A Multi-objective Tolerance Optimization Approach for Economic, Ecological, and Social Sustainability

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Abstract

Sustainable design requires simultaneous consideration of the economic, ecological, and social consequences of design decisions. The selection of dimensional tolerances and materials are two such decisions that have impacts in all three of these areas. This article presents an optimization framework along with generalized models for considering sustainability and understanding how different aspects of sustainability may trade off with one another. A mobile phone design is used as a case study to demonstrate the strengths of the approach when varying manufacturing tolerance and material choice, and the results include three-dimensional Pareto frontiers illustrating the design tradeoffs.

Keywords:

Sustainable Design; Tolerance Analysis; Multi-objective Optimization

1 INTRODUCTION

The three pillars of sustainability, defined by Elkington as economic, ecological, and social, are frequently seen as competing objectives in product design and business strategies [1]. Companies have internal pressure from employees and stockholders to ensure economic sustainability and continued profits, which are often the highest priorities, but external pressures from governments, private organizations, and consumers are also increasingly driving environmentally and socially sustainable behavior. Today, a company that neglects environmental and social concerns faces risks that include lawsuits, lowered reputations, and government fines. Therefore, it is essential that designers and decision-makers take all three aspects of sustainability into consideration.

While the design of a product is not the sole factor that influences sustainability, design plays an important role in the material usage, manufacturing processes, use phase energy consumption, and end-of-life disposal strategy. Embodiment design decisions such as material choice and dimensional tolerances can influence all of these sustainability factors, and this paper presents an approach for optimizing these design decisions for economic, ecological, and social sustainability. This method produces multi-objective optimization solutions that reveal the extent to which the three objectives trade off, allowing designers to better understand their choices and select solutions that align with their corporate goals. The paper is organized as follows: The next section presents a background of the state of the art in relevant research, followed by a presentation of the method, specific models and results for the case of a mobile phone design, discussions, and conclusions.

2 BACKGROUND

This section presents techniques and findings from previous studies that are relevant to the present design approach. The approach can be divided into four parts: understanding how variation propagates and influences assemblability, quality, and waste, measuring the ecological impacts of actions, quantifying the effects of ergonomic loading, and performing multi-objective optimization.

2.1 Variation analysis

Geometric variation is an inevitable part of manufacturing, as no two components will ever be produced exactly alike. Designers account for this phenomenon by specifying tolerances along with every geometric dimension, essentially saying that the actual product may deviate from the specified dimensions by up to some set amount. For product quality assurance, tighter tolerances are preferred, but these are associated with higher manufacturing costs and thereby comprise a design tradeoff.

Some geometric dimensions are visible to the consumer or contribute to the assemblability or functionality of the product, called *critical* or *functional* dimensions, but even those non-critical dimensions often contribute to the critical dimensions through variation propagation. A number of techniques are used for estimating how variation in one component or dimension contributes, or propagates, to variation in an assembly or critical dimension [2]. Depending on the complexity and structure of the product, variation propagation estimation techniques range from simple linear or linearized tolerance accumulation models to more complex statistical tolerancing and Monte Carlo simulation-based methods [3]. These tolerance propagation methods are commonly used for tolerance-cost optimization, for which the results depend strongly on the problem formulation. Some approaches first select targets for allowed variations in critical dimensions, which act as constraints in the formulation where the objective is to minimize costs [4]. In these cases, the results depend on the choice of target allowed variation, which is often not chosen in a rigorously scientific manner [5]. Other approaches to tolerance-cost optimization minimize loss functions that combine costs with approximated values of decreased quality to the manufacturer and customer [6],[7]. These results rely on meaningful models of how geometric variation contributes to some loss in quality on a monetary or monetary-equivalent level.

Another key assumption in variation analysis and optimization is in estimating the relationship between tolerances and manufacturing costs. Because this relationship depends on many environmental variables and can vary from company to company, researchers often construct and use simple mathematical functions such as linear, reciprocal, or exponential models [8].

