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Research Article

Tolerance Allocation Considering Multiple Phases of the Product Life Cycle for Optimum Cost, Performance, and Sustainability Using the HEIM Framework

Shravya Dorna, Rukmini Srikant Revuru*, Julie Zhe Zhang

Department of Applied Engineering and Technical Management, University of Northern Iowa, Cedar Falls, Iowa, USA
Email: rukmini.revuru@uni.edu

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Abstract: Tolerance allocation is usually considered only at the stages when designers are designing the product and manufacturing/process engineers are forming a process flow for manufacturing the product. In this paper, the tolerances for a product are allocated considering the most crucial stages of manufacturing, quality, use, and reuse stages of a product life cycle. This approach helps to sustainably allocate the tolerances. A framework with an example of alternatives with attributes - cost, performance, and sustainability is discussed to achieve the intended tolerance allocation by considering multiple stages of the life cycle using the Hypothetical Equivalents and Inequivalents Method (HEIM). HEIM allocated the weightage to different parameters. In this case, HEIM is used to give weightage for different stages of the product life. This helps to allocate the tolerances with due importance to each stage. This is the main contribution of this paper as the application of HEIM for tolerance allocation is not found in the literature. Extending this framework to products like mobile phones, laptops, watches, etc. would help to avoid the redesigning of the product in the future for making it efficient in terms of cost, performance, and sustainability. Also, using this concept products can be reused with liberalized tolerances to obtain the same performance as new ones leading to cost savings and improving the sustainability of the product. The proposed methodology was used in the present work to estimate the tolerance for the least cost of manufacturing a product.

Keywords**:** tolerance allocation, product life cycle, HEIM, sustainability

Nomenclature

C_o - Cost of the product when its tolerance tends to infinity
r_{Ai} - The normalized score rating of alternative A on attribute i
w_i - The weight of the attribute i
σ^2 - The process variance of X
a - Adjusting coefficient in the reciprocal model of the cost function
b - Negative coefficient in the reciprocal powered model of the cost function
$C(T)$ - The cost of manufacturing a product at tolerance T

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$F(x)$ - Objective function of the optimization problem
$g(x)$ - Constraints developed from consumer-stated preferences to solve the optimization problem
K - Quality loss coefficient in Taguchi quality loss equation
$L(X)$ - Quality loss function of a quality characteristic X
M - Nominal value of the quality characteristic X
n - The number of attributes
T - Tolerance of a product
U - Average value of the quality characteristic X
$V(A)$ - The value of an alternative A
x - The vector of attribute weights in the HEIM method

1. Introduction

Tolerance allocation is the most important step for the designers and manufacturing engineers which must be done thoughtfully considering the multiple life cycle stages of the product. Currently, in most industries, tolerance allocation is carried out considering the functionality, cost, and quality aspects of a product covering only the design, manufacturing, and inspection stages of a product's life cycle. This paper investigates the tolerance allocation method considering the manufacturing, inspection, and use and reuse stages of a product life cycle so that the spotlight is thrown on the aspects of cost, quality, performance, and sustainability of a product.

The product life cycle has various stages such as design, manufacturing, inspection, distribution, use, reuse, or end of life. Tolerance allocation for a product happens in the stages of design and manufacturing. Designers and manufacturing engineers mostly allocate tolerances to a product by considering the functionality and cost involved in making it. Hence, they end up choosing tolerances that can meet the function, are easier to manufacture, and cost less. Products with looser tolerances are easy to manufacture and require less cost. However, a loose tolerance will result in products of higher variability in their quality characteristics stemming from products that do not effectively last throughout their lifetime and thereby increasing the quality loss. Typically, when allocating tolerances, experimental data, drawings, and expertise are used [1]. Hence, manual approaches are commonly used to verify and assign tolerance values through a trial-and-error approach [2]-[4]. However, these methods often overlook the resulting manufacturing costs, relying on qualitative guidelines like "tighter tolerances increase manufacturing costs" [1]. Usually, three questions need to be answered for tolerance allocation [5]:

1. "How good does the product have to be?"
2. "What can be done to improve the quality of the product?"
3. "What is the most profitable action to take?"

