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Systems thinking in tolerance and quality-related design decision-making

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Abstract

This paper describes a new approach for using systems thinking in the context of design decisions that affect product quality. Such decisions include dimensional tolerances, material choice, and product geometry, which are shown to have links with product quality and performance, profitability, sustainability consequences, and resulting market and governance changes. These links are presented in a systems model that maps the drivers and consequences of these quality-related decisions, ultimately showing that design decisions influence future design decisions based on the sustainability-related outcomes of the resulting products. The systems model is then used in a design scenario of a mobile phone, where important information about the consequences of the product is gleaned by using the proposed model.

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Keywords: Tolerance analysis; robust design; systems-level design; systems thinking; sustainable design

1. Introduction

Dimensional tolerance allocation is a primary approach for accommodating product variation from manufacturing systems, assembly processes, and other transportation-, environment-, or use-related factors. Setting appropriate tolerance ranges for each geometric dimension has become a way for designers to ensure a sufficiently robust product at minimal cost. However, these decisions affect more than the geometric robustness and manufacturing costs of the product, as they are tied to more complex attributes and processes that encompass the functional and visual quality of the product, consumer demand for the product and future products, complexity of the assembly processes, sustainability consequences, government or corporate policy actions, and ultimately future requirement specifications. These factors reflect the choices and outcomes of previous products and affect the requirements set on future products in the pursuit of building sustainable product lines around a trusted brand image.

This paper presents a systems model for mapping and understanding the drivers and consequences for tolerance-related decisions, going beyond the typical approach that considers only manufacturing costs and losses to the producers and consumers. The system is comprised of more than thirty interrelated elements that show the consequences and influencing agents of tolerances and concurrent late-stage design decisions, culminating in economic, ecological, and social sustainability indicators for the product that eventually feed back into future product requirements through adjustments to market needs and policy changes. The ensuing subsections survey the literature to reveal how components and interactions of this system have previously been explored in various academic or industrial fields, including robust design and variation, design for sustainability, and systems approaches to engineering design and analysis. This is followed by a presentation and description of the systems model, and then an explanation of its use in the case of a mobile phone design problem. The paper concludes with a discussion on the utility and implications of the model.

1.1. Variation effects

Product variation is an unavoidable result of production processes, and factors such as geometric design, manufacturing machinery, assembly precision, and environmental variables contribute to deviations from nominal designs. To account for these deviations, designers

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specify tolerances with each geometric parameter to inform the producers on how precise their processes must be. The literature on the optimal selection of tolerances focuses on variation propagation measurement and analysis [1], producer cost and loss minimization [2], and product quality assurance [3].

While the major financial consequence of tolerance choices is that of manufacturing precision, where it is more expensive to produce more precisely-machined parts, another factor to consider is scrap parts [4]. When some parts are produced with unacceptable dimensions, those parts must be either discarded or reworked, which adds to the bottom line of production costs [5]. Significant numbers of scrapped or reworked parts can also influence the ecological impacts due to increased material and waste requirements and social impacts due to increased human workload.

Another consequence of tolerance decisions is on how product variation impacts the value to the customer, which some researchers refer to as quality loss [6]. Some of these effects include imperfect functionality or appearance of the product, failure and safety hazards during use, increased maintenance needs, and shortened product lifespans. Particularly for new products that have not been on the market long enough for user reviews to be reliable, with the exception of visual cues, these quality attributes are not known to potential customers prior to making purchasing decisions. Therefore, the initial customer experience, which is largely defined by the appearance, has been the subject of recent research. Some refer to this attribute as "perceived quality" or "craftsmanship", and several research studies have shown the importance of such product characteristics and their links to variation requirements [7,8].

1.2. Sustainability drivers

One objective that is commonly associated with the goals of society is sustainability. This refers to the idea that today's actions should support current goals while also ensuring that future goals are not hampered, and it generally encompasses three areas: economics, ecology, and society [9]. Sustainability researchers have developed genres of tools that support analysis of each of the sustainability areas for a product or system. Life Cycle Costing (LCC) measures economic costs, Life Cycle Analysis (LCA) quantifies ecological effects, and Social Life Cycle Analysis (SLCA) compiles social impacts. However, most business models revolve around immediate economic impacts, and life cycle thinking is generally not a primary concern or requirement for success [10].

