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Visual quality and sustainability considerations in tolerance optimization: A market-based approach

Steven Hoffenson*, Andreas Dagman, Rikard Söderberg

Product and Production Development Chalmers University of Technology Hörsalsvägen 7A, 412 96 Gothenburg, Sweden

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ABSTRACT

During the late stages of product development, dimensional tolerances are chosen to balance quality requirements with manufacturing costs. Designers typically judge how much variation in the product dimensions should be allowed while still maintaining the perception of high quality for the product or brand, but this is rarely based on a quantitative understanding of how consumers actually perceive variation and quality. Likewise, environmental sustainability priorities, which can also be affected by dimensional tolerances through production waste and product lifespan, are often chosen without knowing how such attributes are received by consumers. This paper presents a survey-based technique for understanding how tolerance and pricing decisions influence market demand and manufacturer profits, accounting for consumer perceptions of visual quality and environmental friendliness. A case study of a mobile phone design is explored, including variation propagation simulation, manufacturing cost and environmental impact estimation, online choice-based conjoint (CBC) survey design and administration, consumer demand model construction, and profit maximization for the markets in China, Sweden, and the United States. The results show how consumers make trade-offs in purchasing decisions when choosing among mobile phone attributes including price, environmental friendliness, and visual quality, and different scenarios are compared based on survey design, country of interest, and the company's global product strategy.

1. Introduction

Product developers must understand what drives the market in order to balance their design decisions for optimal sales, revenues, and profits. Decisions made in the embodiment design phase can act as trade-offs between benefits for one design objective, such as lower costs, and benefits for another objective, such as higher quality. The link between manufacturing costs and product quality has been the subject of considerable research in recent decades, particularly in the context of choosing geometric tolerances (Hong and Chang, 2002). The established methods generally seek to minimize production costs within some threshold for allowable dimensional variation; however, economic sustainability for the company also relies on revenues, and it is not well-understood how product quality influences consumer demand and sales.

Moreover, recent studies have shown that tolerance decisions can serve as trade-offs between economic and environmental objectives (Hoffenson et al., 2014), both of which factor into the broad idea of sustainability (World Commission on Environment and Development, 1987; Elkington, 1997). Manufacturers, though, do not have the same incentives to design for environmental sustainability as they do for economic sustainability, and therefore a stronger understanding of how environmental outcomes influence manufacturer profits is needed.

This study investigates how tolerance optimization can be performed in the context of the market by framing an approach to market-based tolerance optimization and showing how such decisions can influence attributes that are important to consumers, namely quality, environmental friendliness, and price. The result is a novel framework for product developers to optimize tolerances with an objective measure of how those tolerances affect demand and profitability. This paper describes a means for quantifying the effect of tolerance-related visual quality and sustainability on consumer demand, presents a practical optimization context, shows how it can be applied with an example case study of a global product, and discusses lessons learned from the case study.

This approach leverages models and techniques from multiple academic and practical disciplines in a new way. First, an engineering-based analysis determines how design decisions regarding tolerances influence outcomes such as manufacturing

* Corresponding author. Tel.: +46 31 772 82 85.
E-mail addresses: stevenh@chalmers.se (S. Hoffenson), andreas.dagman@chalmers.se (A. Dagman), rikard.soderberg@chalmers.se (R. Söderberg).

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costs, product variation, and environmental sustainability. These outcomes then affect the purchaser and end-user from a decision theory perspective, and consumer surveys illuminate how the market will respond to changes in product attributes. Finally, multi-objective design optimization is conducted from the perspective of the profit-maximizing firm to ensure that the best possible solutions are considered from an economic perspective. The ensuing sections discuss the state of the art in these relevant fields, the proposed approach, and the results when implemented in the context of analyzing the optimal design of a mobile phone casing. This is followed by a discussion of the findings and concludes with a summary of the work and contributions.

2. Background

The approach presented in this paper draws from established methods and tools in the areas of tolerance and variation analysis, environmental impact measurement and assessment, decision theory and consumer choice, and design optimization. This section presents a brief overview of the relevant literature in each of these fields.

2.1. Tolerance and variation analysis

For every geometric dimension specified by a designer, there is also a specified tolerance within which the manufacturer must achieve that dimension. However, every dimension is not necessarily visible to or noticed by the customer. Those dimensions that are observable to the customer or are essential to the assembly or quality of a product are called “critical” or “functional” dimensions (Bjørke, 1989). Quality assurance typically requires these critical dimensions to be within some permissible range of variation, but non-critical dimensions are also important because their variation can propagate through the design to affect critical dimensions. Many tolerance analysis techniques and software applications can calculate or simulate this type of variation propagation to predict how geometric variation will affect assembly, functionality, and aesthetic perceptions of quality (Lööf et al., 2007; Shah et al., 2007).

Typical approaches to tolerance optimization involve minimizing manufacturing costs, where there is an inverse relationship observed between costs and tolerances, i.e., tighter tolerances incur higher manufacturing precision costs due to the needs for more expensive equipment or more time- and resource-intensive processes. If the critical dimensions are assigned targets for permissible variation, those targets can be used to constrain a cost-minimization formulation where the tolerances are the design variables (Ostwald and Huang, 1977). However, the assignment of permissible variation is often heuristically chosen by designers.

One scientific approach for assigning these limits is the use of loss functions in tolerance optimization, where the value lost to the customer and manufacturer is calculated based on the amount of variation (Söderberg and Gilmore, 1993). Losses to the manufacturer include those associated with scrap, rework, inspection, and redesign, and losses to the customer can include early product failure, maintenance, returns, and visual defects (Juran and Gryna, 2001). Such an approach coincides with the main principles of lean product development, which seeks to add value while limiting waste and shortening production time (Liker and Morgan, 2006; Gautam and Singh, 2008). While lean product development offers guidelines for increasing perceived value to customers while lowering costs, the present study accounts specifically for environmental impacts and quantification of consumer preferences within a tolerance and profit optimization framework.

A clear understanding of consumers' perceptions of quality as it relates to variation is needed to determine appropriate levels of permissible variation in critical dimensions. Where two parts of a product are joined, the line along which they meet is often visible, referred to as a split line. Designers have used interviews, surveys, and eye-tracking studies to understand how split lines influence consumer perceptions of quality (Forslund and Söderberg, 2010; Wickman et al., 2014). Regardless of whether split line uniformity affects the product functionality, mis-aligned or improperly spaced split lines have been found to negatively influence consumer perceptions of products in several cases (Forslund et al., 2013). Wickman and Söderberg (2007) investigated the amount of split-line variation that people can visibly detect, but a clear quantitative understanding of these phenomena is needed to explain the extent to which it affects consumer demand for a product. This paper shows how such a quantitative understanding can be developed, using the case of a small consumer electronic device.

2.2. Environmental impact

Due to concerns such as global climate change, air and water pollution, and declining reserves of natural resources, environmental sustainability has risen to become a top priority of research and policy initiatives. Tolerance selection influences environmental impacts through equipment and power needs of the manufacturing processes as well as the amount of scrap, rework, early product failure, and maintenance due to critical dimension variation (Juran and Gryna, 2001; Hoffenson et al., 2014). Other, often concurrent, choices such as material selection, locator positions, and the end-of-life strategy can also have profound impacts on a product's environmental footprint.

One of the major challenges in this field is in standardizing the measurement of environmental impact, particularly when there are multiple disparate impact areas to consider, such as global warming potential, waterway eutrophication, and resource consumption (Gaussin et al., 2013). A number of software packages have emerged to simplify the process of quantifying environmental impacts and performing Life Cycle Assessment (LCA) for a product, which involves analyzing all of the impacts caused by the existence of a product, beginning with resource extraction and ending with disposal at the end of the product's useful life. These methods require a Life Cycle Inventory (LCI) database that can help quantify the impacts associated with given materials and processes (Vigon et al., 1993). In order to present different types of impacts, such as carbon emissions and resource depletion, on the same scale, some of these tools normalize all environmental impacts into a single score, such as on the basis of an average person's annual consumption (The Netherlands Ministry of Housing, Spatial Planning and the Environment, 2000) or in monetary terms (Steen, 1999).

