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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

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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.