If a designer chooses tighter tolerances, variability can be prevented, and quality can be improved but it might cost more to manufacture. Sometimes the tighter tolerances are not what the consumers prefer and do not impact the performance of the product. They might choose lower-priced products or loose-tolerance products and are okay with the higher variability if the performance is still not affected. For example, the experimental study done by Hoffenson et al. [6] on a mobile phone outer case with a visible nonparallel gap, shows that most of the consumers did not notice the non-parallel gap and preferred a lower price product over the higher quality/tighter tolerance product. Although tighter tolerances are not always the preference of consumers, producing parts with tighter tolerances may increase the lifetime of a part and can be reused again by disassembling from the assembly made. This helps in sustainable economic development as the resources are reused and manufacturing costs for new assembly are drastically reduced.

This shows that a product would be effective with tighter tolerances in terms of quality loss and sustainability aspects for quality and reuse stages respectively. Products can also be effective with looser tolerances in terms of manufacturing cost, ease to manufacture, and sometimes customer satisfaction (since it costs less) in the manufacturing and usage stages respectively. Hence, the study intends to focus on how to establish a framework that helps determine a tolerance value for a part such that the cost, performance, and sustainability aspects of the part are optimized. This study aims to investigate tolerance allocation at different stages of the life cycle of a product - such as manufacturing, quality, use, reuse, or end of life - to obtain a tolerance at which the value of the life cycle of a product in terms of cost, performance, and sustainability is optimum. This research study will explore the following question: What is the tolerance allocation at which the aspects of cost, performance and sustainability of a product are optimum considering the life cycle stages of manufacturing, quality, use, and reuse? The following assumptions are made in this present work:

a. The performance of a product is measured in terms of satisfaction and perception of quality by the consumer.

b. In practice, the formation of a perfectly circular economy is nearly impossible due to the material degradation mechanism or the imperfect nature of material separation and reclamation during recycling. Apart from the technical issues, there are also legal issues that will arise between industries when they are trying to form a closed loop. This research assumes that the product whose tolerance is being discussed has formed a circular economy and parts are used after disassembly for remanufacturing to the maximum extent possible.

c. For remanufacturing products, the increase in inspection and management costs is negligible and less than the income generated from the reuse of parts.

2. Method of study

This research is based on the review of the literature regarding tolerance allocation and how it is related to the concepts of sustainability, circular economy, and consumer perception of quality. The expected outcome of this review would be a framework to establish tolerance of the product by optimizing the cost, performance, and sustainability.

The tolerance needs to be looser for lowering the manufacturing costs, and tighter for preventing quality loss and sustainable manufacturing of the product. Tolerance requirements vary from tighter to looser depending on the consumer perception of quality. Hence, this research helps to build the framework to obtain the best tolerance suitable for that product and market, by optimizing the cost, performance, and sustainability aspects according to the decision-maker or designer's preferences using the Hypothetical Equivalents and Inequivalent Method (HEIM) technique. HEIM is an operations research method in which weights are systematically allocated to different attributes. It helps to create a multi-selection criteria problem and solve it [7]. Since in this paper different stages of the product cycle are considered, it is important to attach appropriate importance (weights) to each of these stages and find the most optimal and robust tolerance allocation. Hence, the HEIM technique is used in the present work.

3. Analysis

3.1 *Product life cycle*

The six important stages of a product life cycle are:

1. Design: The product idea is conceptualized considering the requirements and budget. Depending upon the specifications, tolerances are assigned by the designer at the end of this stage.

2. Manufacturing: The design developed by the designer is transformed into a physical product. If needed in this stage, the manufacturing engineer would reassign the tolerances as per the manufacturing processes selected.

3. Inspection: The manufactured product undergoes checks to ensure it meets the specifications and there is not much variation in the process or the product.

4. Use: The product made is used by the end customer and customer satisfaction with the product will be discovered in this stage.

5. Reuse: The product may be reused or refurbished if it is still in good condition.

6. End of life: End of life is the final stage where the used product can be recycled, disposed of, or repurposed.

Each stage of the product life cycle has its unique challenges and opportunities that companies need to consider when designing and manufacturing their products. The goal is to create a sustainable product that can be used and reused effectively, minimizing the negative impact on the environment.

3.2 *Manufacturing stage*

The traditional cost and tolerance relationship from the manufacturing point of view should majorly satisfy the three conditions mentioned below. Here, T denotes the tolerance and $C(T)$ denotes the cost at tolerance T.