One way that non-economic issues become relevant to business decision-makers is through government intervention. When governments perceive certain actions as negatively impacting the public, policymakers may enact legislation designed to reduce those actions or their impacts. This has been done on different levels of government from local councils to international collaborations by levying taxes, instituting tradable permit systems, imposing mandates, and offering subsidies [11]. Such actions have met varying degrees of success in the pursuit of reducing negative impacts such as overconsumption of resources, endangerment of wildlife, chemical releases, ozone layer depletion, low wages, and dangerous working conditions. Common regulatory actions for reducing environmental emissions are to restrict emissions, impose taxes on those emissions, or issue tradable permits in a "cap-and-trade" approach [12].

A second major way that ecological and social factors enter the business decisions is when customers value such attributes in their purchasing decisions. When the value customers have for a greener or more socially equitable product is higher than the additional cost of making that product in such a way, a true business case arises for non-purely-economic sustainability. Recent studies have revealed consumer preferences for environmentally- and socially-friendly products [13,14], which shows that designing more ecologically and socially sustainable products can increase demand and revenues for improved economic profitability. One way to increase the extent of these effects is to increase transparency and provide standardized product labels that allow customers to make a relatively objective comparison of product offerings' impacts [15]. This type of solution requires the support of governments or NGOs to ensure impartial evaluations and enforce truthful reporting.

1.3. Systems approaches

"Systems" in engineering can be defined in a number of different ways. A system can refer to a complex product with many parts, such as an automobile. This definition is common in the "systems engineering" field, which focuses on handling the complexity inherent in combining a number of parts and functions into a single product. This accounts for all stages of the design process from setting requirements to producing and distributing final products [16]. In contrast, "systems thinking" is a broader approach that accounts for factors that are not a part of the product itself. This can include the environment that the product is used within, the users, competing and complimentary products, and the economy as a whole. Typical engineering approaches, which use analytical thinking, are primarily concerned with components, whereas systems thinking approaches prioritize a more holistic view [17].

"System dynamics" is a particular type of systems thinking that accounts for input-output relationships and changes over time. All elements in a system dynamics model must be either a "stock" representing some quantity or a "flow" representing a rate of change between two stocks [18]. These elements are mapped using a flow diagram with curved arrows for connections, and often the arrows are specified as positively-correlated with a plus sign or inversely-correlated with a minus sign. When mathematical models can be formulated or estimated for the flows, system dynamics models are typically simulated over a set time period to understand how stocks change. This type of model has been useful in analyzing policy decisions to understand the broader, system-wide impacts of a potential intervention.

