ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

TOLERANCE OPTIMIZATION OF A MOBILE PHONE CONSIDERING CONSUMER DEMAND FOR QUALITY AND SUSTAINABILITY IN CHINA, SWEDEN, AND THE UNITED STATES

Steven HOFFENSON, Andreas DAGMAN, Rikard SÖDERBERG
Chalmers University of Technology, Sweden

ABSTRACT

Dimensional tolerances are chosen during the product development process to balance quality requirements against manufacturing costs. Designers typically judge how much variance should be allowed while still maintaining the perception of a high quality product or brand, but this is rarely based on an understanding of how consumers perceive that variance. Additionally, ecological sustainability priorities are often chosen without knowing how they will be received by consumers. This paper presents a survey-based technique for understanding how tolerance and pricing decisions influence a product developing firm’s profits, accounting for consumer perceptions of quality and environmental friendliness. A case study of a mobile phone design is explored, including variance propagation modeling, the design and administration of an online choice-based conjoint (CBC) survey, construction of consumer demand models, and profit maximization for the markets in three different countries. The results show a slight preference for high quality products compared with stronger preferences for other product attributes like low price, and the differences among the three markets are highlighted.

Keywords: optimisation, sustainability, tolerance specification, user centred design

Contact:
Dr. Steven Hoffenson
Chalmers University of Technology
Product and Production Development
Göteborg
41296
Sweden
stevenh@chalmers.se

1 INTRODUCTION

Product developers must understand what drives the market in order to balance their design objectives for optimal sales, revenues, and profits. Decisions made in the embodiment design phase can trade off benefits for one design objective, such as lower costs, with benefits for another, such as higher quality. The link between manufacturing costs and product quality has been the subject of much research in recent decades, particularly in the context of choosing geometric tolerances (Hong and Chang, 2002). Much of this research seeks to minimize production costs within some variation threshold; 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 tradeoffs between economic and ecological objectives (Hoffenson et al., 2012), both of which factor into the idea of sustainability (Holling, 2001). Manufacturers, though, do not have the same incentives to design for ecological sustainability as they do for economic sustainability, and therefore a stronger understanding of how ecological sustainability influences manufacturer profits is necessary. This paper uses a consumer study to reveal how people value quality, prices, and ecological friendliness when purchasing a new product, all of which relate to tolerance decisions.

The present research method leverages models and techniques from multiple academic and practical disciplines. First, an engineering-based analysis determines how design decisions influence outcomes such as manufacturing costs, product variation, and ecological sustainability. These outcomes then affect the end-user from a decision theory perspective, and consumer surveys illuminate how the market will react 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 the 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 literature in tolerance analysis, environmental impact assessment, decision theory, and optimization. A brief overview of the relevant literature in each of these fields is presented in this section.

2.1 Tolerance 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 critical dimensions to be within some allowed range of variation, but non-critical dimensions are also important because their variations 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, as variation in critical dimensions affects assemblability, 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. If the critical dimensions are assigned a target for allowed variation, the targets can constrain the cost-minimization formulation where the tolerances are the variables (Ostwald and Huang, 1977). However, the assignment of allowed variation is often heuristically chosen by designers. One scientific method for assigning these is to use loss functions, where the value lost to the customer and manufacturer is calculated based on the amount of variation (Söderberg 1993), but this technique also relies on heuristic assumptions of perception and functionality.

A clear understanding of consumer perception of quality as it relates to variation is needed to determine appropriate allowed variations of 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*; many designers believe that these split lines are indicators of quality, and non-uniform or improperly-spaced split lines can negatively influence a consumer's perception of a product (Forslund et al., 2011). While split line uniformity should not affect a product's functionality, such visual quality issues may be seen by consumers as a reflection of build quality, which may vary with demographics and cultural factors. Research has investigated the amount of split-line variation that people can visibly detect (Wickman and Söderberg, 2007), but to the authors' knowledge, this has never been quantified to explain the extent to which it affects consumer demand for a product.

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. Research has shown how tolerance selection can influence environmental impacts through electricity usage and the amount of faulty parts or products discarded early in the lifecycle (Hoffenson et al., 2012). 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 ecological footprint.

One of the major challenges is in standardizing the measurement of environmental impact, particularly when there are multiple disparate impact areas to consider. A number of software packages have emerged to simplify the process of quantifying environmental impacts and performing Life Cycle Assessment (LCA) for a product, all of which draw from some database of impacts associated with given materials and processes (Taghizadeh et al., 2010). 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 on the basis of an average person's annual consumption (Ministry of Housing, Spatial Planning and the Environment, 2000) or in monetary terms (Steen, 1999).

