging:

$$\max_{i=A,B,C}\{I_{Quilting,i}\} - \min_{i=A,B,C}\{I_{Quilting,i}\} > \max_{i=A,B,C}\{I_{Packaging,i}\} - \min_{i=A,B,C}\{I_{Packaging,i}\} \qquad (7.12)$$

Simplifies to:

$$I_{Quilting,A} + I_{Packaging,A} = 0.40 > 0.15 = I_{Quilting,C} + I_{Packaging,C} \text{ (p<0.05)} \qquad (7.13)$$

Equation (7.3) for the non-sentinel attribute pattern:

$$\max_{i=A,B,C}\{I_{Quilting,i}\} - \min_{i=A,B,C}\{I_{Quilting}\} > \max_{i=A,B,C}\{I_{Pattern,i}\} - \min_{i=A,B,C}\{I_{Pattern,i}\} \qquad (7.14)$$

Simplifies to:

$$I_{Quilting,A} + I_{Pattern,A} = 0.39 > 0.14 = I_{Quilting,C} + I_{Pattern,B} \text{ (p<0.05)} \qquad (7.15)$$

Equation (7.4):

$$I_{Quilting,C} = 0.09 < 0.34 = I_{Absorbency,C} \text{ (p = 0.068 <0.10)} \qquad (7.16)$$

Equation (7.5):

$$\text{Preference}_{A,\text{"}Quilted\text{"}} = 1.36 > -1.36 = \text{Preference}_{A,\text{ "Not Quilted"}} \text{ (p<0.05)} \qquad (7.17)$$

Equations (7.10), (7.13), (7.15), and (7.17) are statistically significant at the p < 0.05 level using a Z-distribution Wald test. We also preformed Tukey tests on equations (7.13) and (7.15). The results remain significant (p < 0.05) even after performing the more conservative test accounting for the distribution of the range. Equation (7.11) does not meet the statistical criterion, but the estimated importance parameter values conform to the inequality. Equation (7.16) 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, there was a reversal of the predicted direction of inequality in Equation (7.5) for the hypothesized sentinel attribute of *recycled paper content*: the level hypothesized to be associated with the more-preferred levels of the crux attributes, 0% RPC, was in fact less-preferred as compared to other levels (30%, 60%, 100%). As this violates the hypothesis of Equation (7.5), we find that recycled paper content is not a sentinel attribute for strength, softness, or absorbency. Implications and explanations are addressed in Section 7.6.1.

The aggregate full factorial market shares for all attributes are shown in Figure 7.1. Figure 7.1(a) shows the aggregate full factorial market shares of quilted towels and not quilted towels across the three survey versions (A,B, and C); Figure 7.1(b) shows the same for pattern; Figure 7.1(c) for recycled paper content; and Figure 7.1(d) for packaging. 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 7.1(b), 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 prefer 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. From Figure 7.1(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 7.1(d) 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 7.2 shows market share aggregated in terms of towels with 0% and greater 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 have 100% recycled paper content.

Differences in attribute importance must be accompanied by differences in attribute preference, or preference inconsistency, which Figure 7.1 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 7.1(d), 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 gray in the figure), and thus the preference for "1 roll" does vary significantly across survey version. However, in Figure 7.1(a), the full factorial aggregate market share for "Quilted" (shown in the lightest gray) is significantly different between survey Version A and C, indicating a preference inconsistency.