1. If T_A and T_B are two values of tolerance which are between $(0, \infty)$ and $T_A > T_B$ then $C(T_A) < C(T_B)$.
2. $\lim_{T \to \infty} C(T) = C_o$.
3. $\lim_{T \to 0} C(T) = \infty$.

There are many traditional models such as reciprocal, reciprocal squared, reciprocal powered, exponential, polynomial, hybrid exponential, linear, piecewise linear, spline, and extended splines which show a relationship between cost and tolerance. Sanz-Lobera et al. [8] suggest that during the manufacturing stage, the selection of raw material, processes, equipment, and fixtures are done based on the cost. The processes selected or the equipment chosen will have an impact on the tolerance to be achieved on the product. Hence, tolerance decisions are always made so that the total manufacturing cost could be reduced. In the above case, as the manufacturing engineers and design engineers aim at having lower manufacturing costs, they would prefer to choose looser tolerance T_A.

The Reciprocal model is the simplest model which is expressed as $C(T) = \frac{a}{T}$, where 'a' is an adjusting coefficient and does not fulfill the second condition mentioned above. The Reciprocal squared model is also very similar to the Reciprocal model except that the cost of manufacturing is inversely proportional to the square of the tolerance i.e., $C(T) = \frac{a}{T^2}$. The Reciprocal powered model is expressed as $C(T) = C_o + a.\ T^b$ where b is a negative coefficient and C_o is a constant. Reciprocal and Reciprocal squared models are part of the Reciprocal powered model. When $C_o = 0$ and b = -1 or -2 Reciprocal powered model changes to Reciprocal and Reciprocal squared models respectively. $C(T) = a \cdot e^{bT}$ explains the Exponential model which also doesn't satisfy the second and third conditions. From all the models, we understand that the cost of manufacturing is inversely proportional to the tolerance. This depends upon how fast the cost increases with a decrease in tolerance so the graph looks similar to the model discussed here.

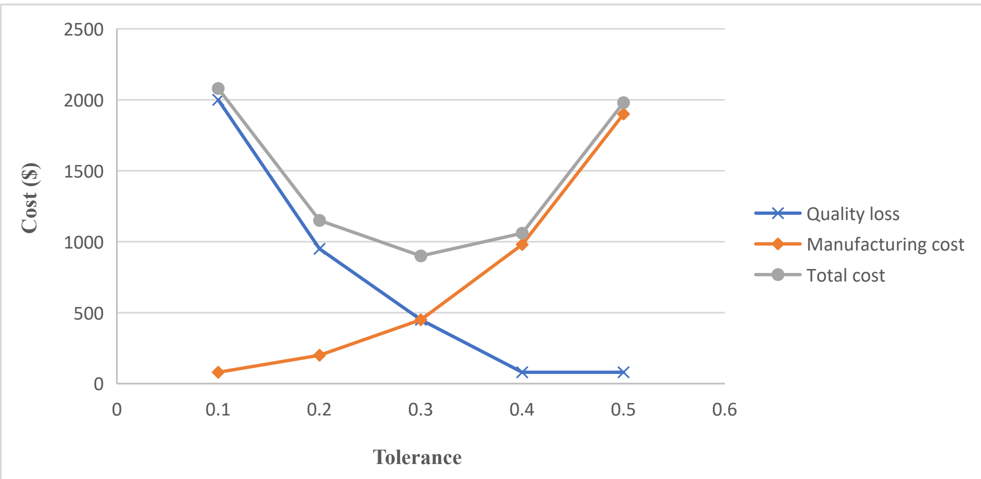

Figure 1. Tolerance and cost function

3.3 *Quality stage*

Sanz-Lobera et al. [8] theorize that the loss that is incurred by society because of the deviation of the product from the mean value, is called quality loss. The quality loss can be found from the equation $L(X) = K(U - M) + \sigma^2$ where U is the average value of quality characteristic X, M is the nominal value of the quality characteristic of X, and K is the quality loss coefficient and the term σ^2 represents the process variance of X. This is called the Taguchi quality loss equation. These losses originate from the cost to produce, the failure to function, the maintenance and repair cost, the loss of brand name (leading to customer dissatisfaction), and the cost of rework and redesign [9].