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. 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 studies of observed choices that have been made in the marketplace and 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 consumer preference information for product attributes through surveys (Sawtooth Software, 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 simple or mixed logit estimation, enabling optimization of these product attributes for consumer preference (Train, 2003).

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, profit maximization (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 equation (1), is the objective that product developing firms should seek to maximize.

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

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 in the design optimization community, the most common of which are gradient-based methods such as sequential quadratic programming (Papalambros and Wilde, 2000). For non-differentiable functions, optimizers can employ response surface methodologies with these gradient-based algorithms or gradient-free methods such as pattern search methods, interpolation algorithms, and evolutionary algorithms (Kramer et al., 2011).

3 APPROACH

The present paper suggests a new approach for tolerance and design optimization, using models and tools from the previously-discussed literature. The modeling approach is illustrated in Figure 1, and it begins after the function, architecture, and geometry have been decided upon. Parameters such as materials, manufacturing processes, and end-of-life strategies are set prior to optimization, though the effects of these factors could be investigated using parametric studies, in which the optimization process is repeated with different values of the parameters. Tolerances and the product prices are variables, for which the optimization process determines the best values to maximize the objective.

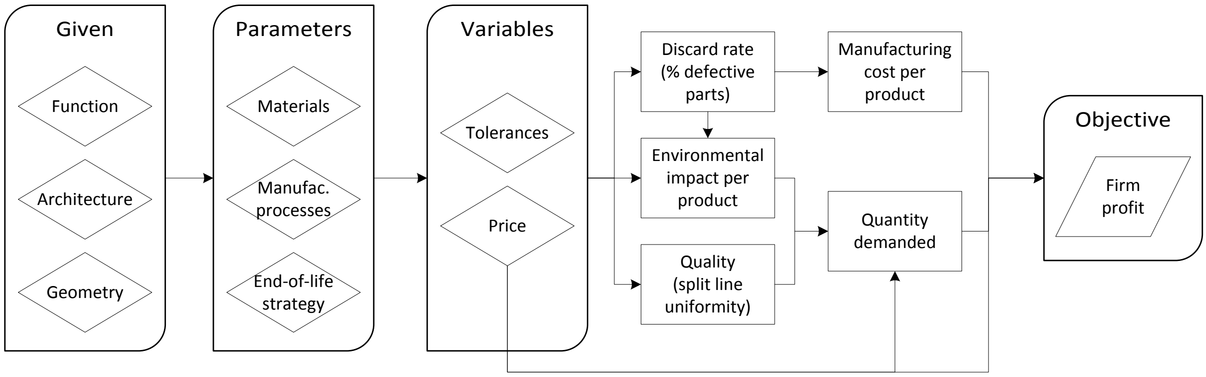

Figure 1. Modeling approach for how business and design decisions influence outcomes

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 calculated as a function of the price, quality, and environmental impact seen by potential consumers. Finally, firm profits are calculated as a function of price, quantity demanded, and manufacturing costs.

3.1 Mobile phone modeling

A model of the outer case of a mobile phone, shown in Figure 2, was constructed using the Robust Design & Tolerancing software (RD&T), a program used for variation analysis and visualization (Lööf et al., 2007). The two parts are connected using pins near the four corners of the inside covers.

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

Tolerances were prescribed in the lengths of the connecting pins, four on each side, stating how much variation from the nominal pin length is allowed; these are assumed equal to one another since the manufacturing process is the same for all pins. The critical measures of the assembly are the gap alignments between the front and back parts on all four sides of the phone. A design of experiments was run with 1,500 input tolerances from 0 to 3 millimeters, conducting a 100,000-run Monte Carlo simulation of variance for each scenario to compute the critical measure distributions. The resulting data were used to calculate the split line angles θ_{top}, θ_{bottom}, θ_{left}, θ_{right} on each edge, 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, the economic cost of producing the case is calculated in Euros with equation (2) and then later scaled to the appropriate currency.

$$C = (1/t + c_{mat}\, m)/(1 - \varphi) \tag{2}$$

The environmental impacts of producing the case of the phone were estimate using an impact assessment method known as Environmental Priority Strategies in product development (EPS), quantified in Environmental Load Units (ELUs), each of which is the equivalent of a one-Euro environmental damage cost (Steen, 1999). This includes estimates of the environmental impacts associated with the production of the ABS plastic materials 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 equation (3).