2.2 Ecological impact

Sustainable businesses are defined today not only by their economic viability, but also by their environmental responsibility. Commitments to protecting wildlife, neutralizing carbon emissions, reducing pollution, and minimizing resource consumption and waste are now seen as valuable corporate endeavors from a public relations perspective. This presents a challenge in accountability, comparability, and standardization in reporting and measuring ecological impacts, particularly when there are many disparate impact areas such as ozone depletion, global warming, resource consumption, landfill use, and human health-related risks.

Several databases, assessment methods, and software tools have been developed to help quantify the environmental impacts associated with different activities, but there is still no consensus on which metric to use and how to report the results. Eco-Indicator 99 is one such assessment method that categorizes all impacts into three damage levels: human health, ecosystem quality, and resources [9]. This database then has the capability to further normalize the impacts to one unit, which corresponds with the average yearly impact of a European resident. Another method that normalizes all impacts into a single unit is Environmental Priority Strategies in product design (EPS), which associates all activities with an Environmental Load Unit (ELU) corresponding with an environmental damage cost in Euros [10]. Still others, like the United States Environmental Protection Agency (US EPA) Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), keep the impact area reporting separate to allow decision-makers to choose for themselves which impacts are important for their specific scenarios [11].

2.3 Ergonomic load

The third sustainability component regards social well-being, and many definitions of social sustainability go well beyond the scope of the product development process to include satisfaction of basic human needs, quality of life, social justice, and social coherence [12]. Product developing firms have social responsibilities regarding health, safety, and quality of life of employees, customers, end-users, and communities that are impacted by the product or production process [13]. The Lowell Center for Sustainable Production highlights six main aspects of sustainable production, one of which deals with worker well-being, and its fifth principle suggests that workplaces be designed “to continuously minimize or eliminate physical, chemical, biological, and ergonomic hazards” [14]. Employee physical and ergonomic well-being is of interest to the present analysis, particularly as a result of repetitive and physically-demanding motion during assembly processes.

For workers who assemble small parts with their hands, one common risk is the development of repetitive motion disorders (RMDs), which typically result from repetitive motions that require unnatural postures or forceful exertions [15]. The United States Bureau of Labor Statistics reported that approximately 3% of 2011 occupational injuries resulted from “repetitive motion involving microtasks”, resulting in an average of 23 days leave from work [16]. A survey of Australian statistics estimates that this type of injury results in a cost to the company that is on average 21,000 Australian dollars [17]. Ergonomic load, or the force exerted during such repetitive tasks, is one measurement that employers should seek to decrease to lower worker injury rates, though an explicit relationship between loading and injury rates has not yet been established.

2.4 Multi-objective optimization

Design optimization can be conducted for any problem that is modeled mathematically, as long as there is a clearly-defined objective function and a set of continuous or discrete variables [18]. A number of mathematical techniques can solve such optimization problems, the most common of which are gradient-based methods such as sequential quadratic programming, provided that the problem formulation is differentiable. When the problem has more than one objective function, multi-objective optimization is typically performed using weighted objectives. This follows the formulation shown in equation (1).

$$\min_x \sum_{i=1}^{N} w_i F_i \tag{1}$$

Here, the optimization objective is to minimize the sum of N objectives F_i multiplied by their respective weights w_i. Solving this problem with different values for the weighting factors typically yields different solutions. The set of these solutions makes up a Pareto frontier, where each point in the set represents a solution that cannot be improved in one objective without sacrifices to another objective.