Aside from private concerns about environmental sustainability, these impacts are important considerations for product developers from an economic perspective for three significant reasons. First, there are many types of savings that are considered “win–win” for the economy and the environment, such as reducing consumption of electricity and materials and reducing waste (Figge and Hahn, 2012). Second, these types of impacts are often a target of legislation aimed at reducing the negative externalities associated with the actions of companies and consumers, and emissions and waste are increasingly being restricted and taxed in developed nations. Finally, consumers are increasingly showing higher demand for more environmentally friendly products (Yalabik and Fairchild, 2011), and it is believed that transparent and standardized methods for displaying environmental footprints of products to consumers can further increase the way consumers value environmental-friendliness (Limnios et al., 2009). In the pursuit of better understanding how designers should make decisions surrounding environmental impacts and visual quality, the present study investigates these links from both an engineering design and a consumer choice perspective.

2.3. Decision theory

After quantifying how tolerance and design choices influence variation and environmental impacts, the next step is to understand how these outcomes influence consumer purchasing decisions. This includes how consumers perceive and experience products as well as how they value those products and specific product attributes or features. Product experience research concerns the subjective responses of how people interact with products, and studies by Bloch (1995) and Schifferstein and Hekkert (2008) have revealed that visual appearance of quality and craftsmanship, among other attributes, are critical to the success of a product. This includes split line quality, as discussed previously in Section 2.1, and the extent to which people value such experiences may vary with demographics and cultural factors.

Cultural differences in global markets can affect how consumers value specific attributes when purchasing new products. This applies to both how people from different backgrounds appreciate attributes as well as how they behave during surveys and interviews, and the design and analysis of choice experiments should account for these differences (Smith, 2004). This study includes a case study on preferences for different product attributes in three different countries—China, Sweden, and the United States. These preferences are used for profit-driven design optimization that selects prices and manufacturing tolerances in each market individually and together for the case of a global product.

Basic economic theory states that rational consumers, when faced with alternatives, choose the option that maximizes their utility or perceived utility (von Neumann and Morgenstern, 1944). Many techniques exist for learning how consumers value and trade off various product attributes, including empirical studies of observed choices that have been made in the marketplace and theoretical studies of stated choices where study subjects are presented with hypothetical scenarios to choose among. When new technologies or applications arise with no empirical data that can be used for observed choice studies, stated choice techniques such as interviews, focus groups, and surveys are preferred (Louviere et al., 2000).

Choice-based conjoint (CBC) is a popular discrete choice technique for acquiring information on consumer preferences for individual product attributes through surveys (Sawtooth Software, Inc., 2008). This method involves asking survey-takers to choose among different products presented, each with a unique combination of attributes and attribute-levels. With a large number of responses, the relative value of each attribute-level can be derived using aggregate or Hierarchical-Bayesian (HB) logit estimation, enabling optimization of these product attributes for consumer preference (Train, 2003). The CBC survey method along with HB estimation is employed in this study to understand how consumers make trade-offs among environmental impacts, visual quality, and price, and that information is then used to model consumer behavior in a simulated marketplace.

2.4. Profit maximization

The outcome of interest from these decision theory models is an understanding of how product attributes and prices influence the quantity of the product demanded by the market. These factors contribute to the main economic objective of most businesses, which is to maximize profits (von Neumann and Morgenstern, 1944). Profits π are calculated as the difference between revenues, the product of price P and quantity sold Q, and costs, the product of Q and per-unit manufacturing costs C. This mathematical function, given as Eq. (1), is the objective that many product developing firms seek to maximize:

$$\pi = Q(P - C) \tag{1}$$

To determine the optimal design and pricing points, mathematical models are required to relate the variables to the objectives and constraints. A number of optimization algorithms have been proposed for solving such problems, the most common of which are gradient-based methods such as sequential quadratic programming (SQP) (Papalambros and Wilde, 2000). For non-differentiable functions, optimizers can employ response surface methodologies with these gradient-based algorithms or instead choose gradient-free methods such as pattern search methods, interpolation algorithms, and evolutionary algorithms (Kramer et al., 2011). In this study, manufacturers are assumed to be profit-maximizers, and models are developed to optimize Eq. (1) using a gradient-free space-filling global search algorithm to ensure that the solutions are indeed global maxima rather than local maxima.

3. Approach

This paper suggests a new approach for tolerance and design optimization of consumer products, using models and tools from the previously discussed literature to account for consumer preferences within a profit-maximization scheme. The modeling approach is illustrated in Fig. 1, and it begins after the product's function, architecture, and geometry have been decided upon. Parameters such as materials, manufacturing processes, and end-of-life strategies are set prior to optimization. Tolerances and the product price are variables, for which the optimization process determines the best values to maximize the objective.

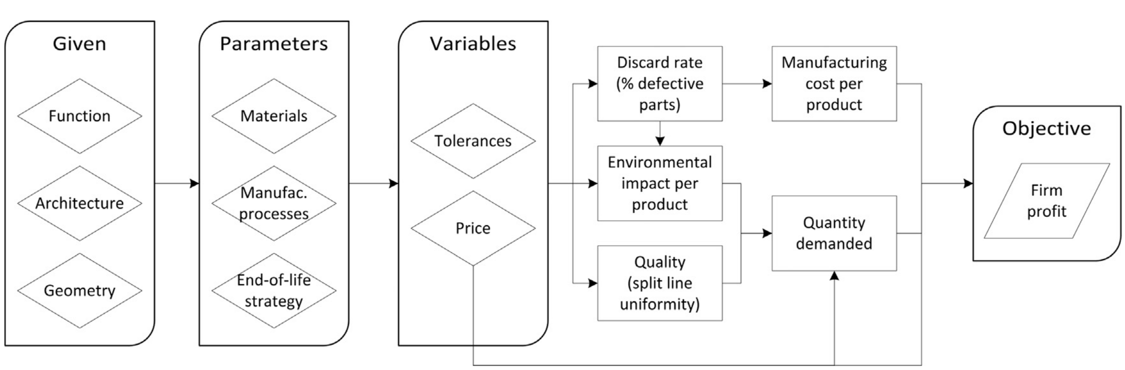

Fig. 1. Modeling approach for how business and design decisions influence outcomes.

All of the design inputs influence the calculations of product discard rates, environmental impacts, and product quality. The discard rate then influences the manufacturing cost per product as well as the environmental impact, as discarded parts and products must be compensated for by producing more parts and thus incurring additional economic and environmental costs. The quantity demanded is then estimated as a function of the price, quality, and environmental impact seen by potential consumers using Hierarchical-Bayesian logit estimation on the results of a choice experiment. Finally, firm profits are calculated as a function of price, quantity demanded, and manufacturing costs following Eq. (1).

3.1. Mobile phone modeling

A model of the outer case of a mobile phone, shown in Fig. 2, was constructed for use in the Robust Design and Tolerancing software (RD&T), a program used for variation analysis and visualization (Söderberg and Lindkvist, 1999). The front and back parts of the phone case are connected using pins near the four corners of the inside covers, as seen on the right side of the figure.

This product has prescribed tolerances in the lengths and positions of the eight connecting pins, four on the front and four on the back, stating how much variation from the nominal pin dimensions is permissible; these are assumed to be equal to one another since the manufacturing process is the same for the entire part and therefore all pins. The critical measures of the assembly are the angles of the split lines on all four sides of the phone where the front and back parts come together, as well as the ability of the four pins to meet up with one another in assembly. The former measures, referred to as θ's, are used to represent visual quality, and the latter measure, referred to as ϕ, represents the discard rate or percentage of parts that are discarded during the assembly phase. A design of experiments was conducted with 500 input tolerances ranging from 0.004 to 2 mm, each consisting of a 100,000-run Monte Carlo simulation of variation propagation to compute the critical measure distributions. The high number of Monte Carlo simulations for each input tolerance was chosen to take advantage of the time available, as higher numbers increase the confidence in the results; however, fewer simulations would have likely been sufficient and yielded similar results. The resulting data were used to calculate the maximum of the four split line angles θ_{max}, as well as the percentage of products that must be discarded due to the parts not fitting together, ϕ.