The component $(U - M)^2$ would indicate the variability of a component quality characteristic from the nominal value. If Y_o is the nominal value and T the tolerance, then $M = Y_o$ and $U = Y_o \pm T$, the component $(U - M)^2 = T^2$. Choosing looser tolerances, $(U - M)^2$ is maximum, and hence, quality losses are maximum. According to Wang et al. [10], this shows that there are high-quality losses in choosing looser tolerances which would lead to passing unsatisfactory products.

Considering the manufacturing and quality stages of the life cycle, the total cost is the sum of manufacturing cost and the quality loss [10]. The tolerance of a product is plotted against the total cost as shown in Figure 1. The lowest point of cost where the manufacturing cost graph meets the quality loss graph would indicate the optimized tolerance of the product on the X-axis.

This is an example graph representing Tolerance Vs. Total Cost Function, from this we can derive that the best suitable tolerance that balances both manufacturing cost and quality loss is 0.3 mm.

3.4 *Use stage*

This stage is based purely on the consumer and their opinion on the product performance and the visual appearance. Product performance is directly proportional to customer satisfaction. If the customer is pleased with the product, then it means the product performance is at its best. Designers see tighter tolerances as correlating with higher performance of the product, but does the consumer also perceive the performance of the product in terms of tolerances? If yes, the tighter the tolerances, the higher the manufacturing cost which would lead to an increase in the Product's price. So, it is important to also think about whether the preference of the consumer is tolerance or the price.

According to Hoffenson et al. [6], when a survey was conducted for consumer preferences regarding a mobile phone casing, most of them opted for lower prices followed by the quality and recyclability of the material used. This survey also stated that the respondents were shown two sets of mobile phones with one of them having an angled split-line gap which is not noticed by 75% of respondents. Respondents from a few countries have shown more interest in angled split-gap products as they are available for a cheaper price. Hoffenson's research is a perfect example showing how consumer preferences change depending on various factors.

Preferences change based on product type, the country where a product is sold, and the demographic details of consumers. If we can evaluate consumer preferences accordingly during the product development stages while making tolerance decisions, we can avoid the overachievement of fits that are not mandatory for consumers. Also, if the use stage is considered in early design changes, we can completely avoid redesigning products in the future to bring a balance between manufacturer supply and consumer demand. Performance and consumer preferences of a product can be evaluated using a survey that asks the end user of the product to share his or her perceptions and assign a rating when compared to other products.

3.5 *Reuse stage*

Tolerance allocation not only impacts the economic aspect of the business but also has an impact on the ecological aspect of a business. The looser tolerances would hinder the ease of assembly and functionality of the product and this might lead to an increase in the number of discarded parts without completing their expected life [10], [11]. Also, the tighter tolerance part cannot be reused, repurposed, or recycled easily because little damage to the part during the disassembly might lead to scrapping the entire part. Discarding parts or products is a waste of resources available and would damage the sustainability of the company. If the reuse stage is considered during the initial product development, tolerances can be suitably allocated as per the future of the product.

With the current awareness of sustainability, Circular Economy is gaining prominence [12]. It is an economic model that aims to minimize waste and fully utilize resources (Figure 2). According to Haanstra et al. [13], the circular economy is an emerging paradigm used for the sustainable development of business and to increase business opportunities. This is a regenerative design like the cradle-to-cradle philosophy with the principles of:

i. **Closing material loops:** Biological and technical cycles of an organization should form a closed loop. The biological cycle encloses the earth's ecosystem and metabolizes all that earth's ecosystem can take. The technical cycle will take care of reusing the resources that cannot be metabolized by the earth. In this way, the finite number of resources available can be put to their highest values always.

ii. **Functional life extension:** Extend the product life as much as possible by reuse, repair, and maintenance so that the higher efficiency of the material is obtained for the same functionality of the product.

iii. **Cascading:** If the materials are unable to fit in the closed material loops, then recover them to use for a less demanding purpose that is different from the original purpose of the material.

iv. **Renewable energy use:** Always use renewable energy resources and avoid using nonrenewable resources to prevent the depletion of resources.

v. **Performance economy:** Developing an economy that is not bound by product sales but is determined by consumer demand fulfillment. This will help in developing new business opportunities across fields such as product design, service, food, farming, biological feedstocks, and products that can be beneficial in maintaining the closed material loops.