$$E = (E_{mat} + E_{proc} + E_{eol})/(1 - \varphi) \tag{3}$$

3.2 Data collection

Several techniques were considered for gathering consumer choice data to build a market demand model. Because data on visibly imperfect split lines are not known for products on the market, revealed-choice data could not be gathered and thus a stated-choice technique was needed. This left two options: (1) in-person interviews and focus groups, which are resource-intensive and limit the number of respondents, and (2) 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 CBC was chosen for its demand modeling strengths. One considerable limitation of this method is its representation of actual decision-making, as consumers in true purchasing scenarios would choose a product based on a defect-free 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 changes to company and product reputations, online customer reviews, and future repeat customers would compensate for how consumers would behave if they observed a product's aesthetic quality prior to the purchase.

Data were gathered through a CBC survey that asked smart phone consumers from China, Sweden, and the United States about their mobile phone preferences. The survey was administered online to approximately 250 respondents from each country, limited to those who speak English and have experience using smart phones. The main part of the survey was a series of CBC questions, which presented subjects with twelve different purchasing scenarios, each presenting three phone options with randomly varying values for the price, storage space, and percentage of recyclable material used, as well as a picture of the phone's appearance with varying size, edge styling, and alignment between the two parts. A sample scenario from these questions is given as Figure 3.

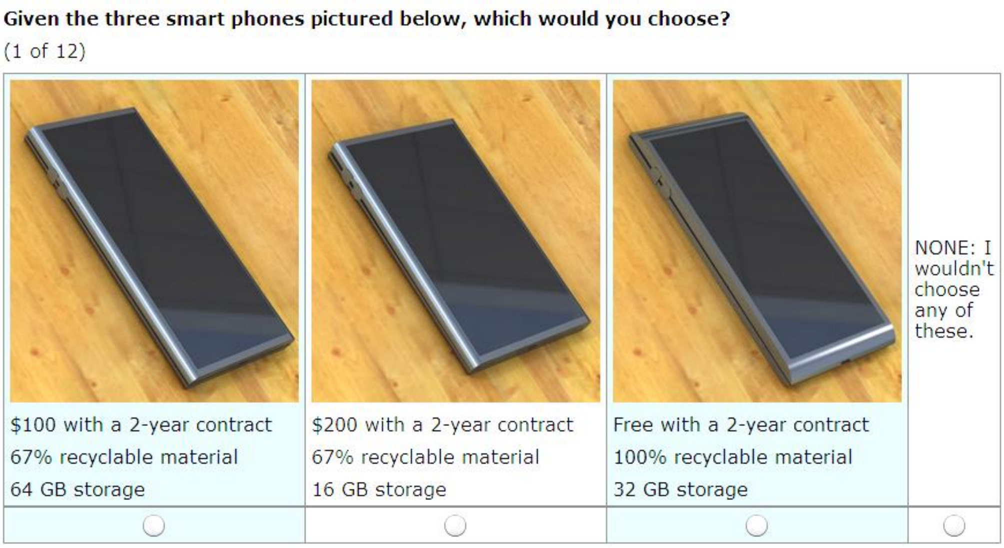

Figure 3. Example choice-based conjoint (CBC) question for U.S. respondent

The 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, the prices without a contract were ¥3000, ¥4000, ¥5000, and ¥6000, and those with a contract were ¥250, ¥300, ¥350, and ¥400 per month, which includes a service plan. Sweden's market and currency value were similar to that of China, and the values presented were exactly the same, but in Swedish kronor instead of Chinese yuan. The U.S. 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.

Prior to the CBC questions, the respondents were asked about their experiences and preferences for smart phone brands and operating systems, as well as whether they prefer to buy on- or off-contract, and the CBC price levels presented to them were adapted based on the country and contract preference. They were also presented with two different phone case images and asked to study them and point out the differences between them, to familiarize the respondents with the images and their characteristics prior to presenting them alongside numerical information. They were then told that the phones in the study represent new models from the brand they indicated preference for, in order to reduce brand association with the different styles. The split line was intentionally not pointed out to the respondents prior to the choice tasks, intending to reduce bias and better reflect independent decision-making, but also raising the potential that the respondents might overlook split line defects in the images.