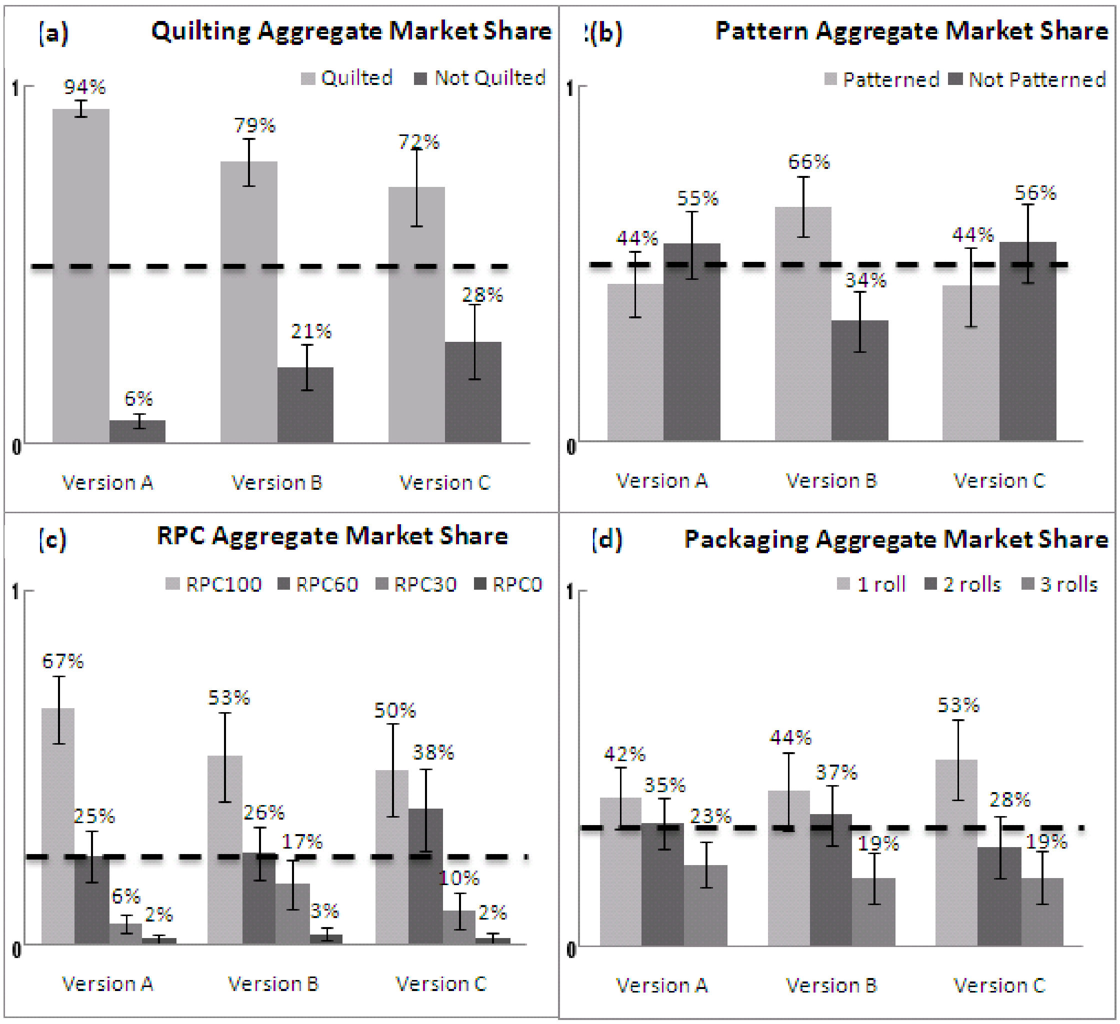


Figure 7.1 Aggregate full factorial market shares.