3 MODELING APPROACH

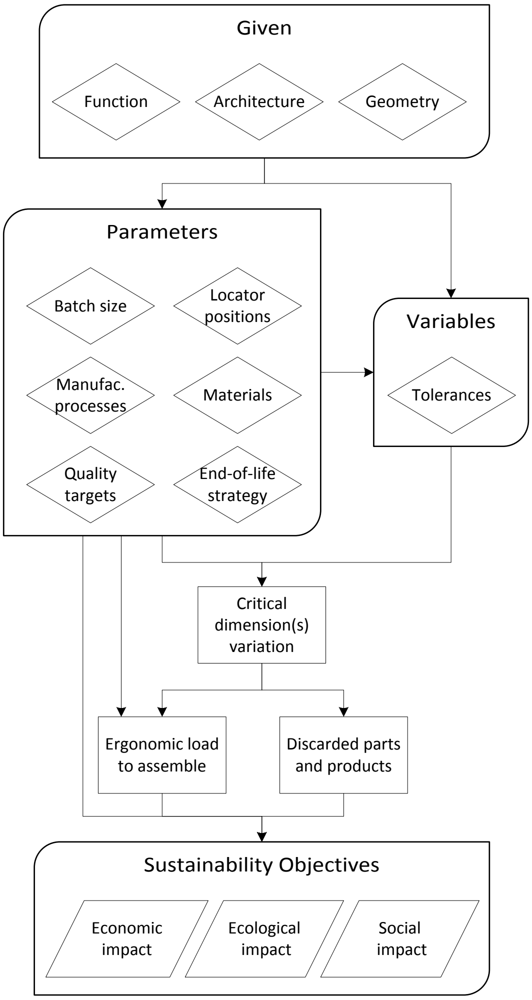

Figure 1: Framework for calculating sustainability outcomes.

The three sustainability objectives of companies revolve around economics, ecology, and social well-being. Design optimization for improving a product's impacts in these areas requires models that predict the effects of changing certain variables and parameters. In this case, tolerances and material choice are the inputs of interest. A framework showing the relationship structure among the inputs and outputs is outlined in Figure 1.

3.1 Economic sustainability

Firms are economically sustainable if they bring in more money than they spend. This framework only considers spending, in particular manufacturing costs, as the economic objective, since this is the component of economic sustainability most clearly affected by the variables and parameters of interest. If revenues and non-manufacturing costs do not change, a company should seek to lower its manufacturing costs to increase profits. Calculating these costs relies on several relationships: the ways that costs change with manufactured tolerances and material choices, how part tolerances propagate to influence assemblability and variation in critical dimensions of the assembly, and how critical dimension variation influences the quality and acceptability of the final product.

First, a cost-tolerance model must be chosen. Given the lack of available empirical data and following the choices in the literature [8], a reciprocal cost function is used, shown in equation (2) where C_{man} is the cost associated with manufacturing and t_i are the n manufactured tolerances.

$$C_{man} = \sum_{i=1}^{n} \frac{1}{t_i} \tag{2}$$

Manufacturers also must pay for the materials themselves, the costs of which depend on the choice of material as well as the quantity of material used in production. Equation (3) provides this relationship, where C_{mat} is the total material cost for the product, c_{mat} is the material cost per unit mass, and m is the mass.

$$C_{mat} = c_{mat} m \tag{3}$$

Next, variation propagation is modeled, which is associated with two outcomes: (1) the ability to physically assemble the parts without breaking them or imposing excessive internal stress in the product, and (2) the variation of critical dimensions in the assembled product. While the second of these outcomes typically dominates the first, i.e., parts that cannot be assembled would also have unacceptable critical dimensions, it is important to calculate both for understanding assembly ergonomics. Simple geometries can be modeled using mathematical relationships regarding statistical tolerancing and stress analysis. For more complex geometries, this is modeled using Monte Carlo simulations in RD&T, a software package specializing in variation propagation simulation and visualization [19]. This involves simulating the product geometry a large number of times with distributed input tolerances to generate a distribution of output variations. With these distributions, estimates can be made for the critical-to-assemble or critical-to-quality dimensional variation as a function of input tolerances, which can result in functions for $\varphi_{fail}(\boldsymbol{t})$, the percentage of parts that cannot be assembled, and $\varphi_{qual}(\boldsymbol{t})$, the percentage of products that do not meet the manufacturer's quality requirements and must be discarded, both of which are functions of $\boldsymbol{t}$, the vector of n input tolerances t_i. When these quantities are correlated and failing assembly implies failure of the quality test, the formula for economic cost C can be written as equation (4).