Additional questions were asked following the CBC questions to find out how important the respondents believed each attribute was to their decision. They were then asked whether they noticed the gap between the front and back piece and whether the non-parallel phones were perceived to be that way because of intentional design, a defective product, or poor quality. The survey closed with questions about the perceptions of environmental friendliness in phone design and optional demographic questions about the respondents.

3.3 Mobile phone optimization

The profit model from equation (1) is the maximization objective, were cost C is defined by equation (2), price P is a variable, and quantity Q is determined using a demand function constructed from the survey data. Q itself is a function of price P, visual quality θ, and environmental impact E, the latter two of which depend on the input tolerances t. Thus, the optimization formulation follows equation (4), where P and t are the optimization variables to be solved for.

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

4 RESULTS

The objective of this approach is to determine an optimal tolerance and pricing strategy that will maximize the profits associated with this product. However, the exact solutions for the present case study may not be the most significant findings of the research, as they rely on a number of assumptions in each of the models. Therefore, separate discussions ensue regarding the tolerance analysis results and the survey findings prior to combining them to solve the optimization problem.

4.1 Variation propagation

From the design of experiments in RD&T, mean and standard deviation data of the critical measures were fit with linear regression models. As expected, the true angles in degrees on the top and bottom edges were distributed equally with a half normal distribution, and these angles had larger values than those on the left and right, so only θ_{top} is used for the quality measure. The regression model for the mean of this value, μ_θ, as a function of tolerance t in millimeters is given as equation (5), and it fits the data perfectly with a coefficient of determination equal to 1.

$$\mu_\theta = 0.2855t \tag{5}$$

The measure used to calculate the discard rate φ follows the percentage of products that have at least one corner with either contact or a gap larger than 2 mm (from a 1-mm nominal gap). Since these are independent measures, the percentage of unacceptable outputs in each corner can be linearly interpolated as a function of t separately, and these four models φ_1, φ_2, φ_3, and φ_4 were combined using equation (6), which assumes independence of the models.

$$\varphi = 1 - (1 - \varphi_1)(1 - \varphi_2)(1 - \varphi_3)(1 - \varphi_4) \quad (6)$$

In this particular application, the tolerances and variation propagation are relatively simple and could be calculated using statistical and mathematical equations rather than sophisticated software. However, the results would be the same, and the software was used in this paper to demonstrate how the approach can be applied to even the most complex product geometries.

4.2 Survey findings

The consumer survey was designed to elicit information about demand for certain product attributes, in particular price, environmental friendliness, and quality. A total of 741 valid responses were received with 227 from China, 251 from Sweden, and 263 from the U.S., and the results for all three countries show clear monotonic preferences for lower prices, higher recyclable material content, higher storage, and straighter split lines. The survey, however, revealed that a significant portion of respondents did not notice the gap between the parts, illustrated in Figure 4.

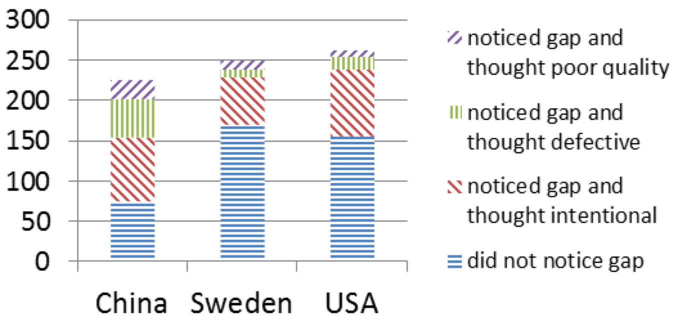

Figure 4. Responses to survey question about perception of split line in CBC questions

The Chinese respondents self-reported the highest proportion noticing the gap with 67 percent, while Sweden and the U.S. reported 32 and 41 percent, respectively. Those who noticed the gap and believed that it was unintentional were even fewer, with 32, 8, and 9 percent in the three countries, and those who claimed to associate the misaligned gap with poor quality included only 11, 4, and 3 percent 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 are filtered to include all respondents who noticed the gap, ensuring that the analyzed responses reflect attentive survey-takers.