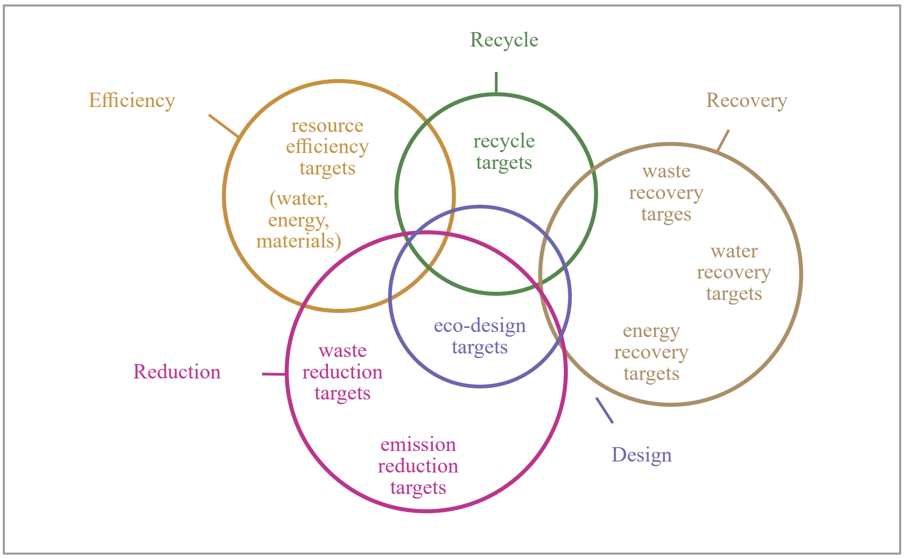

Figure 2. Circular economy [14]

Allocating the tolerances to a product such that the product falls into the circular economy, as mentioned above, will help to improve sustainability, and decrease the remanufacturing cost of the new products or the cost of the existing life-extended products. According to Liu et al. [15], it is a great challenge to make the reuse parts meet the standards of new parts and achieve the assembly precision, but the tolerance grading allocation method proves that the tolerance on remanufactured parts can be liberalized by 41.4% and can still ensure the stability and reliability of the assembly quality. The tolerance grading allocation method is generally used in the remanufacturing industry where the parts are graded based on the dimensional tolerance precision by measuring the sizes. The grading is done in such a way that all the higher spec limit (Nominal + tolerance) parts are separated from the lower spec limit (Nominal − tolerance) parts. Thereafter, a selective assembly method is used in such a way that either all upper spec parts or all lower spec parts are used together for making the assembly. This way assembly deviations and uncertainty of remanufacturing parts can be reduced by ensuring the remanufactured product quality.

Sustainability can be measured in Environment Load Units (ELU). Hoffenson et al. [11] suggest that in this rating system, one ELU is equivalent to an environmental damage cost of one Euro. In scenarios of reuse, assign negative ELUs as the reusing resources reduce the future need to produce usable materials from raw minerals.

3.6 *Tolerance allocation*

From the discussion above, it can be observed that tolerance requirements change from one stage of the life cycle to the other. Some stages need tighter tolerances while others need looser tolerances. Cost is an attribute of the manufacturing and quality stages, while the performance of the product rated by the consumer is an attribute of the use stage, and the sustainability of a product is an attribute of the reuse stage. Hence, there is a need for balancing these attributes to obtain an optimum tolerance that is best suitable for all the stages of the product life cycle.

Cost of a product = Manufacturing cost + Quality loss

Performance = Consumer satisfaction rating with his/her perception of quality

Sustainability = In terms of Environment Load Units (ELU) developed by Environmental Priority Strategies in product design (EPS).

3.7 *Alternatives formation for Tolerance allocation*

The tolerance needs to be looser for lowering the manufacturing costs, and tighter for preventing quality loss. The tolerance requirement varies from tighter to looser depending on the consumer perception of quality and sustainable manufacturing of the product. Hence, this research helps to build the framework to obtain the best tolerance suitable for that product and market, by optimizing the cost, performance, and sustainability aspects according to the decision-maker or designer's preferences using the HEIM technique.

The alternatives for the tolerance allocation are chosen below (Figure 3):

1. Obtained from the cost optimization technique - alternative #1.
2. Tighter tolerance than alternative #1 - alternative #2.
3. Looser tolerance than alternative #1 - alternative #3.