The cost of manufacturing the phone casing is estimated as a function of the material cost per unit mass c_{mat} and mass m, the tolerances t, and the percentage of parts being discarded ϕ. Using a reciprocal cost function for manufacturing precision as is common in the literature (Chase and Greenwood, 1988; Wu et al., 1988; Choi et al., 2000; Li et al., 2008), the economic cost of producing the case is calculated in euros with Eq. (2) and then later scaled to the appropriate currency:

$$C = \frac{1/t + c_{mat} m}{1-\phi} \tag{2}$$

The environmental impacts of producing the case of the phone were estimated using an impact assessment method known as Environmental Priority Strategies (EPS) in product development, which quantifies all impacts in terms of the Environmental Load Unit (ELU), each of which represents the equivalent of a one-euro environmental damage cost (Steen, 1999). This includes estimates of the environmental impacts associated with the production of the polypropylene plastic material E_{mat}, the injection molding process E_{proc}, and the end-of-life disposal in a landfill E_{eol}, and it is also affected by the discard rate ϕ. The environmental impact calculation follows

$$E = \frac{E_{mat} + E_{proc} + E_{eol}}{1-\phi} \tag{3}$$

3.2. Consumer data collection

Several techniques were considered for gathering consumer choice data to build a market demand model. Because empirical data on visibly imperfect split lines are not known for products on the market, revealed-choice methods were excluded and thus a stated-choice technique needed. Two options were considered: (1) in-person interviews or focus groups, which are resource-intensive and have practical limitations on the number of respondents, and (2) widely distributed surveys, which limit the information to one-way communication and two-dimensional images. In the interest of gathering data from a large number of respondents from different parts of the world, an online survey method was selected, and the CBC method was chosen for its proven ability to be used for the construction of market demand models.

One considerable limitation of this method for the present study is its representation of actual decision-making, as consumers in true purchasing scenarios would choose a product based on a defect-free floor-model or image and only later discover variation-related defects after opening the box. Common stated-choice data collection methods are not capable of handling these situations, and so the study proceeded under the assumption that product returns, changes to company and product reputations, online customer reviews, and future repeat customers might compensate for how consumers would behave if they observed a product's aesthetic quality prior to the purchase. This assumption is discussed later in the article.

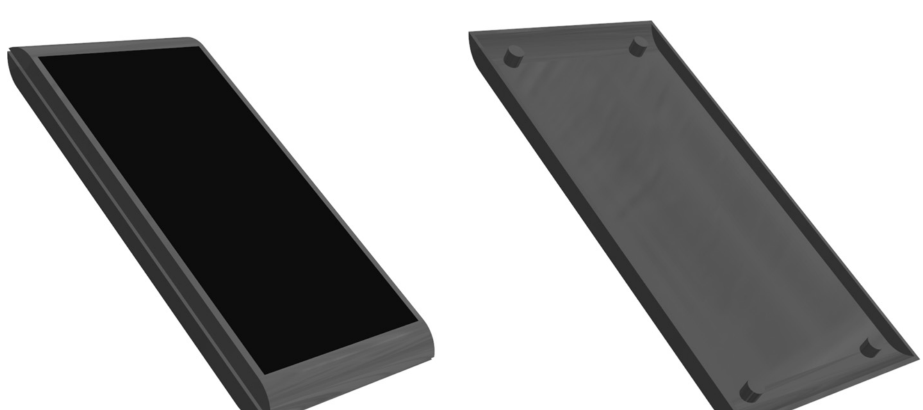

Fig. 2. Mobile phone case assembled (left) and inside of back part (right).

Data were gathered through an online survey that asked smart phone consumers from different countries about their mobile phone preferences. To include representatives and understand the cultural differences among the three largest markets, North America, Europe, and Asia, the selected countries were China, Sweden, and the United States. The survey was administered online to approximately 250 respondents from each country, limited to those who speak English and have experience using smart phones. One additional requirement was that the respondents were using a computer screen rather than a smartphone or tablet, as scaled-down images would present difficulties in distinguishing among the quality levels. The main part of the survey was a series of CBC questions, or a "choice experiment," which presented subjects with 12 different purchasing scenarios, each asking the respondent to choose among three phone options with varying attributes.

3.2.1. Conjoint attributes

Six attributes of the phone were presented in these scenarios, of which three are related to the tolerance decisions and profit maximization problem: price, environmental friendliness, and split line quality. The discrete pricing levels were chosen based on the smartphone markets in each of the three countries, as well as the structure of buying a phone with or without a two-year contract in those countries. In China, smart phones without a contract were found to range in price from ¥3000 to ¥6000, and so the options presented in the choice experiment were ¥3000, ¥4000, ¥5000, and ¥6000. Also in China, those with a contract were found to range from ¥250 to ¥400 per month including service, and so the options presented were ¥250, ¥300, ¥350, and ¥400 per month. Sweden's market and currency value were similar to that of China, and the values presented were exactly the same in Swedish kronor instead of Chinese yuan. The US phone market is structured in a different way, and the off-contract prices presented were similarly valued at $400, $500, $600, and $700, but the on-contract prices do not include service and represent a one-time payment of $0, $100, $200, or $300.

Since information on environmental friendliness is not currently widely available in existing phone specifications or marketing material, some metric was needed to represent this attribute in the survey alternatives. The requirements for such a metric were that it is concisely written, easily understandable, representative of environmental friendliness, quantifiable on a continuous scale, and not likely to confound the respondents' opinions of other phone attributes like durability and reliability. After considering several options such as percentage of recycled material, being locally produced, and using low-impact materials, the final decision was to list the percentage of recyclable material. This was shown in four discrete levels, so each phone alternative was given the attribute of 0, 33, 67, or 100 percent recyclable material. Later, this is interpreted as the consumer's value for general environmental friendliness on a scale from 0 to 100.

Split line quality was varied in three discrete levels using a Computer Aided Design program to alter the angles along an edge. The longest edge of the phone was chosen, as it would be the most visible, and the width of the split line gap was made as wide as possible without appearing unrealistic. This design allowed for up to 0.8° off parallel before the corners overlapped, so the discrete levels chosen were 0°, 0.4°, and 0.8° from parallel. These three models were rendered and touched up using Adobe Illustrator so that they looked more like photographs of products than computer-rendered models. The perspective, lighting, and contrast were adjusted to maximize visibility of the split line without compromising a realistic look, based on the judgement of the survey design team and 20 pilot survey respondents. At this point, the previously mentioned requirement for the respondents to be using a full-size computer screen was set.

Three additional attributes were varied in the choice scenarios: storage space, edge design, and length–width ratio. While these attributes are not directly related to the goals of the study, they were included because they are part of a real-life mobile phone purchasing decision and their presence might help us to diffuse respondent bias. If the only difference in presented attributes had been price, recycled material, and very similar images that only differed in the split line, respondents would likely overvalue these attributes and perhaps be able to surmise the type of information the survey was trying to uncover. The discrete values for storage space were chosen based on existing phones on the market to be 16 gigabytes (GB), 32 GB, and 64 GB.

The edge design included two alternatives, based on a rectangular prism with different patterns of rounded edges. Three patterns were developed, one with rounded edges on the top and bottom, one with rounded edges on the left and right, and one with rounded edges in the corners, shown in Fig. 3. In the pilot studies, it was found that respondents associated the third design with a popular phone on the market, which biased some of their opinions throughout the survey; therefore, only the first and second options were used in the fielded survey. The final attribute varied in the experiment was the length–width ratio of the phone, which included two alternatives: one corresponded with the proportions of the leading smartphone on the market, and the other corresponded with the golden ratio. Both length–width ratio options were constructed to have the same screen area.