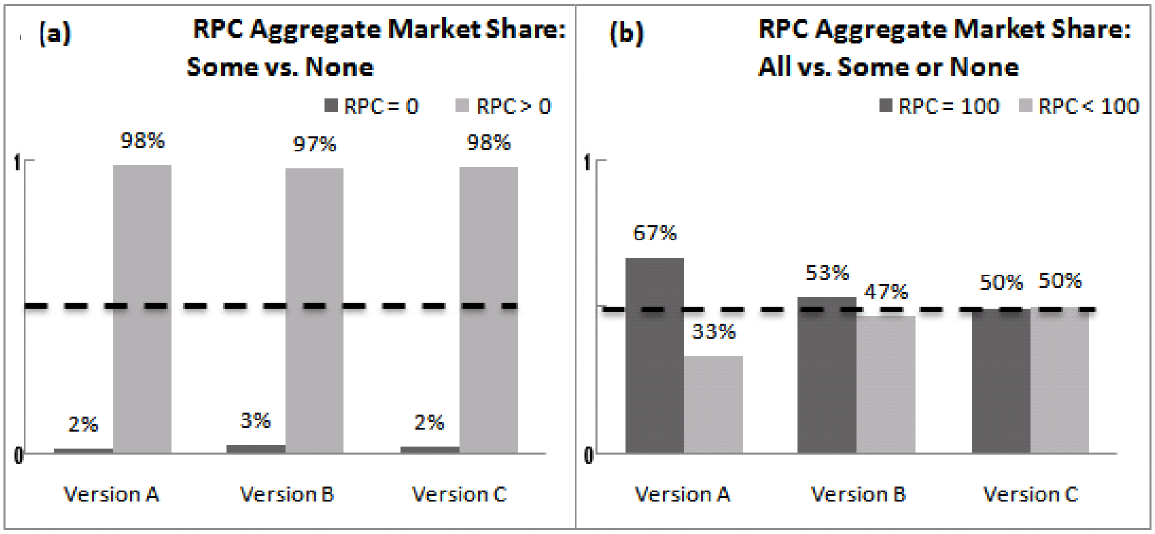


Figure 7.2 Aggregate market share in the full factorial marketplace for recycled paper.

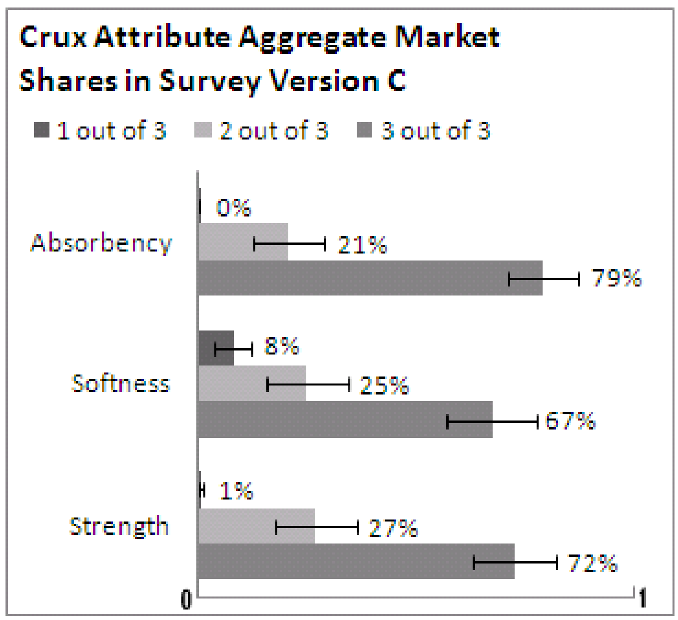


Figure 7.3 Full factorial aggregate market shares for strength, softness, and absorbency.

The importance of the crux attributes—strength, softness, and absorbency—must also be investigated. 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 7.3. 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.

To investigate if respondents perceived dependencies between attributes that were not related to the crux/sentinel relationship, main effects were analyzed with Sawtooth's SMRT 'Counts' routine (Sawtooth Software 1999). 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 ($p<.01$) and the other attributes were not. In version B, recycled paper content and quilting had a significant effect ($p<.01$). In version C, strength, softness, absorbency, and recycled paper content were all significant predictors of choice ($p<.01$). 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 (7.4) 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 – while quilting is a significant predictor only in versions A and B, recycled paper remains a significant predictor across all three versions.

The counts of responses to the two fixed questions, described in Section 7.4 are reported in Table 7.6. A chi-squared 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's respondent population preferred a 100% recycled paper towel than that of the other versions' respondent populations, but this difference was not statistically significant.

Table 7.6 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%)	

7.6. Discussion

7.6.1. 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 Equations (7.1) through (7.5). 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 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 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, because the hypothesis in Equation (7.5) 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, Blamey 2001). Findings in Chapter 4 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 lay 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 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.

7.6.2. Implications in paper towel design case study

For KermitCo, these results are promising. They can proceed with an active approach to designing for construction of preference, using a method structured around Section 7.6.3 below. Using this method, they can investigate any number of product attributes, such as specific towel patterns, prints, colors, textures, and wrappings that will trigger a favorable construction of preference for towels with recycled paper content. Using the design optimization approaches of Chapter 6, they can assess what range of manipulation of preference for recycled paper content is possible and choose to include specific design features (and potentially an associated advertising claim) in an attempt to trigger in customers the specific construction they have identified as optimal for the sales of their product.

KermitCo is also concerned that their customers perceive a link between low quality and recycled paper content. The results of this chapter indicate no such link, but for reasons discussed in Section 7.6.1, these results cannot be considered conclusive. However, the results indicate that it is within the realm of possibility that customers can construct their towel preferences without perceiving a link between recycled paper content and low quality.