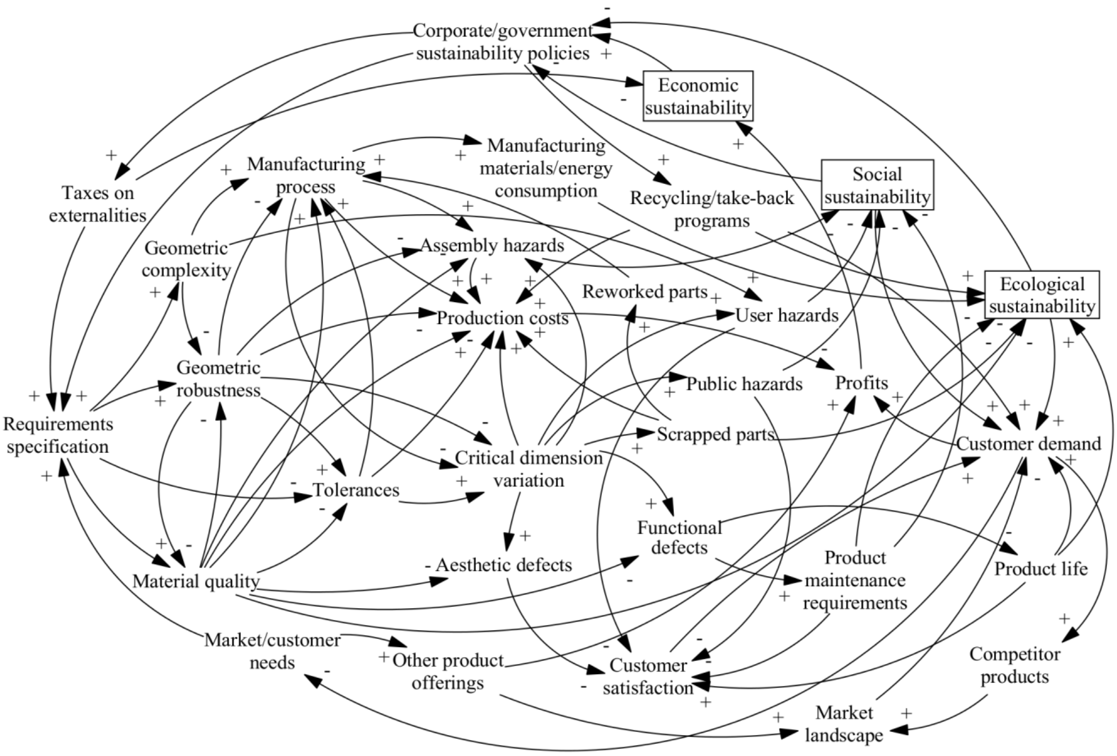

Fig. 1. Systems model of quality-related design decisions and sustainability outcomes

2. Model

This paper uses a system dynamics approach for mapping the societal impacts of tolerance and quality-related design decisions. As such societal impacts have been shown to affect future policies and demand for later-generation products, it is clear that the system mapping should result in a closed loop with feedback and balancing effects. By mapping the process, designers should gain a valuable understanding of the system-level impacts of their decisions.

The model is shown in Fig. 1. Beginning on the left side is the requirements specification, which is a key part of the product development process that heavily influences specific design decisions. These design decisions that relate to quality outcomes are the geometric design, tolerances, and material choices. Geometric design has been divided into two components: robustness and complexity. Robustness refers to how sensitive the product design is to different sources of variation, in particular how the critical dimensions are affected by manufacturing or environmental variation during the production and use phases. A more robust product can function under a wider range of variation. Complexity accounts for the numbers of functions and parts, and while increased complexity can in some cases deliver more value to the customer, it can also cause lower robustness and increased manufacturing costs.

A key element that transfers design decisions into quality-related attributes is the critical dimension variation. A critical dimension is any geometric measurement that can influence the way that the product performs or is otherwise received by the customers or users. Such variation is influenced by the geometric robustness of the design, the manufacturing processes chosen, and the tolerances specified for the individual part dimensions. In turn, it affects the likelihood and severity of functional and aesthetic defects, the amount of scrapped parts discarded during assembly or quality assurance checks and in turn the process of reworking some or all of those scrap parts, and hazards to workers, users, and the public. Many of these quality-related attributes directly or indirectly impact customer satisfaction, which plays a significant role in demand for the current and future products, as well as other products on the market.

The combined effects that these decisions have on production costs and customer demand affect profits to the company, which are vital to the economic sustainability of the company and the industry. Several quality-related factors can also influence the ecological impact of the product, including scrapped parts, material choice, manufacturing processes, and defects that might reduce product life. Some quality-related factors also influence the social sustainability of the product, primarily through hazards to assembly works, users, and the public, and also due to product reliability and maintenance requirements. These outcomes can play a role in customer demand, as long as there is some level of transparency that communicates these impacts to potential customers. They also influence the total impact that the product has on society, as measured here through the three sustainability attributes.

These sustainability outcomes in turn influence future strategic policies and decision-making. From a corporate perspective, this includes setting requirements for new products that may raise or lower the ecological and social impact expectations of new products through targets or implementation of programs such as recycling. From a public policy perspective, governments may choose to tax or otherwise regulate the ecological and social impacts produced by companies, which will in turn cut into the economic bottom line of the producers and influence future requirements. A final way that the next generation requirements are influenced by this process is through the projected future market demand. This is affected by the current demand and all of the process elements affecting it, such as customer satisfaction, product life, and sustainability.