Additional attributes were considered such as processor speed and camera resolution, but including these with the number of respondents planned would have yielded insufficient data to

Fig. 3. Different edge styles considered (only left and center were fielded in final survey).

reliably compute part worth utility values. The six-variable experiment design, summarized in Table 1, was tested to ensure that the number of variables and responses would be efficient, and the result showed standard errors for all main effects below 0.035 and for all two-way interaction effects below 0.075, within the recommended 0.05 and 0.10 limits (Sawtooth Software, Inc., 2008). A sample scenario from the choice questions in the final survey is provided as Fig. 4.

3.2.2. Survey design

The complete survey began by asking respondents about their experiences and preferences for smart phone brands and operating systems, as well as whether they prefer to buy on- or off-contract. This was designed so that the respondents would begin thinking about smart phones, and the information was later used to adapt the pricing scenarios in the choice experiment based on the individual respondent's country and contract preference. They were then presented with two different phone case images, shown in Fig. 5 and asked to study them and point out the differences, to familiarize the respondents with the images and their characteristics prior to presenting them alongside numerical information in the CBC questions. This page of the survey was also designed to give the respondents an opportunity to notice the split line gap, as the left alternative was presented with a perfectly parallel gap while the right alternative had a noticeably non-parallel split line. The other differences in the images were the edge design and the length–width ratio, and the respondents were told that there were at least three differences between the two phones. Following this question, the respondents were told that the phones in the ensuing choice scenarios represent new models from the brand they indicated the highest preference for at the beginning of the survey, which was intended to reduce brand association with the different styles. Next, the 12 questions of the choice experiment were administered.

One important survey design question was whether the split line should be pointed out to the respondents prior to the choice experiment. As the pilot study revealed, fielding a survey without specifically pointing it out resulted in two major drawbacks: (1) a high likelihood of the respondents not noticing the split line in the choice tasks, and (2) some respondents believing that the non-parallel gap represented a design feature, such as a sliding keyboard. This first drawback is likely because consumers assessing

Table 1
Conjoint attributes and levels.

Attribute	Level 1	Level 2	Level 3	Level 4
Price (China)	È250/È3000	È300/È4000	È350/È5000	È400/È6000
Price (Sweden)	250 kr/3000 kr	300 kr/4000 kr	350 kr/5000 kr	400 kr/6000 kr
Price (USA)	$0/$400	$100/$500	$200/$600	$300/$700
Recyclability (%)	0	33	67	100
Split line angle (^{0})	0	0.4	0.8	–
Memory (GB)	16	32	64	–
Edge design	Top-bottom	Left-right	–	–
Length–width ratio	Golden	Tall	–	–

Note: Prices are on-/off-contract; attributes below line are treated as constants in demand estimation

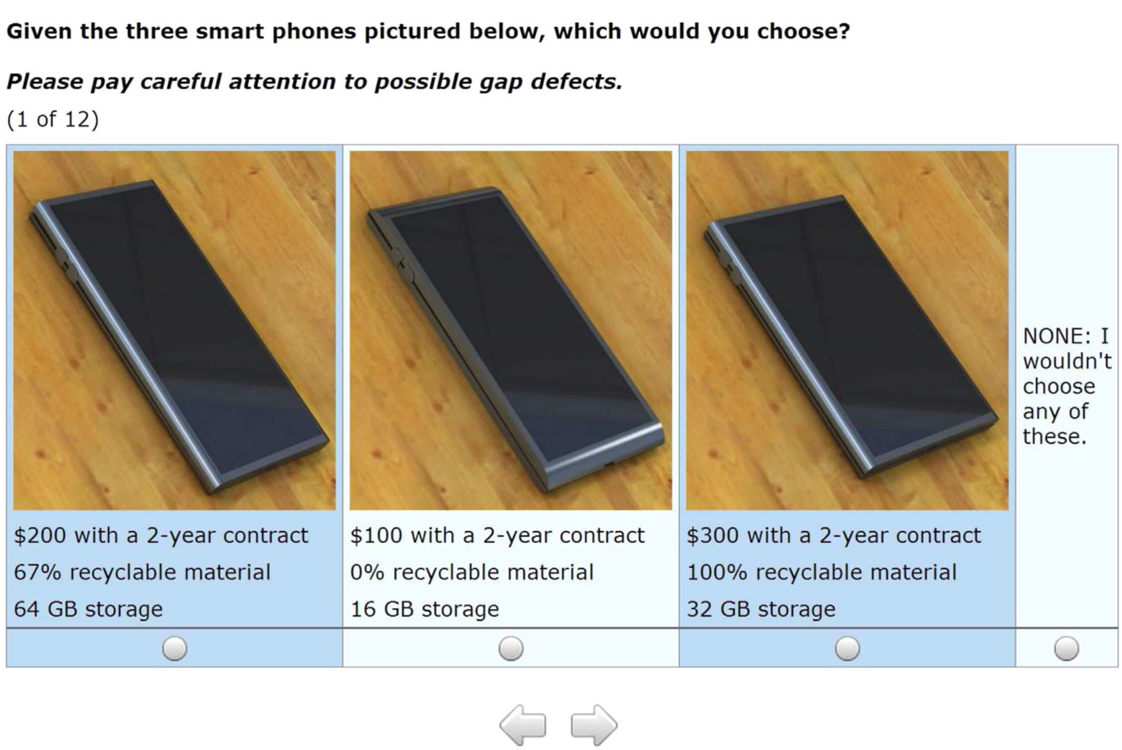

Fig. 4. Example CBC task for US respondent (shown from primed survey).

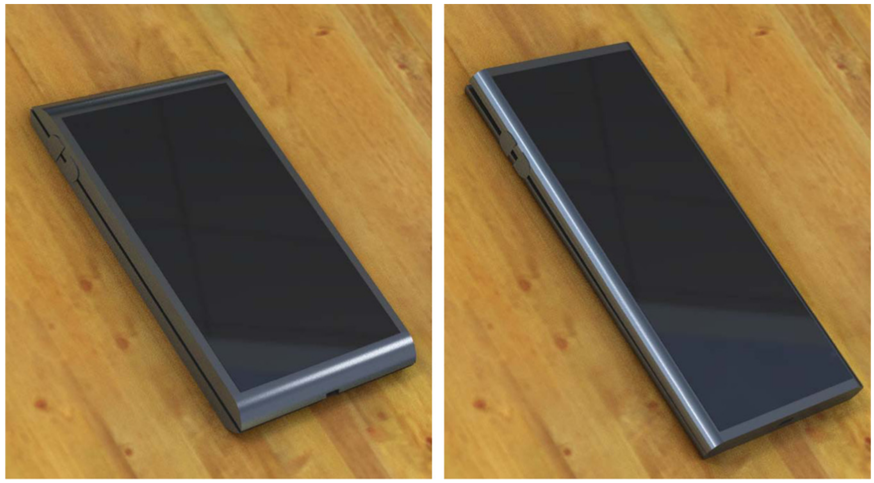

Fig. 5. Two phone images used for comparison questions.

photographs of products have been found to make judgements based on their interpretations of the intended design rather than the pictured quality (Forslund et al., 2013). However, fielding the choice tasks after pointing out the defective split lines was expected to raise significant bias in the results, specifically, overvaluing the quality attribute. To better understand these phenomena, the survey was conducted twice: one version did not mention the split line gaps prior to the CBC questions (the "unprimed" survey), and one version specifically pointed it out and labeled it as a defect rather than a design feature (the "primed" survey).

In both versions of the survey, the choice experiment was followed up by additional questions to find out how important the respondents believed each attribute was to their decisions. The primed survey then asked respondents a practical question about how they would react to discovering a split-line defect after purchasing a product, specifically whether they would return it and whether they would choose a different brand in the future. The survey closed with questions about how the respondents perceive environmental friendliness in mobile phones as well as optional demographic questions about the respondents' genders, ages, and income levels.