7.6.3. Generalized constructed preference design method 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. A constructed preference design method for studying attribute relationships in any product is given below, with relevant material from this chapter included in parentheses.

1. Identify product attributes for study (crux/sentinel attributes)
2. Hypothesize relationships between the importance metrics of the attributes (Equations (7.1) through (7.5))
3. Choose a set of preference elicitation scenarios to test the hypotheses (Table 7.1)
4. Use these scenarios to design an experiment (Section 7.4)
5. Administer the preference elicitation experiment (Section 7.4)
6. Analyze results, estimate preferences (as part-worths, results in Table 7.4)
7. Check that the different scenarios elicit statistically different preferences (see below)
8. If applicable, calculate full factorial aggregate market shares (Equation (7.6))
9. Calculate attribute importance metrics in the various scenarios (Equation (7.9), results in Table 7.5)
10. Test hypotheses numerically; accept or reject (Section 7.5)
11. Analyze results graphically to understand findings (Figure 7.1, Figure 7.2, Figure 7.3)
12. Discuss implications of results (Section 7.4)

As a note to Step 7 above, our approach in the present study was to check that: (a) 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 values; (b) the variance on the parameters were in the same range; and (c) the differences between estimated part-worths across versions fit the hypotheses about the relationship between crux and sentinel attributes. Here, the fit (a) was tested by estimating parameters that the three versions shared (quilting, pattern, packaging, recycled paper content) with log likelihood maximizations of combined and separate models. The combined model had a LL of -2200 and the separate models had log likelihoods of-652,-792, and -721 for versions A, B, and C. A Chi-squared distribution with 8 degrees of freedom was used to determine that the separate models provided a better fit than the combined model ($p<.001$).

One can use the generalized 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 the 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 generalized 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.

To use the methodology to investigate for product attributes that trigger, or cue, certain constructions of preference for green product attributes, new hypotheses can be investigated based on importance relationships. The researcher would be looking for product attributes that, when included in the choice experiment, boost the importance of the green product attributes without necessarily increasing their own importance. The basic hypotheses for the identification test would look something like:

Table 7.7 The basic structure for an importance-based green preference trigger test.

Attribute	Scenario A	Scenario B
Trigger (T)	Not mentioned	Fixed
Green (G)	Configurable	Configurable

$$I_{T,B} < I_{G,B} \tag{7.18}$$

$$I_{G,A} < I_{G,B} \tag{7.19}$$

$$I_{T,A} \approx I_{T,B} \tag{7.20}$$

Based on the results of the above case study, it is suggested that this green preference trigger experiment be conducted with actual products instead of worded descriptions in a manner that takes extra precautions against creating social desirability bias in respondents' product decisions. After preference triggers are identified, specific design details, paired with advertising and marketing work, could move constructed preference to a precise location in the customer's mind during purchase. Further discussion of this approach is left to future research.

7.6.4. 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 of the 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, 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. note this difference in approach, without explicitly stating the reason as construction of preference (Pullman, Moore & Wardell 2002). They compare customer preferences elicited from QFD and directly from conjoint analysis (a discrete choice survey), and the resulting optimally designed products. They note that the products were different on important attributes, and state 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 generalized constructed preference design method detailed in Section 7.6.3 is directly applicable in the QFD process. If a design team were 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 were 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 maneuverability. Maneuverability (function) may be perceived to be a sentinel attribute related to safety (also a function). The customer will not put themselves purposefully into harms' way to test the crux attribute safety, but will rely on assessing the sentinel attribute of maneuverability for their assessment of safety. Now consider the same example with in 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 maneuverability 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 generalized 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.

7.7. Conclusion

This study 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 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 whether one attribute can serve as a sentinel for two different crux attributes at the same time.

Exploring the relationship between crux and sentinel attributes 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 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. Understanding preference inconsistencies offers greater insights into the relationship between user and product design.

Chapter 8. Conclusion

8.1. Contributions

This research offers three contributions to the incorporation of construction of preference in engineering design: a generalized framework to help designers understand the construction of preference as preference inconsistency, heterogeneity, and a combination of the two; a method of incorporating construction of preference into an integrated marketing and engineering design optimization; and a new design method that uses construction of preference to identify relationships that customers perceive as existing between product attributes.