The model was formulated by the authors as a result of a number of case studies that showed the interrelationships among these quality-related decisions and societal goals. The first element considered was the design decision “tolerances”, which eventually led to the inclusion of the other design decisions that interact with the tolerancing process. These decisions were soon mapped to customer demand and the three sustainability outcomes, and they then came around to the new requirements through market needs and corporate and government policies. The process continued to expand as new factors were brainstormed, and it is likely that new elements will continue to be added to the model as additional cases and feedback is considered. At one point, it was decided to account for the increasing or decreasing nature of the relationships, to better fit into the system dynamics framework. This is shown through a plus sign at the tip of the arrow when a response element increases as a result of the input element increasing or through a minus sign when the response element decreases as a result of the input element increasing. Some assumptions were necessary regarding the nature of the relationships, such as the increase in ecological sustainability with increasing material quality. These relationships should be reexamined on a case-by-case basis.

As a design tool, this process mapping can help designers to better understand the impacts of their decisions early on in the design process. It shows how some of their quality-related decisions can influence the important outcomes to the company and to society, and how this might in turn affect their future requirements. While a simple application of the model is to make designers familiar with the diagram in general, it could also be used as a checklist or by adapting the model to a specific product being designed. This is expected to help designers make early adjustments to improve the quality and sustainability of their products.

3. Application to mobile phone design

To demonstrate the utility of the process model, this section examines the example design scenario of a mobile phone case. While this represents a rather late-stage design, the process model shows a way to make inexpensive and rapid assessments of the decisions and trade-offs being made regarding product quality. The mobile phone case is shown in Fig. 2a, and it consists of a front and back part joined by four pins as seen on the inside-back cover in Fig. 2b.

One quality issue that was found with this design is the way the front and back parts fit together. If the tolerances of the locator pins are not tight enough and the pins do not align correctly between the front and back parts, problems can arise in assembly or with finished products that are visually or functionally imperfect. These issues should be a part of the tolerance decision-making, but it is unlikely that those making such decisions are aware of the full scope of the product system. A mapping of this system is shown in Fig. 3, which was adapted from Fig. 1 with the specific example case in mind.

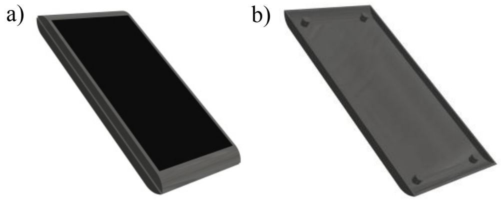

Fig. 2. (a) Assembled mobile phone case, (b) back part of case

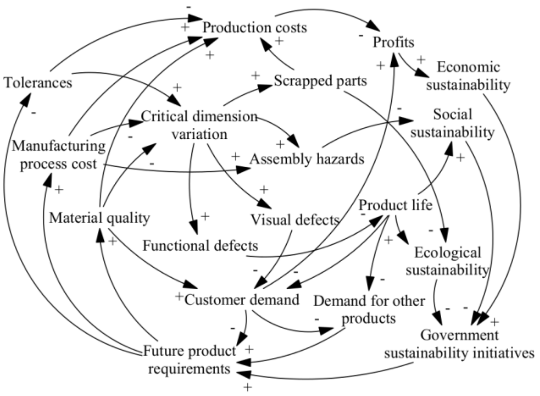

Fig. 3. Process model adapted for the mobile phone case design

This mapping, like that of Fig. 1, begins with design decisions that influence product quality: tolerances, manufacturing process, and material quality. Each of these influences production costs and variation in critical dimensions, in this case referring to the alignment of the pins. When the alignment is too poor to fit together, the result is scrapped parts and an accommodating increase in production costs and ecological impacts. When the alignment is slightly better, the result may be a need for assembly workers to exert additional force and effort to fit the parts together, which could raise the risk of repetitive motion injuries for assembly workers, a social concern. Such assembly hazards are also influenced by the manufacturing processes chosen. Finally, alignment that allows assembly may still result in a flawed product, either visually where the split line between the parts is visibly non-parallel or functionally where the case is more likely to crack due to internal stresses.