3.3. Design optimization

Using the variation data from the simulations and the information gathered by the surveys, an optimization formulation is solved from the perspective of the manufacturer to maximize profits. In this formulation, Eq. (1) acts as the maximization objective, where cost C is defined by Eq. (2), price P is a variable, and quantity Q is determined using a demand function constructed from the survey data. The demand function Q is itself a function of price P, visual quality θ_{max}, and environmental impact E, the latter two of which depend on the input tolerances t. Thus, the optimization formulation follows Eq. (4), where P and t are the decision variables:

$$\max_{P,t} \pi = Q\big(P, \theta_{max}(t), E(t)\big) \cdot (P - C(t)) \tag{4}$$

To estimate Q, the results of the choice experiment are first analyzed using Hierarchical-Bayes (HB) estimation, which allows for part-worth estimates at the level of the respondent rather than the population level and has become common in conjoint estimation due to its robustness against noise in heterogeneous data sets (Sawtooth Software, Inc., 2008). This analysis yields a part-worth utility estimate for each level of each attribute, where higher part worth utilities correspond with higher preferences for that attribute-level. The total utility of a product to a customer can be calculated by summing the part-worth utility estimates for all of that product's attributes. In this case, six attributes contribute to the utility of the product, three of which relate back to the tolerance design decisions: price, environmental friendliness, and quality. Since the HB analysis yields discrete estimates for variables that are treated as continuous in the optimization, cubic spline interpolation is used to estimate part worth utility values that lie between the choice experiment levels (de Boor, 2001); for example, estimating the part-worth utility of 50% environmental friendliness is done by interpolating between the values associated with 33% and 67%. The other three attributes, memory, edge design, and length–width ratio, are treated as constant in this study, so they are set to the most popular values from the survey.

The calculation of total utility is summarized in (5), where U_p is the total utility for a given product, u_i are the variable part-worth utility estimates, and k_i are the constant part worth utility estimates:

$$U_p = u_{price} + u_{env} + u_{qual} + k_{mem} + k_{edge} + k_{ratio} \tag{5}$$

In some cases interaction effects are important, as there may be significant utility associated with the product of two or more of the attributes. If so, this would require additional terms in (5), which are not enumerated here for the sake of brevity. Such effects are tested for in the ensuing analysis.

The probability of a consumer choosing a product with utility U_p from the market is estimated using

$$\Pr(U_p) = \frac{e^{U_p}}{e^{U_p} + e^{U_o}} \tag{6}$$

This approach is often used to account for competition, in which case additional terms for the utility of the other products are included in the denominator and U_o represents the utility of not purchasing any phone. Such an approach requires information on the competitors' products and an analysis of the competition using game theory, which is left out of this analysis due to a lack of market information regarding these attributes. Here, U_o is the utility of the "outside option," which includes choosing another phone on the market or foregoing a purchase. This value is calibrated to the model and set as constant, which follows the assumption that the other products on the market are not permitted to change. Finally, Q is calculated by multiplying $\Pr(U_p)$ by the size of the yearly market, which is set to 25 million each in the US and China and 2.5 million in Sweden.

The formulation in Eq. (4) is solved using the DIRECT derivative-free space-filling global search algorithm (Jones et al., 1999), first evaluated separately for each dataset and for each country. A modified version of (4) is also solved where the three countries' profit functions are summed in a global profit objective function and optimized over four variables: the price P in each of the three countries and a single tolerance t. This latter scenario represents the likely strategy that the manufacturer will produce a single product for the global market. The resulting profits from the separate (regional) optimization scenario are then compared to those of the global optimization scenario to examine the value of customizing product quality to individual markets.

4. Results

The main objective of the previously described approach is to determine an optimal tolerance and pricing strategy that will maximize a smart phone manufacturer's profit from a single product. However, the exact optimal solutions for the present case study are not intended to be the most significant findings of the research, as they rely on a number of assumptions in each of the models as well as hypothetical purchasing scenarios. Therefore, separate discussions ensue regarding the tolerance analysis results and the survey findings prior to combining them to solve the optimization problem, and the optimization results are discussed and compared in a relative context.

4.1. Variation propagation

From the design of experiments conducted in RD&T, the distributions of the critical measures were found as a function of input tolerance t. The discard rate ϕ was fit with a piecewise function, given as Eq. (7), which was found to match the simulation data with a coefficient of determination (R^2-value) of 0.9993:

$$\phi = \begin{cases} 0 & \text{for } t < 0.16 \\ 0.9681\left(1+e^{(-0.2713-\log(t))/0.3096}\right)^{-1} & \text{for } t \geq 0.16 \end{cases} \quad (7)$$

The other critical measure relates to the split-line quality, specifically the maximum of the split line angles on the four sides of the product θ_{max}, where are phone with perfectly parallel split lines on all four sides has $\theta_{max} = 0^{\circ}$. These values were observed to have a normal distribution with mean μ_θ and standard deviation σ_θ increasing with t, each of which were fit to linear models with coefficients of determination above 0.9999. These equations are given as (8) and (9), where t is measured in millimeters and θ in degrees:

$$\mu_\theta = 0.4584t \quad (8)$$

$$\sigma_\theta = 0.2281t \quad (9)$$

Later in the optimization formulation, these equations are used in the calculations of economic cost C and environmental cost E as functions of ϕ, as well as quantity demanded Q as a function of the distribution of θ_{max}.

4.2. Consumer survey

The main component of the consumer survey was the conjoint experiment, designed to elicit information about demand for certain product attributes, in particular price, environmental friendliness, and quality. Both the unprimed and primed surveys sought 250 respondents from each of the three countries. The actual valid response numbers for the unprimed survey were 227 from China, 250 from Sweden, and 250 from the US, and for the primed survey there were 231 from China, 250 from Sweden, and 250 from the US. In both datasets and all three countries, clear monotonic (i.e., strictly increasing) preferences were revealed for lower prices, higher recyclable material content, and higher storage. In the primed version of the survey, preferences were found to increase with higher quality as well; however, in the unprimed survey the preference for straighter split lines was not evident for many of the respondents. This finding could be explained by the question following up the choice tasks, which revealed that a significant portion of respondents did not notice the gap between the parts, and of those that did, most of them believed it to be part of the design. The responses to this follow-up question are shown in Fig. 6.

The Chinese respondents self-reported the highest proportion noticing the gap with 67%, while Sweden and the US reported 32% and 41%, respectively. Those who noticed the gap and believed that it was unintentional were even fewer, with 32%, 8%, and 9% in the three countries, and those who claimed to associate the misaligned gap with poor quality included only 11%, 4%, and 3% of the respondents. Since the sample sizes are too small if only those are considered who noticed the gap and either recognized it as defective or poor quality, the data from the unprimed survey are analyzed twice: first in the full group of 727 responses, and a second time after filtering to include only the 340 respondents who noticed the gap, which may be interpreted as a reflection of only the most attentive survey-takers. When the responses are filtered in this way, a slight preference for higher quality is revealed. Thus, the ensuing analysis and optimization is performed with three data sets: the full set of respondents from the unprimed survey, the filtered set of respondents who self-reported noticing the gap in the unprimed survey, and the full set of respondents from the primed survey.

The HB estimation procedure was performed on the CBC data from each dataset and each country, and the resulting part-worth utilities for each relevant attribute-level are shown in Fig. 7. Most of the datasets exhibit the same trends, in that lower prices are the most preferred attribute, followed by higher recyclability and higher quality, and the exact values differ from country to country. Despite the US pricing levels being closer together in absolute monetary value than those of the other two countries, American respondents showed higher sensitivity to price and storage capacity than the Swedish and Chinese respondents. Swedish respondents revealed the highest preference for recyclability, followed by the Chinese and then the American respondents. The quality metric was found to be relatively insignificant for the full respondent base in the unprimed survey, which shows seemingly random, non-monotonic preferences. In the filtered unprimed respondent base and the primed respondents, the importance of the measure was more evident and seen as the most important by the Swedish market and followed by the US market; however, despite a significantly higher number of Chinese respondents self-reporting that they independently noticed the angle (see Fig. 6), the Chinese data revealed a much lower preference for high quality compared to the other two datasets. As expected, these trends are much stronger in the results from the primed

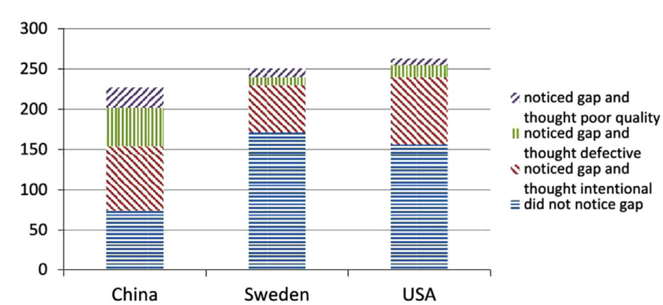

Fig. 6. Responses to unprimed survey question about noticing the split line.