$$C = \frac{\sum_{i=1}^{n} {}^{1}/_{t_i} + c_{mat} m}{1-\varphi_{qual}} \tag{4}$$

3.2 Ecological sustainability

A product's ecological impact is also affected by the rate φ_{qual}, as discarding parts adds to the production and end-of-life phases of the lifecycle impact. To measure these impacts, however, the ecological consequences of producing and discarding parts and products must first be quantified. To do so in a comparable scale to the economic impact, the EPS framework is adopted for calculating the environmental impact of various activities in ELUs. Steen has developed a database that lists impacts of resource consumption E_{res}, material production E_{mat}, manufacturing processes E_{man}, energy generation or resource use in the use phase E_{use}, and disposal strategies E_{disp} [10]. Drawing from these databases and using the discard rates from the RD&T analysis, equation (5) represents the ecological impact E as it may relate to tolerances.

$$E = E_{use} + \frac{E_{res}+E_{mat}+E_{man}+E_{disp}}{1-\varphi_{qual}} \tag{5}$$

3.3 Social sustainability

The final sustainability component of the model regards ergonomic load, as higher forces required of assembly workers will likely result in more injuries. Employee injuries often result in worker compensation claims, giving companies a financial incentive to seek injury reduction, but they also have ramifications on personal health, employee morale, and the social structure of the workplace, which these companies should prioritize for social sustainability. In order to standardize the units among the three objectives, social sustainability is quantified in monetary terms from worker injury claims, but the analyses will show how optimization results change with different valuations and priorities toward worker injuries.

In assembly, ergonomic load requirements depend on the design of the components. Robust designs and tight tolerances correspond with lower forces required in assembly, since increased variation may cause locator positions to not align perfectly and require additional pressure from the workers to bend the materials and force the parts together. In hand assembly, workers are recommended to not exceed 10 newtons of routine force [20]. Due to a lack of specific injury risk data, this is assumed to carry a safety factor of 20, such that 200 newtons of force over a worker's lifetime corresponds with a 35% likelihood of one worker injury. For lack of a scientifically-validated hand injury probability curve and because these curves typically follow a Weibull function, the present analysis further assumes the structure of the femur injury probability curve used by the automotive industry [21]. This equation is scaled down by a factor of 1,000 and given as equation (6), where the force requirement F in newtons is ultimately a function of input tolerances $\boldsymbol{t}$. The specific function for F depends on the application, but in general it can follow the stress-strain relationship of equation (7), where σ is stress, A is cross-sectional area, δ is the distance compressed depending on $\boldsymbol{t}$, L is the total length, and E is the material-specific modulus of elasticity.

$$P_{injury} = \left(1 + e^{5.795-0.5196 {}^{F}/_{20}}\right)^{-1} \tag{6}$$

$$\sigma = {}^{F}\!/_{A} = \frac{\delta(\boldsymbol{t})}{L}\mathrm{E} \tag{7}$$

Once calculated, the probability of injury over the career of a worker P_{injury} is associated with a financial cost of injury-related leave L. Multiplying this by W, the number of worker-lifetimes needed to manufacture the full product line, and C_{injury}, the average economic cost per worker injury, and dividing by the number of total products produced $N_{product}$, L is calculated using equation (8).

$$L = \frac{W \cdot C_{injury}}{N_{product}} P_{injury} \tag{8}$$

3.4 Optimization

Using the models described in this section, an optimization formulation can be constructed following equation (1). Here, the three objectives are cost C, ecological impact E, and social cost of injury-related leave L. When the weighting is equal, i.e., $w_C = w_E = w_L$, a single solution dictates the optimal tolerance choices and outcomes. However, it is interesting to see how the outcomes may change when societies and corporations value the three sustainability pillars unequally, and so Pareto frontiers are used to show the relationships and tradeoffs among the objectives.