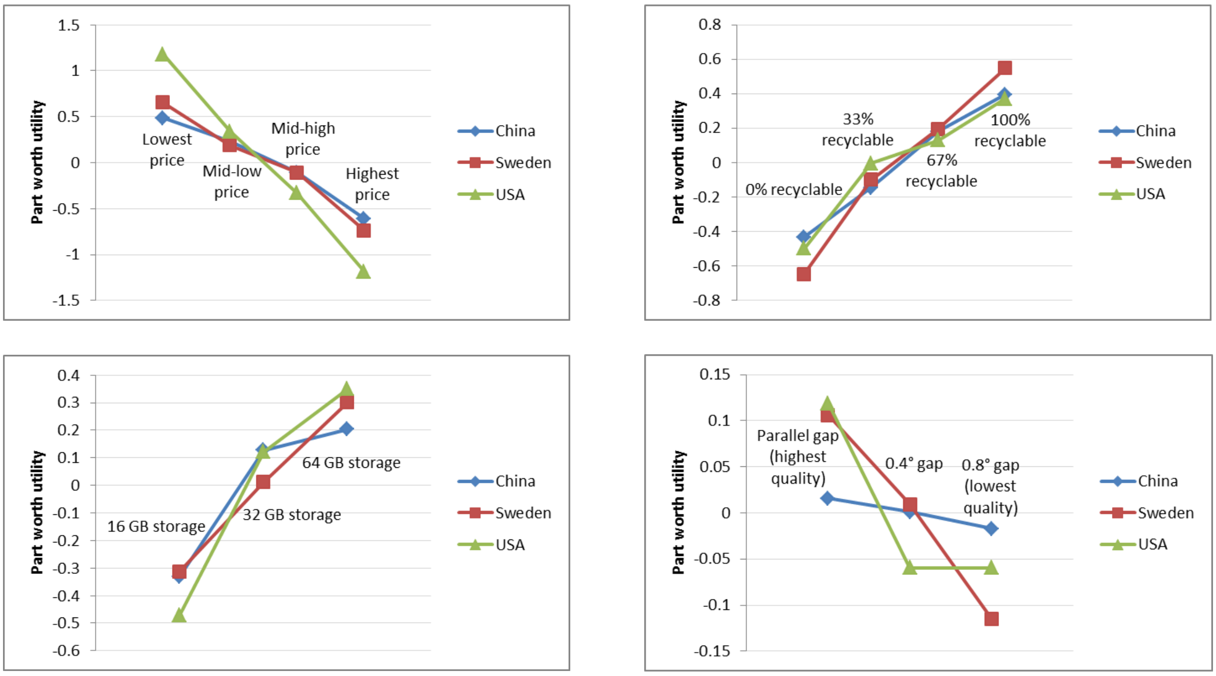

Figure 5. Part worth utilities from simple logit analysis of CBC data

An aggregate logit analysis was carried out over the filtered CBC data of each country (Sawtooth Software, 2008), and the resulting part worth utilities for each attribute-level are shown in Figure 5. Higher part worth utilities correspond with higher preference for that attribute-level. The trends are the same for each country, in that lower prices are the most preferred attribute, followed by higher recyclability, higher storage, and higher quality, but the exact values differ from country to country.

Despite the fact that the U.S. pricing levels were closer together than the other two, American respondents showed higher sensitivity to price and storage capacity than the Swedish and Chinese respondents. Swedish respondents revealed a higher preference for recyclability than the American and Chinese respondents, and interestingly the gap between 16GB and 32GB was seen as more important than the gap between 32GB and 64GB despite the fact that the latter gap accounts for twice the storage capacity of the former. The quality metric, measured by the angle seen at the split line, was seen as the most important by the Swedish market and followed closely by the U.S. market; however, despite a significantly higher number of Chinese respondents self-reporting that they noticed the angle, the Chinese data revealed only a very slight preference for high quality compared to the other two.

Although the internal storage attribute is shown to significantly influence consumer utility, this factor was not included in the design optimization because it is not affected by tolerance or price choices. The recyclability attribute is also not influenced by the design variables, but another environmental factor measured in the lifecycle ELUs of the product is used instead. 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 matches the utility associated with 100% recyclability, and the widest tolerance product with the most ELUs matches the utility associated with 0% recyclability.