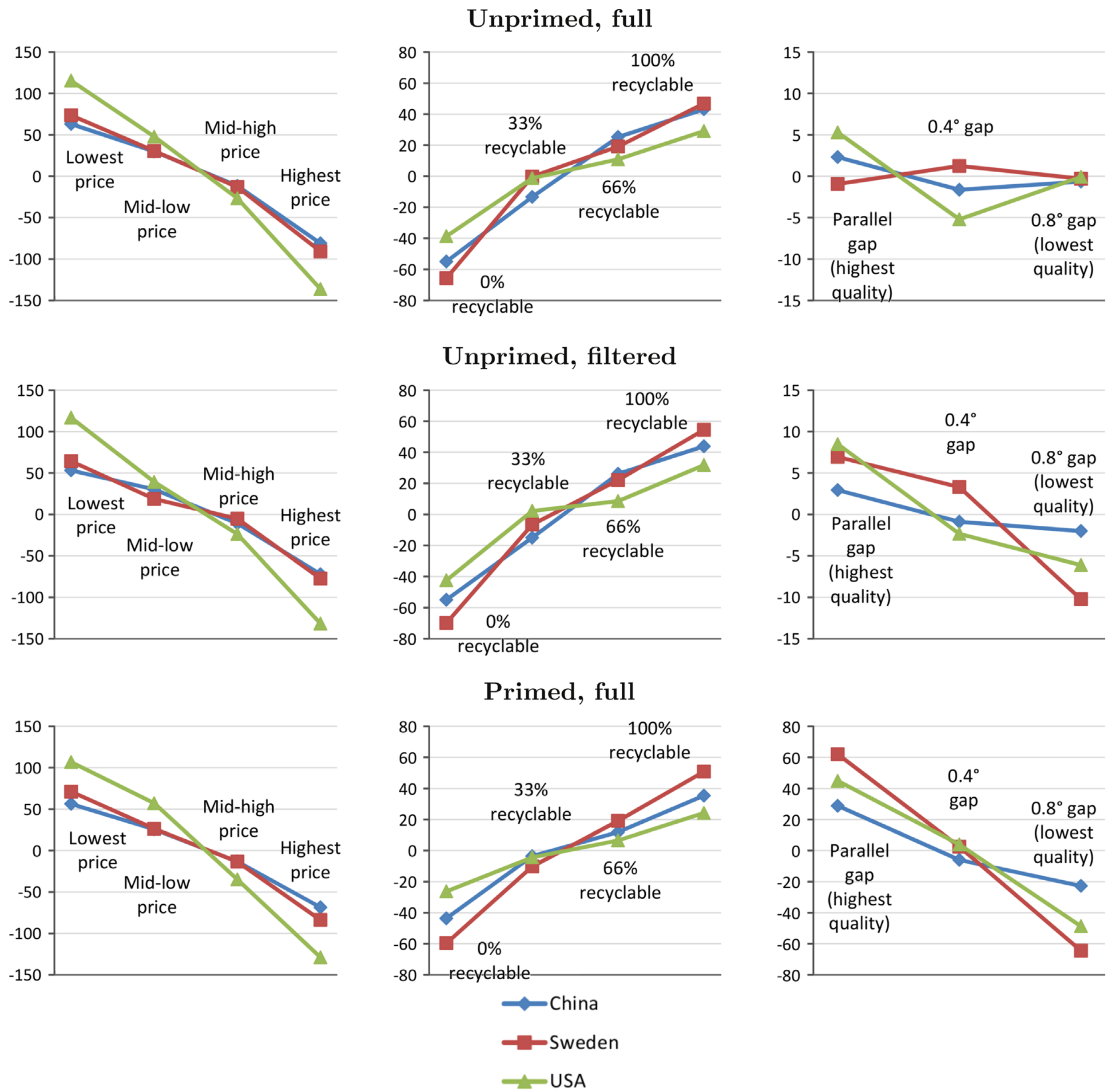

Fig. 7. Part worth utilities for price, recyclability, and quality.

survey, and in the cases of the Swedish and US markets quality is shown to have more influence on utility than recyclability.

The choice experiment also captured information about three additional attributes: storage, edge design, and length–width ratio. As expected, monotonic preferences for higher storage were found. The design preferences differed from respondent to respondent, but the averages slightly favored the left–right edge design and the golden ratio proportionality. Covariates were also examined to see whether combinations of the attributes in the images had significant contributions to utility, such as quality, length–width ratio, and edge style. These were found to have minor contributions, possibly because respondents did not have consistent preferences for length–width ratio and edge style (some people preferred one style and some preferred the other). As the effects were at least one order of magnitude lower than the main effects shown in Fig. 7, covariates were excluded from the ensuing analyses.

In the primed survey, respondents were asked how they would react to discovering a visual defect after taking a product home. A majority indicated that they would simply exchange their device for a new one, shown in Fig. 8. American respondents were most likely to keep the defective phone (the “nothing” response), while Swedish respondents were least likely to do so. Chinese respondents were most likely to return the phone for a different model, both within the same brand and switching to a different brand. Interestingly, only 7%, 3%, and 2% of respondents in each country would return the defective phone and switch brands.

Regarding future phone purchases, which are likely to occur one or two years after the initial purchase, Swedish and American respondents stated that a large majority would not be influenced by such aesthetic defects. The Chinese respondents revealed that slightly more than half expect that such a defect would “probably” affect their future purchase decisions, but still only 3% felt certain that they would switch brands after that experience.

4.3. Optimization

Design optimization was performed for each of the nine scenarios spanning the countries and data sets. Fixed values are