A functionally defective product will increase the likelihood of early product failure. This would negatively impact ecological sustainability, as new products would be required, and social sustainability, as customers would be inconvenienced by the device failure. Shortened product life would actually in the short-run increase future customer demand due to the need for replacement devices, a factor that would also be influenced by visual defects and material quality. This in turn combines with the production costs to affect producer profits, the key element of economic sustainability for a company. The three sustainability outcomes subsequently affect a government's sustainability initiatives: Low ecological or social sustainability might induce action, as might excessively high economic profits. These government policies combine with customer demand for the current and competing products to drive future product requirements, which influence future design decisions.

One of the useful aspects of this process model is that it reveals trade-offs in design decisions. An even number of negative signs in a chain indicates a positive correlation between two elements, while an odd number indicates an inverse correlation. For example, when looking at the links between material quality and customer demand, there are three possible paths. The direct path has only a positive arrow sign, indicating that increased material quality should lead to higher customer demand. Another path, which goes through critical dimension variation and visual defects, has two negative signs and therefore also indicates that higher material quality leads to higher demand. However, the longest path, going through critical dimension variation, functional defects, and product life, has three negative signs and shows how higher material quality may decrease demand. This tells the designer that there are conflicting forces that may lead designers to choose higher or lower material quality for improved demand. If the designer has some level of familiarity with the problem, they may be able to estimate which effects are more important, but otherwise it may call for further evaluation before an appropriate decision is reached.

Another interesting result of the model is that it reveals feedback loops, which can be reinforcing or balancing. Reinforcing loops, which have even numbers of negative links, have the effect that a change in one element results in additional change to that element in the same direction. For example, the loop connecting tolerances, critical dimension variation, scrapped parts, ecological sustainability, government initiatives, and future product requirements has four negative links. This means that increasing the tolerance is expected to have effects that will encourage future increases of product tolerances. Likewise, decreasing the tolerance would have effects that encourage future decreases of the tolerance. This can lead to instability, but fortunately there are other loops that can be identified that can curb these effects. These are called balancing loops, and they have odd numbers of negative links, such as in the outermost loop of Fig. 3 connecting tolerances, production costs, profits, economic sustainability, government initiatives, and future requirements. This has the opposite effect, meaning that increasing a tolerance is likely to result in future decreases of that tolerance.

4. Discussion

The systems mapping presented in this paper reveals a valuable way to design for quality during all stages of product development. This is particularly useful in early phase design, when designers have the most freedom and the least sophisticated analytical models of the product, but it can also be used into the later stages of design. While traditional tolerance selection methods account for the financial implications of tighter or wider tolerances, this approach also shows the value in considering societal goals that contribute to ecological and social sustainability.

This paper has demonstrated the value of using systems-level thinking in tolerance through an actionable model and the case study of a mobile phone design. The design decisions surrounding product geometries, materials, tolerances, and manufacturing processes are discussed along with their co-dependencies and implications. The effects of these choices on functional and aesthetic quality lead to different failure rates, maintenance needs, product replacements, and ultimately consumer satisfaction, demand and sales. These outcomes along with production costs determine the economic viability and sustainability of the product. The same decisions' effects on resource consumption, energy use, production waste, and maintenance and replacement needs have implications on the ecological sustainability of the product. Finally, social sustainability costs result from assembly and maintenance requirements as well as potential hazards to workers, users, and the general public.

While many practitioners do not consider ecological and social sustainability to be necessary for successful business decisions, many of the system elements are shown to have intrinsic links with one another, and they all influence future products through market demand, government regulations, strategic business decisions, and other product offerings within the same firm and from competitors. This shows the cyclical and interconnected nature of tolerance and quality-related decisions as well as the importance of considering all elements of the product system during design decision-making.

5. Conclusion

The approach presented in this paper offers a new way for designers to consider the implications of tolerances and other quality-related design decisions on the goals of society. Examining the case study of a mobile phone design has shown how this approach is useful in the context of design for understanding input-output relationships, tradeoffs and feedback loops. Finally, the cyclical nature of the system illustrates how sustainability-related outcomes eventually influence long-term business-related decisions and objectives.

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