The part worth values shown in Figure 5 are used to construct a choice probability model that estimates the quantity demanded as a function of the attributes. In this model, the utility U_p of a product is the sum of the part worth values for all attributes of that product. For the optimization model, the three attributes price, recyclability, and quality are considered on continuous scales, and so linear interpolation is used to calculate values between the sampled points. Equation 7 is used to calculate the probability of a consumer choosing a product with utility U_p while the utility of choosing another alternative, including not purchasing any phone, is U_o.

$$Pr(U_p) = \frac{e^{U_p}}{e^{U_p} + e^{U_o}} \tag{7}$$

In this study, the outside option is assumed to have a fixed utility U_o equal to 3, which indicates that a product that is averagely-valued in all attributes with U_p equal to 0 should have a 4.7% chance of being chosen in the market. This probability of choice is calculated 10,000 random times within the distribution of quality metric θ, and it is then adjusted based on the size of the market M to estimate the quantity demanded Q. For the optimization results presented in the next section, the yearly market for smart phones is assumed to be 25 million in the U.S. and China and 2.5 million in Sweden.

4.3 Optimization

The optimization problem was first solved for each of the three countries separately using a direct search algorithm, and the results are shown in Table 1. In this case, the more popular on-contract pricing schedules are assumed for all consumers, 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.

As expected, the optimal tolerances are tighter where the people showed higher preferences for straight split lines and environmental friendliness, with Sweden requiring the tightest tolerance and China the loosest. All products were optimized to interior price points, and in the U.S., 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.

Since most large mobile phone manufacturers now focus on global product development, a further optimization study was done to design a single product for all three countries. In this problem, there are three pricing variables, one for each market, along with the one tolerance variable, and the solution converges on approximately the same prices as those in Table 1 and a tolerance of 0.35 mm. The profit projected from this design marketed in all three countries is $910 million, which is within $1 million of the combined profits from the products individually optimized for each country. Upon further inspection of the objective function behavior, it is clear that the sensitivity of the tolerance on the profit objective near the optimal solutions is very small compared to that of the price.

Table 1. Optimization results

	China	Sweden	USA
On-contract price (variable)	¥356/month	350 kr/month	$165 one-time
Tolerance (variable)	0.56 mm	0.24 mm	0.29 mm
Profit (objective)	¥3.65 billion	441 million kr	$258 million
Quantity demanded	1.45 million	0.19 million	1.6 million
Market share	5.8%	7.4%	6.4%
Profit (converted to USD)	$586 million	$66 million	$258 million
Profit per unit	$404	$347	$161
Profit per person in market	$23.4	$26.4	$10.3

5 DISCUSSION

This study is the first, to the authors' knowledge, to quantify the effects of visually perceived quality on product sales. Survey results show how people in three countries value mobile phone pricing, storage, recyclability, and visual quality in a stated-choice experiment. A profit maximization formulation was constructed and solved to show the value of consumer choice information for product developers. Furthermore, this formulation shows how ecological impacts and perceived quality can affect a purely economic objective through consumer demand.

The optimization results show that the pricing strategy is important to balance the financial benefits of increased prices with the drawbacks of decreased demand for the product. It is also clear that demand functions from different populations that follow the same general trends and monotonicity, i.e., increasing or decreasing with each parameter, can result in different optimal solutions. When prices and tolerances are the only optimization variables, a global product is recommended with market-specific pricing, as the difference in profits from individual tolerance optimization and combined tolerance optimization was within one-tenth of a percent.

The limitations of the study include a number of potential biases that are inherent to stated-choice studies. The first is that the consumers know that they are not actually purchasing the product, and not all of the information that would normally be available with a phone choice is presented, such as details about the service and features. Another limitation is that of social desirability bias, and it is likely that respondents overstated their preference for recyclability because they believed that is how society wants them to respond. People from different countries and cultures are likely to experience these biases in different ways and to different extents. Finally, as was anticipated, not all respondents noticed the split line, which lowers the part worth calculations for that attribute to an unknown extent.

There are a number of possible explanations for people not noticing and valuing the split line, as well as whether this reflects true attitudes toward split lines in products. The survey was designed with the intention of displaying a product with a clear and noticeable split line without explicitly pointing it out. The majority of respondents not noticing it may be attributed to a combination of factors, such as respondents trying to answer the questions too quickly, assuming that visual quality in a photo or image would not be an issue, and poor vision or screen resolution.

Future studies may address these problems in a number of ways. One way to increase the split line noticeability would be to point it out prior to the CBC questions as a quality defect, which might lead to respondents overvaluing the split line in their responses. Another technique would be to conduct interviews with physical prototypes that the subjects could inspect like they would an actual product, which would involve costly prototypes and time-consuming interviews, and would achieve a much smaller response rate than an online survey.