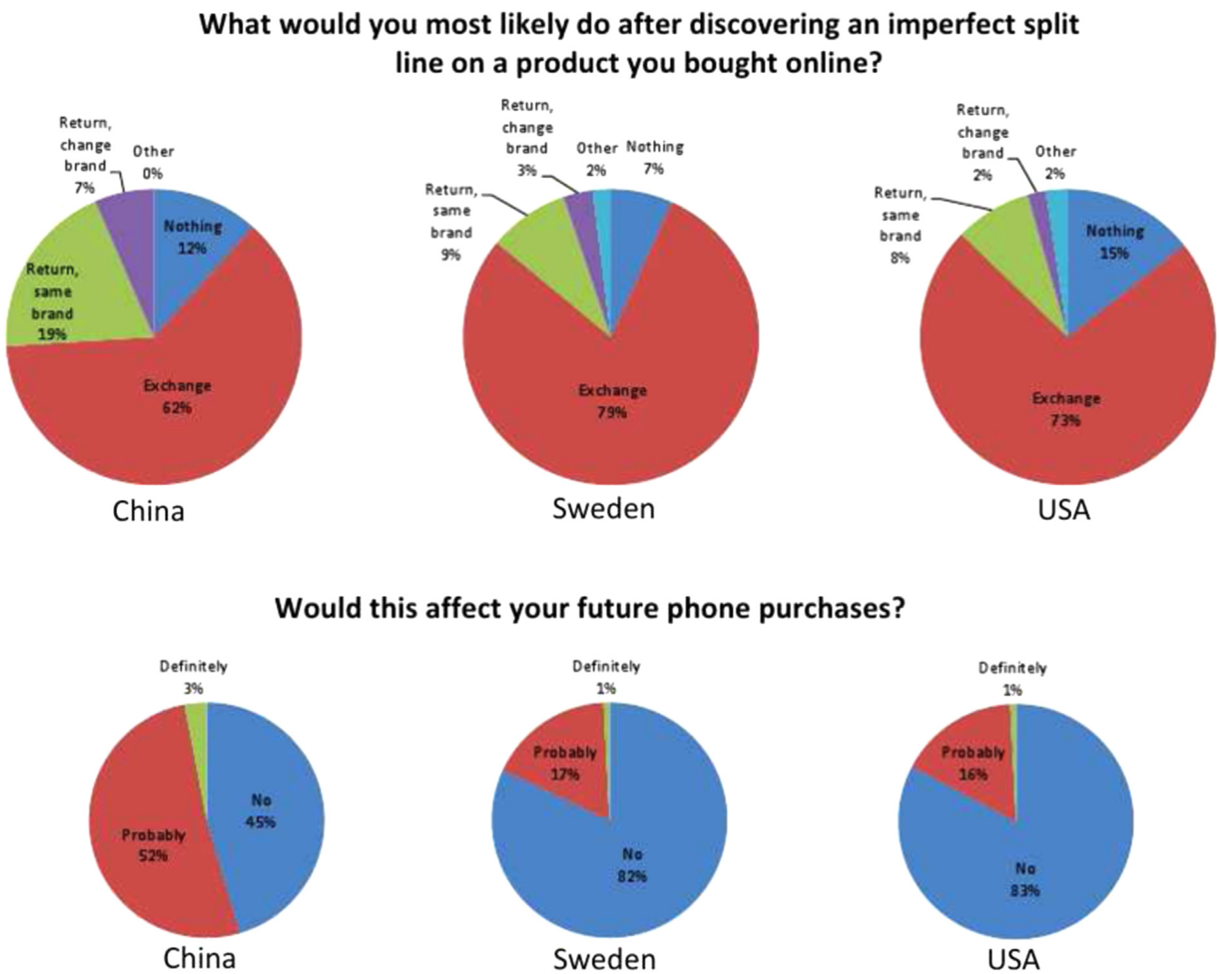

Fig. 8. Responses to question about receiving a visually defective device.

assumed for internal storage, edge design, and length–width ratio corresponding with neutral levels of those attributes, where the part-worth utility associated with them is set to zero. As previously discussed, the recyclability attribute is not influenced by the design variables, but instead an environmental factor measured in the lifecycle ELUs of the product is used. In this case, it is assumed that consumers valued recyclability in the survey as a score of environmental friendliness, and so the range of ELU values for the different input tolerances was scaled to fit a range from 0 to 100% environmentally friendly. With this normalization factor, the tightest tolerance product with the fewest ELUs was fit to match the utility associated with 100% recyclability, and the widest tolerance product with the most ELUs matched the utility associated with 0% recyclability.

The demand functions follow Eq. (6). In this study, the utility values are normalized and the outside option adjusted such that a product that is neutrally valued in all attributes with U_p equal to 0 would have a 4.7% probability of being chosen in the market and thus capture 4.7% of the market. This probability of choice is calculated 10,000 random times within the distribution of quality metric θ_{max}, and it is then adjusted based on the size of the market M to estimate the quantity demanded Q.

4.3.1. Regional product optimization

The optimization problem was first solved for each of the three countries separately, with the results for the three data sets shown in Tables 2–4. In this case, the more popular on-contract pricing schedules are assumed for all consumers (corresponding with approximately 60% of the respondents), and the hardware costs of the phone not related to the outer case production are assumed to be equal to the discount provided by the two-year contract agreement, i.e., the cheapest price offered was set to correspond with zero profits.

As expected, the optimal tolerances in the first two scenarios are found to be wider than in the third scenario, where the respondents were specifically told to value the split line visual quality. For the first data set, where the Swedish respondents revealed an atypically higher value for the middle quality than the highest quality, the Swedish market converged on the highest of the three tolerances. In these results as well as the second set of results with the filtered respondents, the US market converged on the tightest tolerance, likely due to the high slope of the preference profile separating the highest and middle quality measures. However, in the third set of results using the primed survey, the American market converged on the largest of the optimal tolerances, likely due to the respondents' relatively high sensitivity to price and low sensitivities to quality and recyclability. Also in the results using the primed sample, Sweden had the tightest of the tolerances due to their relatively high sensitivities to quality and recyclability.

All products were optimized to interior price points, and in the US, which had the highest price sensitivity, the price is the lowest relative to the range. Because the pricing schemes result in the user paying more for a contract phone in China and Sweden, the profits per unit and per person in those markets were significantly higher than those in the American market.

Table 2
Optimization results for unprimed survey, all respondents.

Country	China	Sweden	USA
No. of respondents	227	250	250
Tolerance (mm)	0.24	0.31	0.22
On-contract price	È È 352/month	349 kr/month	$152 one-time
Market share (%)	6.3	6.6	7.1
Quantity demanded (million)	1.58	0.164	1.76
Profit (converted to million US$)	611	57.8	257
Profit per unit (US$)	387	352	146

Table 3
Optimization results for unprimed survey, filtered respondents.

Country	China	Sweden	USA
No. of respondents	153	80	107
Tolerance (mm)	0.26	0.24	0.22
On-contract price	È È 354/month	361 kr/month	$171 one-time
Market share (%)	6.3	7.3	6.5
Quantity demanded (million)	1.58	0.183	1.62
Profit (converted to million US$)	625	72.4	267
Profit per unit (US$)	396	396	165

Table 4
Optimization results for primed survey, all respondents.

Country	China	Sweden	USA
No. of respondents	231	250	250
Tolerance (mm)	0.084	0.078	0.16
On-contract price	È È 361/month	358 kr/month	$133 one-time
Market share (%)	6.7	10.5	11.1
Quantity demanded (million)	1.67	0.263	2.78
Profit (converted to million US$)	690	98.1	346
Profit per unit (US$)	413	373	124

4.3.2. Global product optimization

Since many large mobile phone manufacturers now focus on global product development, the optimization formulation was solved again to design a single product with the same tolerance for all three countries. In this formulation, there are three pricing variables, one for each market, along with the one tolerance variable, and it was solved for each of the three sample groups of interest. The solutions, provided in Table 5, all converge on price levels that are similar to those found in the regional optimization results as well as tolerances that fit within the ranges from the previous results.

As expected, optimizing the preferences of the primed respondents resulted in the design with the tightest tolerance, which is in fact below the threshold of 0.16 mm where discarded parts become a factor in (7). This indicates that the design corresponds with the most preferred environmental impact, and the motivation to tighten the tolerance from 0.16 to 0.11 mm is based purely on the consumers' preferences for parallel split lines. In the case of the unprimed survey results, however, the wider tolerances correspond with discard rates around $\phi = 2\%$, and so they are being driven up by the cost function and down by the demand for higher environmental impact and parallel split lines.

When comparing the global sales quantity and profit with the totals from the regional results, it can be seen that switching from a regional product to a global product is predicted to reduce the profits by only very small amounts. In the case of the full sample from the unprimed survey, there was actually a slight increase in sales accompanying the negligible profit decrease of 0.01%. The filtered sample from the unprimed survey showed negligible decreases in sales and profits, and in the primed sample the sales decreased by almost 3% while the profits only saw decreases of 0.6%.

5. Discussion

This study lays a foundation for designers to quantify the effects of tolerances and split-line quality on consumer demand. Although the case study represents a hypothetical product and the data have inherent limitations, detailed in Section 5.1, the results provide valuable insights into the general ways that visually perceived quality can affect optimal product design across different markets. The key findings from the study include trends on the relative valuations of these product attributes under different simulated market scenarios, as well as a deeper understanding of the biases involved in this type of large-scale survey. These lessons learned result in a number of opportunities for further research and for practical application of the proposed tolerance optimization approach.

Table 5
Global optimization results and comparison with regional totals.