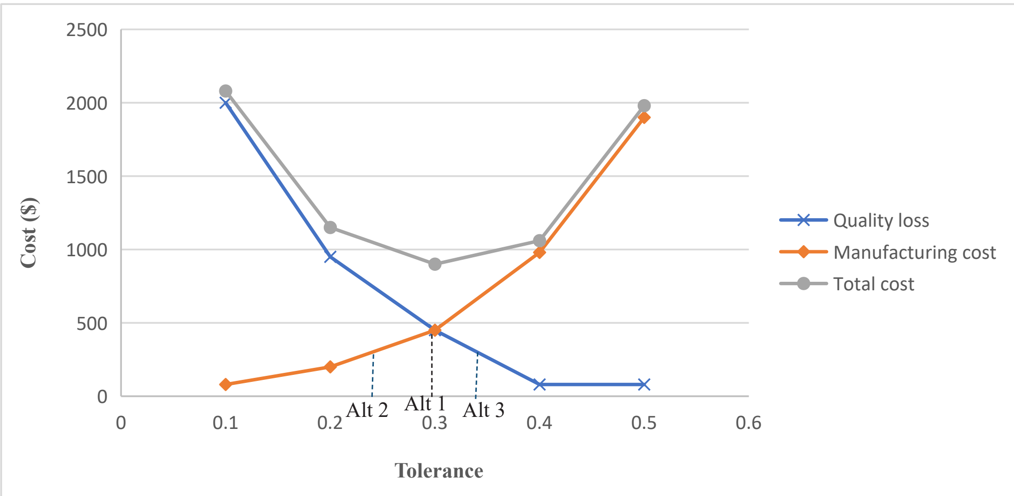

Figure 3. Tolerance and cost function with alternatives

The values of all three attributes - cost, performance, and sustainability - are evaluated for each alternative. HEIM is used to find the weightage for each attribute according to the decision-maker preferences and the total value of each alternative is found. The alternative with the highest value is the tolerance that is more feasible for the manufacturing of the product.

4. HEIM method

The HEIM is built to draw out stated preferences from a decision-maker with reference to a set of different alternatives to evaluate the importance of the attributes and calculate the weights from the preferences set by the decision maker [7]. The weightage of each attribute is found by solving the optimization problem such as:

$$Min\ F(x) = \left(1 - \sum_{i=1}^{3} w_i\right)^2, \text{ where } 0 \le w_i \le 1 \tag{1}$$

Subject to $g(x) \le 0$.

Here, the objective function ensures that the sum of the weights of attributes is equal to one.

x is the vector of attribute weights.

$F(x)$ is the objective function of the optimization problem.

$g(x)$ are constraints developed from consumer preferences to solve the optimization problem.

w_i is the weight of the attribute i.

For example, if the values of the Attributes are as shown in Table 1 (these values are an illustration to showcase the application of the HEIM method to choose an alternative out of the three alternatives). The attribute cost is in the unit of dollars ($), performance is the percentage (%) of customer satisfaction with the product and sustainability is in the units of Environment Load Units (ELU). For alternative #1, the product cost is low, the performance is good, but the sustainability factor indicates that there is high environmental damage. For alternative #2, the cost is moderate, and the performance of the product is low, and the environmental damage is medium. For alternative #3, the cost is high, but the performance is low due to low customer satisfaction, but the sustainability factor shows the environmental damage is low. All three alternatives have a few positives and negatives. Hence, HEIM is used to pick the best alternative among the three.

Table 1. Example values of attributes for all the alternatives

Alternatives	Attribute 1- Cost ($)	Attribute 2- Performance (%)	Attribute 3- Sustainability (ELU)
Alternative #1	6,650	100	80
Alternative #2	7,900	50	50
Alternative #3	8,820	50	20