4 CASE STUDY: MOBILE PHONE

The approach of Section 3 is demonstrated through the design scenario of a touch-screen mobile phone. This section describes the modeling process and an analysis of the optimization results for this example case, revealing the capabilities of the approach detailed in the previous section.

4.1 Case-specific models

The mobile phone of interest is pictured in Figure 2a, and the main components are a front and a back piece joined by four snap connectors, shown on the inside of the back piece in Figure 2b.

(a) (b)

Figure 2: Mobile phone model, (a) assembled and (b) back part.

Each of the four snap connectors on the top and bottom has a defined tolerance in both the lateral and longitudinal directions, for a total of sixteen tolerance inputs. Since these are form features of two symmetric parts, all of them are set to the same value, t. These tolerances affect two assembly outcomes: (1) the flushness of the edges of the two pieces, which can be measured by the alignment of the four corners between the front and back pieces, and (2) the ability to assemble the four snap connectors without excessive internal stress in the parts. The first of these outcomes is a perceivable quality concern, and the manufacturer is assumed to discard any device where the deviation on any corner exceeds one millimeter. The second regards assemblability; here, the assembly is prescribed by three locator points corresponding with three of the snaps, and the assemblability is defined by how well the fourth snap in the upper-left corner of the device aligns between the front and back pieces. Larger deviations between the fourth snap locations on the two pieces indicate more stress required during assembly and therefore a larger probability of the parts cracking or the assembly worker developing a repetitive motion injury.

First, the relationships between the tolerances and outcomes are studied using a Monte Carlo simulation over a range of input tolerances. The tolerances t were simulated with 300 values ranging from 0.01 to 3.0, and the resulting means and standard deviations of the outputs were recorded and fit to linear models as functions of t. The two corner measures at the top of the phone had equal and substantial output variation, and the corner deviations at the bottom of the phone were relatively insignificant. Quality is thus characterized by the mean and standard deviation of the top-right corner alignment, denoted μ_q and σ_q, and similar values for the top-right snap locator which define assemblability are denoted μ_a and σ_a. The regression models are given as equations (9-12), all of which fit with a coefficient of determination of at least 0.999.

$$\mu_q = 0.6055t \tag{9}$$

$$\sigma_q = 0.3896t \tag{10}$$

$$\mu_a = 0.08406t^2 + 0.1439t \tag{11}$$

$$\sigma_a = 0.05798t^2 + 0.2050t \tag{12}$$

Since the absolute values are represented here with means near zero, a folded normal distribution is assumed [22]. Thus, with quality target T_q representing the permitted variation, the cumulative distribution function is used to calculate φ_{qual} in equation (13).

$$\varphi_{qual} = 1 - \int_0^{T_q} \frac{1}{\sigma_q\sqrt{2\pi}} e^{-\frac{\left(-x-\mu_q\right)^2}{2\sigma_q^2}} dx - \int_0^{T_q} \frac{1}{\sigma_q\sqrt{2\pi}} e^{-\frac{\left(x-\mu_q\right)^2}{2\sigma_q^2}} dx \tag{13}$$

A similar formulation can be used for φ_{fail} when an assemblability threshold T_a exists, shown in equation (14). In this scenario, there is also a need for the distribution of this output, as it affects ergonomic load patterns. The probability distribution function f_{snap} is given as equation (15) for top-right snap offset δ, which depends on t.

$$\varphi_{fail} = 1 - \int_0^{T_a} \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{\left(-x-\mu_a\right)^2}{2\sigma_a^2}} dx - \int_0^{T_a} \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{\left(x-\mu_a\right)^2}{2\sigma_a^2}} dx \tag{14}$$

$$f_{snap}(\delta|\mu_a, \sigma_a) = \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{\left(-\delta-\mu_a\right)^2}{2\sigma_a^2}} + \frac{1}{\sigma_a\sqrt{2\pi}} e^{-\frac{\left(\delta-\mu_a\right)^2}{2\sigma_a^2}} \tag{15}$$