Sample	Unprimed, full	Unprimed, filtered	Primed
Tolerance (mm)	0.24	0.23	0.11
China on-contract price (È/month)	351	353	362
Sweden on-contract price (kr/month)	351	362	356
US on-contract price ($ one-time)	151	172	139
Quantity, regional optimization (million)	3.51	3.39	4.71
Quantity, global optimization (million)	3.51	3.37	4.59
Sales change by switching to global (%)	0.08	−0.38	−2.61
Profit, regional optimization (million US$)	925	965	1134
Profit, global optimization (million US$)	925	964	1127
Profit change by switching to global (%)	−0.01	−0.02	−0.58

5.1. Findings

The results show primarily how optimal design from a profit-maximization perspective might be influenced by dimensional variation and product visual quality. Although the demand functions from the different populations follow the same general trends and monotonicity, i.e., strictly increasing or decreasing with each parameter, different optimal solutions are found for each market. For example, it is seen that in countries like Sweden where the consumers exhibit stronger preferences for high visual quality, producers can gain relatively high percentages of the market share by manufacturing with comparatively tighter tolerances than in other markets. These optimal designs also depend on preferences for lower environmental impact and prices, as the tolerance decision also affects material waste and manufacturing costs, and the true value of the survey results is that they show how consumers trade off one attribute (such as quality or environmental friendliness) for another (such as price). When prices and tolerances are the only optimization variables considered, a global product is recommended with market-specific pricing, as it is likely that unaccounted-for manufacturing efficiencies gained from doing so will outweigh the predicted profit loss of less than 0.6%.

A key finding from the choice experiments is the impact of priming on the ways that respondents appear to value visual quality. In the unprimed survey, most of the respondents did not notice or value visual quality when choosing among the alternatives, and the non-monotonic preference profiles seen in the first row of Fig. 7 reflect this. To an extent, this may reflect the true preferences of consumers, as in a physical product it is possible that many consumers will not notice or care about visual quality. When the responses are filtered to only those who claimed to notice the non-parallel split lines, which also may be more reflective of actual consumers since it likely represents respondents who paid more careful attention to the survey, a weak monotonic preference for straighter split lines is found. In this case, however, there are still many respondents who did not perceive the split lines as an indicator of quality, and so it may still underrepresent values of straight split lines. In contrast, in the primed survey that explicitly pointed out this quality issue to the respondents prior to the choice tasks, straighter split lines were revealed to be almost as important as lower prices. This is likely to be an overrepresentation of how consumers value quality in real purchasing situations, as salespeople are not likely to point out visual quality defects when they want to sell products to customers. Therefore, it is expected that the true preferences of consumers lie somewhere in between the results from the three samples presented here, and further studies that draw from these lessons learned should be conducted to gain a more accurate representation of consumer preferences.

Aside from the issue of priming the survey respondents, the results are influenced by different types of respondent biases that are inherent in stated-choice studies. The first is that the respondents know that they are not actually purchasing a product in these choice scenarios, and although they were instructed to consider all features and attributes not listed on the page as equal among the alternatives, this still did not mirror the types and amount of information they would be given in a real purchasing situation. Therefore, it is likely that the respondents did not consider the options as carefully as they would when actually purchasing a new smart phone. Another important bias that is likely affecting the results is social desirability bias, in which many people overstate their preferences for attributes perceived as socially desirable, like recyclability, or those perceived as the "right" answer according to the survey-providers, in this case being straighter split lines. The authors suspect that part of the high value for straight split lines seen in the primed survey can be attributed to social desirability bias, as well as a portion of the value for recyclability seen in all of the samples.

Another result of the study was the discovery of slightly different values by the respondents from different countries, which may be attributed to three factors: (1) cultural differences in perception based on experience and societal views, (2) cultural differences in the aforementioned biases, and (3) differences in understanding and interpretation of the English-language survey, despite the self-reported survey prerequisite of being able to fluently read and respond in English. From the response distributions shown in Figs. 6 and 8, it appears that the Swedish and American respondents are more culturally similar than either group is with the Chinese respondents. Despite showing a much lower value for straight split lines in the choice experiment, Chinese respondents reported higher rates of noticing the gap than the other two groups as well as higher likelihoods of returning defective phones and switching brands in future purchases.

5.2. Opportunities

These findings are subject to a number of limitations, each of which raises opportunities for advancing the approach put forth in this paper. While this analysis was limited to a single design decision, the manufacturing tolerance, there are many other design decisions that influence visual quality and sustainability. The approach outlined here can be extended in future work and in practice by accounting for additional attributes such as material choice, surface finish, and disassemblability, which may help designers make decisions and evaluate trade-offs in a more comprehensive way.

Different approaches to data collection and analysis of consumer preferences may be able to answer some of the remaining questions and temper the biases in the present results, but each has its limitations. Further online surveys could be fielded that find some balance in the way that people are introduced to the product and its visual quality, such as using different priming mechanisms and indicators for sustainability and presenting the product with variations on the angles and lighting, but they would retain many of the biases from the previous studies. An alternative would be to conduct in-person interviews or focus groups with physical prototypes that people can inspect in an environment that more closely resembles a mobile phone or provider store. This method would require a significantly larger investment of time and resources and would likely achieve a much smaller and more homogeneous respondent base than the online survey, and it still might suffer from respondent bias issues. Another way to gather such information would be to actually sell subjects working phones that have been chosen or modified to have small visual defects, which would force the respondents to actually put their own money toward their stated choice. This would require some sort of discount or incentive to bring in respondents, and it would likely present major challenges when it comes to branding, as manufacturers would be reluctant to allow their phones into a study that might result in a reputation for low quality.

Using the information on respondent demographics and phone habits as well as the heterogeneity found in the HB estimates, future work could investigate optimization of a line of products rather than a single product. This would take advantage of the known heterogeneity in the market by grouping the respondents and designing different products for each market segment. Alternatively, different analysis techniques for arriving at heterogeneous utility estimates such as latent class or nested logit analysis could also be used (Sawtooth Software, Inc., 2004). However, such techniques require additional steps, uncertainties, and assumptions, and they have not yet been proven to improve utility estimate accuracy. Another opportunity is to use the information gathered in the survey about likely reactions to taking home a visually defective product (shown in Fig. 8). From this information, a more realistic simulation could be constructed to represent online sales of consumer electronics, including an analysis over time about the sustainability of the business model considering returns, exchanges, and lost future purchases.

This type of quantitative understanding is useful for designers, businesses, and policymakers who want to know how their decisions may affect the economic and environmental sustainability of products and markets. Designers should use this to gain a competitive edge in creating products that consumers value and will purchase. Product-developing businesses can use the described information and methods to optimize prices and set product requirements that meet their market goals, as well as in determining marketing strategies for different product attributes. Policymakers who want to understand how increasing transparency, as in implementing standardized metrics for environmental sustainability or quality, might influence market behavior and overall economic and environmental sustainability. This work brings tolerance optimization into a market systems framework, contributing knowledge and techniques to the design research community as well as design practice.

6. Conclusions

Whereas previous work in the field has shown that customers value split lines when evaluating product quality (Forslund and Söderberg, 2010; Forslund et al., 2013), this study describes a means to quantify that preference in a useful way for manufacturers. The article introduces the idea of employing a stated-choice experiment to quantify the effects of tolerance choices and the resulting visual quality and environmental friendliness on product sales. As a case study, survey respondents from three countries reported on their preferences for mobile phones in a choice-based conjoint setting considering the design, price, recyclability, and visual quality, and this process was repeated to see the effect of priming survey respondents by pointing out the quality issue compared with not doing so. Results from the choice study were combined with an engineering analysis of the variation propagation due to tolerance selection and its effects on cost, environmental impacts, and visual quality of split lines. Using these models, a profit maximization formulation was developed and solved to show the value of such consumer choice information for product developers.

In effect, this paper offers a new way to integrate environmental impacts and visual quality into a purely economic design objective that can provide financial motivation for companies to develop environmentally friendly and high-quality products. This type of tool is valuable for designers, businesses, and policymakers wishing to analyze how their decisions will affect sustainability and the marketplace.

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