6 CONCLUSIONS

This study shows how product quality attributes such as split lines can affect a product-developing firm's profits, and how they can account for quality and environmental impact in design optimization. Using such a method that first reveals preferences for product attributes and then uses them for profit maximization can inform product developers of how much variance should be allowed in critical dimensions while simultaneously setting the price points. For the mobile phone case study in this paper, it is seen how different markets that value prices, environmental impacts, and quality in their own ways can demand different products, and it is also shown that designing this particular product for global distribution may be in the best financial interests of the firm.

ACKNOWLEDGMENTS

The authors acknowledge valuable intellectual and modeling contributions from Jessica Dagman and Casper Wickman of the Department of Product and Production Development at Chalmers. This work, carried out at the Wingquist Laboratory VINN Excellence Centre within the Area of Advance – Production at the Chalmers University of Technology, in Gothenburg, Sweden, was supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA). That support is gratefully acknowledged.

REFERENCES

Bjørke, Ø. (1989) *Computer-Aided Tolerancing, 2nd Edition*. New York: ASME Press.

Forslund, K., Wagersten, O., Tafuri, S., Segerdahl, D., Carlsson, J.S., Lindkvist, L. and Söderberg, R. (2011) Parameters influencing the perception of geometrical deviations in a virtual environment, *International Design Engineering Technical Conference*, Washington, D.C., 28-31 August: ASME.

Hoffenson, S., Dagman, A. and Söderberg, R. (2012) A tolerance optimization framework for economic and ecological sustainability. Submitted to *Journal of Mechanical Design* (12 October).

Holling, C.S. (2001) Understanding the complexity of economic, ecological, and social systems. *Ecosystems*, Vol. 4, No. 5, pp. 390-405.

Hong, Y.S. and Chang, T.C. (2002) A comprehensive review of tolerancing research. *International Journal of Production Research*, Vol. 40, No. 11, pp. 2425-2459.

Kramer, O., Echeverria Ciaurri, D. and Koziel, S. (2011) Derivative-free optimization. In Koziel, S. and Yang, X.-S. (eds), *Computational Optimization, Methods and Algorithms*, New York: Springer, pp. 61-83.

Louviere, J.J., Hensher, D.A. and Swait, J.D. (2000) *Stated Choice Methods: Analysis and Applications*, Cambridge, UK: Cambridge University Press.

Lööf, J., Hermansson, T. and Söderberg, R. (2007) An efficient solution to the discrete least-cost tolerance allocation problem with general loss functions. In Davidson, J.K. (ed), *Models for Computer Aided Tolerancing in Design and Manufacturing*, Dordrecht: Springer, pp. 115-124.

Ministry of Housing, Spatial Planning and the Environment (2000) *Eco-indicator 99 Manual for Designers*. The Hague, The Netherlands.

Ostwald, P.F. and Huang, J. (1977) A method for optimal tolerance selection. *Journal of Engineering for Industry*, Vol. 99, No. 3, pp. 558-565.

Papalambros, P.Y. and Wilde, D.J. (2000) *Principles of Optimal Design*. Cambridge, UK: Cambridge University Press.

Sawtooth Software (2008) *The CBC System for Choice-Based Conjoint Analysis*. Sequim, WA, USA.

Shah, J.J., Ameta, G., Shen, Z. and Davidson, J. (2007) Navigating the tolerance analysis maze. *Computer-Aided Design & Applications*, Vol. 4, No. 5, pp. 705-718.

Steen, B. (1999) *A systematic approach to environmental priority strategies in product development (EPS) version 2000 – General system characteristics*. Gothenburg, Sweden: Chalmers University of Technology Technical Environmental Planning.

Söderberg, R. (1993) Tolerance allocation considering customer and manufacturer objectives. In B.J. Gilmore (ed), *Advances in Design Automation*, Albuquerque: ASME, pp. 149-157.

Taghizadeh, A., Dagman, A. and Almefelt, L. (2010) Evaluation of four tools for environmental impact life cycle assessment in sustainable product development, *17th CIRP International Conference on Life Cycle Engineering*, Anhui, China, 19-21 May: University of Technology Press.

Train, K.E. (2003) *Discrete Choice Methods with Simulation*. Cambridge, UK: Cambridge University Press.

von Neumann, J. and Morgenstern, O. (1944) *Theory of Games and Economic Behavior*. Princeton, NJ: Princeton University Press.

Wickman, C. and Söderberg, R. (2007) Perception of gap and flush in virtual environments. *Journal of Engineering Design*, Vol. 18, No. 2, pp. 175-193.