Using the discussion of decision context and experimental framework presented in Chapter 4, designers can create decision experiments that manipulate a selected element of decision context to capture the inconsistency and/or heterogeneity in their product's customers' preferences. There remains no hard rule for when to model heterogeneity versus inconsistency, or when to model both. As the analysis of the case study suggests, it is up to designers to choose which model to use, based on their understanding of their customers and examination of their interaction with the preference elicitation procedure.

Chapter 6 integrates customer preference and engineering data in a design optimization for maximum choice share. Two approaches for addressing construction of preference are introduced: proactive and reactive. In the reactive approach, construction of preference is modeled as an uncertain design parameter, with the expectation of the uncertain parameter referenced by the optimization. In the proactive approach, variable construction of green preference is modeled as a variable in the design optimization. Using a weighting factor on the spline function of green preference values, the optimization determines the optimal construction of preference as well as the configuration of other design variables.

Chapter 7 provides a design method that uses preference inconsistencies to identify customer-perceived relationships between product attributes, demonstrated on the identification of the crux/sentinel attribute relationship. Hypothesized inequalities between the estimated importances of attributes in product decisions are the foundation of the method. A new technique called the full factorial marketplace allows the design methodology to be used with homogenous multinomial logit model estimates. The merits of the new design method are discussed, including its potential for identifying product attributes that can trigger specific construction of preference for "greenness," along with a brief proposal of the accompanying experimental structure. The design methodology of Chapter 7 paired with the green design advice in Chapter 2 forms the beginning of a green preference trigger exploration.

These chapters serve as a starting point to the incorporation of construction of preference in engineering design, with a case study in a field of design that is both critically important and susceptible to preference inconsistencies: green product design. These contributions help designers to consider construction of preference in future attempts to integrate customer preference with engineering considerations in green design, and aim to alleviate reliance on other product attributes, such as efficiency savings, to sell green products. The results give hope that "greenness" can be an appealing product attribute in its own right.

The case study did not determine that people associated recycled paper content in towels with low quality. However, because of probable social desirability bias in the survey respondents' answers, the results are inconclusive. The survey respondents that were interested do not actually purchase green products in the market. This behavior, a preference inconsistency, may be due to a number of factors. These respondents may be particularly susceptible to social desirability bias; they may be uneducated as to the greenness of the products they currently buy; or green products may be unavailable where they shop. Whatever the reason for the discrepancy, designers can most likely influence their preference constructions through inclusion of key product attributes.

There are at least eight cognitive intermediaries between environmentally-concerned attitudes and environmentally-friendly behavior documented as documented in academic literature that designers should consider addressing in green product design. It may be that people do not have a *sense of responsibility* for the problem: they feel perhaps that government or business should take care of their environmental concerns. They have not developed the resources required to make the *complex decisions* involved in buying green, nor have they developed the supplemental *decision heuristics* to help them make these decisions. They may not *trust* the companies that say their products are green or the many different eco-labels that purport the same. When they learn that decisions they make negatively impact the environment, they may experience *cognitive dissonance* that causes them to change their attitudes in order to resolve this dissonance. They may feel *guilty* and therefore deny or disguise their non-green purchases. Lacking *motivation*, people may be concerned, but not willing to change. Finally, although they do care, they may see buying green as *altruistic* and perceive an implicit sacrifice in purchasing green product. These cognitive intermediaries all play some part in the question at hand and interact in the construction of preferences for green products.

8.2. Open questions

An investigation of green product cues, or product attributes that provide a heuristic to the customer for judging a product's greenness, is a field of research complementary to that of green preference triggers: the latter would trigger a customer to assess greenness, and the former would indicate greenness. Perhaps one product attribute could do both. The author plans to repeat experiments from Chapter 4 and Chapter 7 with physical paper towel prototypes in the near future, adding preference cues and trigger experiments.

The cognitive intermediaries discussed in Chapter 2 must each be better understood for designers to utilize them effectively in green design strategies. Their role in the construction of green preferences can be better understood through preference inconsistency experiments. For example, it may be possible to determine specific levels and timing of incentives involved with the use phase of a green product in order to prompt a shift from extrinsic to intrinsic motivation for green product use and purchase. Knowing that people are likely uneducated or in denial about the environmental impacts of the products they currently use, and understanding that it would be to the advantage of green products to change this situation, designers can study marketing strategies for introducing negative information about competing products and incorporate ideas from these strategies into their designs.