For this product, it is observed that all products failing assembly will also fail the quality test, following cost equation (4). With only one tolerance specification and a fixed product volume of 7.6 cubic centimeters, cost can be calculated as equation (16), where ρ is the material density in kg/cm^3, found along with the c_{mat} data in [23].

$$C = \frac{{}^{1}\!/_{t} + 7.6\rho c_{mat}}{1 - \varphi_{qual}} \tag{16}$$

Since the use phase impact of a mobile phone is primarily the electricity consumption, which is unrelated to tolerance and outer shell material choices, it is left out of the ecological sustainability calculation. This reduces equation (5) to equation (17), where the material-based values for the E_is are found in [10].

$$E = \frac{E_{res}+E_{mat}+E_{man}+E_{disp}}{1-\varphi_{qual}} \tag{17}$$

The front and back pieces are expected to require elastic bending during assembly when the locator snaps do not line up correctly, and so force is calculated as a function of deflection distance, or the top-right snap offset δ. This is calculated using equation (7), where the cross-sectional area diagonally across the device is 130 square millimeters and the total length being compressed is 130 millimeters. The relationship is given in equation (18), where F is force in newtons and E is the material-specific modulus of elasticity in megapascals, found in [23].

$$F = \frac{130\delta\mathrm{E}}{130} = \delta\mathrm{E} \tag{18}$$

Finally, this force affects the likelihood of worker injury. Because F is not constant for every device assembled, the probability distribution from equation (15) is multiplied by the injury probability and integrated across the range of δ values to develop an expected injury probability per worker. This is then multiplied by the economic cost of an injury to a firm. Assuming 1,000 worker-lifetimes to create 10 million total products, and each injury costs the company an average €20,000 through a combination of worker compensation claims, paid leave, and other expenses, the financial cost of injury-related leave L is calculated as equation (19). Recalling equations (11), (12), and (15), this is ultimately a function of tolerance input t.

$$L = \frac{(1000)(20000)}{10000000} \int_0^{\delta_{max}(t)} P_{injury}(\delta) f_{snap}(\delta) d\delta \tag{19}$$

Here, $\delta_{max}(t)$ is the highest expected deviation given the maximum allowed variation T_q, which can be calculated using the means and standard deviations of the quality and assemblability variations from equations (9-12).

With C, E, and L as explicit functions of tolerances and materials, the tri-objective sustainability optimization formulation is complete.

4.2 Results

The optimization was first solved with all weights set equal, using ABS plastic and end-of-life disposal in a landfill. The results give an optimal design with tolerance t of 1.053 mm, which corresponds with an economic manufacturing cost C of €1.19, ecological cost E of 0.02 ELU, and worker injury costs L of €1.60. While this is an interesting result, the numbers are based on models that hold many assumptions. The present model is most useful to understand the tradeoffs among the objectives when the weighting changes.

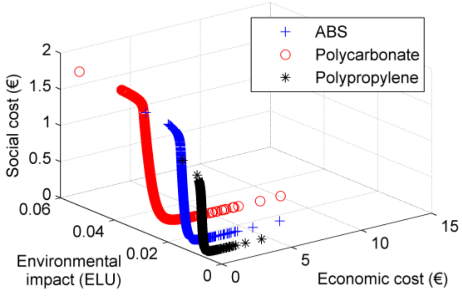

Figure 3: Three-dimensional Pareto curves.

Solving the same problem ten thousand times with different randomly-selected weights w_C, w_E, and w_L generates a three-dimensional Pareto frontier showing the tradeoffs among the economic, ecological, and social objectives. Since the problem only contains one variable, this frontier is a curve following a single path as the optimization suggests tighter or wider tolerances. This curve, depicted for three different materials in Figure 3, travels as the optimal tolerance increases from solutions with high C and low E and L values to those with lower C and higher L values to those with still lower C and higher E values.