Allocate the normalized scores to each attribute of an alternative. This can be done by assigning the highest value of an attribute with a score of 1, the least value with a score of 0, and anything in between with a score of 0.5. In the above example, alternative #1 gets the best score of 1 for attribute #1 due to low cost, the best score of 1 for attribute #2 due to high customer satisfaction, and a low score of 0 for attribute #3 due to higher environmental impact. Alternative #2 gets a medium score of 0.5 for attribute #1 due to moderate cost, a low score of 0 for attribute #2 due to low customer satisfaction, and a medium score of 0.5 for attribute #3 due to medium environmental impact. Alternative #3 gets a low score of 0 for attribute #1 due to high cost, a low score of 0 for attribute #2 due to low customer satisfaction, and a high score of 1 for attribute #3 due to low environmental impact. Table 2 summarizes these normalized values for all alternatives and the value of the alternative can be found using the below equation. The equations are based on the literature [16] and are formulated for the specific study.

$$V(A) = \sum_{i=1}^{n} w_i r_{Ai} \tag{2}$$

where,

$V(A)$ is the value of an alternative A.

w_i is the weight of the attribute i.

r_{Ai} is the normalized score rating of alternative A on attribute i.
n is the number of attributes.

Table 2. Normalized values of attributes for all the alternatives

Alternatives	Attribute 1	Attribute 2	Attribute 3	Value of Alternative
Alternative #1	1	1	0	$w_1 + w_2$
Alternative #2	0.5	0	0.5	$0.5w_1 + 0.5w_3$
Alternative #3	0	0	1	w_3

Constraints are formulated from statements of designers such as
"I prefer alternative 1 to alternative 2."
"I prefer alternative 2 to alternative 3."

$$\Rightarrow V(1) > V(2) \text{ and } V(2) > V(3) \tag{3}$$

$$\Rightarrow V(1) > V(2) \;\Rightarrow V(2) - V(1) < 0 \;\Rightarrow V(2) - V(1) + \delta \le 0 \tag{4}$$

$$\Rightarrow V(2) > V(3) \;\Rightarrow V(3) - V(2) < 0 \;\Rightarrow V(3) - V(2) + \delta \le 0 \tag{5}$$

Where δ is 0.001 and is added to ensure the inequality of two values

$$-0.5w_1 - w_2 + 0.5w_3 + \delta \le 0 \tag{6}$$

$$-0.5w_1 - 0.5w_3 + \delta \le 0 \tag{7}$$

Solve the below function to get the weightage of w_1, w_2 and w_3 using both inequality constraints by means of the optimization technique.

$$Min\ F(x) = (1 - (w_1 + w_2 + w_3))^2, \text{ where } 0 \le w_{1,2,3} \le 1 \tag{8}$$

Subject to constraints:

$$-0.5w_1 - w_2 + 0.5w_3 + \delta \le 0 \tag{9}$$

$$-0.5w_1 - 0.5w_3 + \delta \le 0 \tag{10}$$

After finding the w_1, w_2 and w_3, use them to find the value of alternatives 1, 2, and 3 from Table 2. Once the value of the three alternatives is known, choose the alternative that has the maximum value as the tolerance that must be applied to the product.

5. Limitations and delimitations

1. For a single product with a specific manufacturing cost and sustainability index, the tolerance obtained might

vary for different markets as consumers from different markets have different perceptions of quality. Hence, the results of this research vary within different products and different markets.

2. The performance indicator of a product required for this research can be measured by a quantitative survey research design and might include biases such as sample selection bias, social desirability bias, and yes bias.

6. Summary and conclusions

This study builds upon a literature review focusing on tolerance allocation and its relation with sustainability, circular economy principles, and consumer perception of quality. The intended outcome of this review is to develop a framework that optimizes the tolerance of a product in terms of cost, performance, and sustainability. The Hypothetical Equivalents and Inequivalent Method (HEIM) is employed as the approach for tolerance optimization. Additionally, an optimization technique is proposed to solve the inequality equations derived from the HEIM. This can help future research for solving mathematical inequalities related to manufacturing. Furthermore, this research can be extended by conducting experiments to determine the tolerance for various products, such as mobile phones, accessories, laptops, watches, and other electronic equipment, which are produced in substantial quantities. By leveraging economies of scale for reused products through this framework, the sustainability of these products can be enhanced. The proposed technique helps to avoid redesigning the product while encountering issues at different stages like manufacturing, quality, use, and reuse since all the stages are considered while allocating the tolerances in the initial stage. This also helps to save manufacturing costs by reducing rework/adjustments and maintaining quality. The proposed method may be validated through experimentation.

Conflict of interest

The authors declare that they have no conflicts of interest.

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