An important contribution to a product's environmental footprint is how a person uses the product: its use. People do have preferred uses of a product, and when presented with a new, green use option for a familiar product, people may not switch to the green usage option even if they originally bought the product for this reason. For example, a dishwasher may be purchased for its water-saving cycle options, but a customer may not understand how to use these options or may never use them out of habit. A condensed version of laundry detergent may be used in the same quantities as the previous non-condensed version. Thoughtful design can aid in green product use as well as green product purchase, and this dissertation does not address this important part of green product design, although it does provide new methods that could help other researchers to do so.

The proactive model in Chapter 6 can be expanded in a number of ways. Controlling the construction of preference is modeled as a scaling term of the preference parameters for recycled paper content. More research can be done on how to represent the control of construction of preference via manipulating the values of preference parameters: is it realistic to use a scaling parameter? When should a more complex functional relationship be used? How can the appropriate function be identified? How might this function change if preference is controlled via design, advertising, policy, or education efforts? With the exploration of these questions, there is the potential to link the pro-active optimization to models of life cycle analysis, advertising cost models, models of technology policy implementations, and perhaps even education-related models, such as models of learning.

The model assumes that green preference construction of a particular configuration can be triggered through the inclusion of a product attribute. This preference construction is a variable in the design model. It is also a variable in the log likelihood maximization of the latent class model. These two maximizations could be linked so that the variable part-worths are adjusted simultaneously in the two models. Also, the assumption of a green preference trigger could be changed to a different type of marketing model inclusion.

Some contributions of this dissertation could be supplemented with additional mathematical analysis. The analysis technique of the full factorial marketplace deserves a formal mathematical exploration, including a thorough examination of the meaning and implications of attribute importances in models other than the mnl model. The technique may be useful to a wide variety of researchers, as it could potentially allow for importance comparisons across different types of models. There is opportunity to further develop the preference inconsistency framework of Chapter 4. Future work in this area will include the preference testing of "artificial" data sets to illuminate the different modeling approached, as well as a discussion of how the modeling of error fits into these considerations. The framework leads to the inevitable question of exactly how much decision context can change before there is nothing to learn from the experiment: what constitutes a preference inconsistency test *versus* a comparison of two different decisions? Conversely, what makes one decision unique or distinguishable from another?

If two engineering models of the same process or property relationship exist, it is typically possible to verify that one is more accurate by comparing the results to empirical data. However, this is not possible with inconsistent preference models in engineering design, as there are no empirical data for a purchase decision of a product that has not yet been designed. Chapter 4's discussion and framework of preference inconsistency and heterogeneity highlights that customer data can be modeled in multiple fashions. As of now, it is left to the designer's intuition to select the modeling approach that is best for the design decisions at hand. As optimization typically implies that a “best” solution can be reached, the multidisciplinary optimization community must recognize that this word has different meanings for different models from different fields, and address this difference.

Designers can use the methods presented here to explore how they construct their own preferences during the design process. We too are prone to inconsistent preference constructions, and it would make for interesting research to see how designers' preference inconsistencies interact with the design process. To this end, a chart or map of all documented judgment heuristics, biases, and effects could be created and investigated for links with the design process. Designers could be made aware of latent biases in their decisions.

One way design communicates with people is through evaluations and judgments based on perceptions: perceptions of products, perceptions of product attributes, and perceived relationships between product attributes. When product decisions touch on complex decisions, such as environmental impact, perceived relationships between product attributes that are difficult or impossible to evaluate and those that are easy to evaluate play an important role in the formation of *product heuristics* that guide decision making about products. With the advent of product attributes that are imperceptibly small, such as product functions provided through "nano-features"; imperceptibly present, such as biotechnology advances in health; and/or partially intangible, such as service design and software design, communication between the product and person will grow increasingly reliant on heuristics.

The number of products available to consumers continues to climb, and consumers have more choice now in product categories than ever before. Also, manifold psychological issues have become important during product purchase and use, such as concern for the environment, safety, morality, and individualism. As demonstrated, regarding environmental concerns, issues of psychological import can have unanticipated effects on product decisions, via the construction of preference. Designers will use methods such as the ones presented here to shape the product decisions of the future, in which customers will evaluate imperceptible attributes to make imperative decisions. Form will no longer follow function, but instead will guide judgment.

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