Cross-sectional views of Figure 3 show more about the shape of the curves and the ways the material choice can influence the outcomes. A cross-section perpendicular to the “environmental impact” axis examines the first tradeoff as the optimum moves from the tightest tolerances toward looser tolerances, shown in Figure 4. This corresponds with initially decreasing economic costs and increasing social costs. Here, the size of the box corresponds with the tolerance, so a larger box indicates a wider optimal tolerance.

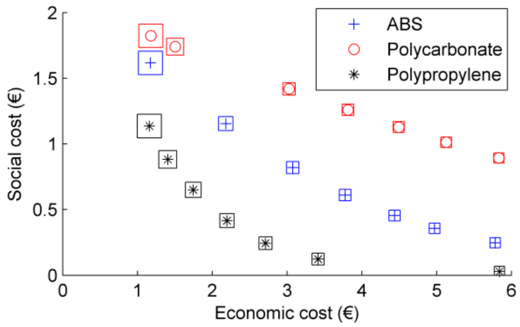

Figure 4: Tradeoff between economic and social objectives.

As the tolerances become even wider, economic cost continues to decrease and environmental impact begins to increase. This behavior is shown with a cross-section perpendicular to the “social cost” axis in Figure 5.

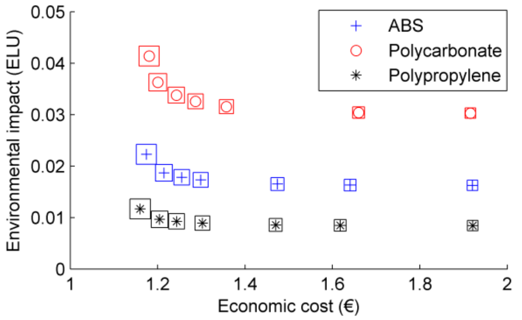

Figure 5: Tradeoff between economic and ecological objectives.

For both of the tradeoffs shown, polypropylene appears to be the most sustainable material choice, as it affords better solutions with respect to all objectives than those of ABS and polycarbonate.

5 DISCUSSION

Using multi-objective optimization for tolerance and material choices can reveal tradeoffs among sustainability objectives for economic, ecological, and social outcomes. The results presented in the previous section for the mobile phone case study show how, even with only one design variable, a firm’s and designer’s sustainability priorities can significantly influence the optimal design and outcomes. Depending on the objective function weighting, the solution may converge on any feasible tolerance choice within the allowed range. This behavior is due to the specific structure of the models used, as economic objectives demand wider tolerances while ecological and social objectives push for tighter tolerances.

In a scenario with more than one tolerance variable to be optimized, the three-dimensional Pareto frontier may consist of a convex surface rather than a single path through space. Each point on the surface would correspond with an optimal combination of the design variables and the associated sustainability outcomes.

As with any modeling work, additional considerations could be included to make for a more complete formulation. From an economic perspective, more information about specific cost-tolerance relationships as well as revenue-related models might be added. The ecological modeling might include additional considerations or variables such as the source of materials, manufacturing processes, and the impact of low-quality products failing early and needing replacement. The characterization of social sustainability could benefit from an empirical relationship between loading, frequency, and hand injuries, as well as additional injury or social well-being considerations for both the employees and the customers. The value of including such additional models depends on the case of interest, and this is left for future research and practical applications.

6 CONCLUSIONS

To make truly sustainable design decisions, all three of the sustainability pillars must be considered in the product modeling and optimization processes. Sustainable tolerancing must consider the economic impacts of material and manufacturing costs, the ecological impacts of material resources, processing, and disposal, and the social impacts of worker injuries. This paper demonstrates how an explicit tri-objective optimization formulation can inform sustainability decisions in tolerancing and material choice. Rising interest in ecological and social sustainability by policymakers and consumers is expected to further link these three objectives for when a manufacturer seeks to maximize its profits from a product.

7 ACKNOWLEDGMENTS

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