TOLERANCE OPTIMIZATION FOR ECONOMIC AND ECOLOGICAL SUSTAINABILITY USING RD&T

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ABSTRACT

Product developers choose tolerances to go along with every geometric dimension, and they typically do so based on how the tolerances influence variation in so-called “critical” dimensions of the final assembled product. A common decision-making approach is to minimize costs given some acceptable critical dimensional variation, but this strategy often conflicts with ecological sustainability objectives. This paper introduces a new approach to simultaneously considering the ecological and economic consequences of tolerances through a software tool that combines Robust Design and Tolerancing (RD&T) with Environmental Priority Strategies in product development (EPS). This allows designers to simultaneously assess the economic and ecological sustainability outcomes associated with geometry, material, and tolerance choices, and it is demonstrated through design optimization of an automotive part.

INTRODUCTION

Product designers are aware that manufacturing processes produce products with slight deviations from the designed dimensions, and they account for this by specifying dimensional tolerances. Tighter specified tolerances require more precise manufacturing methods and tools, which typically come at higher costs and thus raise an important design trade-off between low-cost manufacturing and high-quality manufactured products. For decades, researchers and practitioners have studied this problem and developed tools and software to aid in variation analysis and design decision-making. These solutions typically seek to minimize manufacturing costs while somehow accounting for quality losses.

Another product development consideration that is becoming increasingly important is ecological sustainability. Consumers want to buy sustainable products, businesses want to sell their products to those consumers, and governments want to encourage businesses and consumers to behave more sustainably. As a result, a number of methods have been developed for assessing the environmental impacts of products and actions, many of which consider the entire life of the product from the extraction of raw minerals to the end-of-life disposal; these are known as Life Cycle Assessment (LCA) tools.

Proponents of ecological sustainability and LCA tools advocate that designers should consider ecological impacts in all stages of product development, from the conceptual design phase through the design for disassembly and disposal. One part of the design process is the embodiment design phase, where tolerances and other decisions such as materials are chosen. This paper describes a tool that integrates an LCA method into tolerance analysis software, facilitating environmental considerations in this stage of design.

MATERIALS AND METHODS

The present work enhances an existing software package for measuring variation propagation, Robust Design & Tolerancing (RD&T), by integrating into it an established environmental impact assessment method, Environmental Priority Strategies in product development (EPS).

Robust Design & Tolerancing (RD&T)

RD&T is a computer-aided tolerancing (CAT) program used to analyze variation in a product based on assembly locating schemes and input dimensional tolerances (Söderberg & Lindkvist, 1999). The software is compatible with commercial computer aided design (CAD) programs, and it can import models and report sensitivity and robustness calculations based on Monte Carlo simulations of the tolerance distributions. Such a tool enables designers to understand a product’s geometric sensitivity and robustness prior to physical prototyping.

Environmental Priority Strategies in product development (EPS)

EPS is an LCA tool that follows the International Organization for Standardization (ISO) 14040 and 14044 standards on environmental impact assessment (Steen 1999). It is aimed to be used in product development and includes weighting by calculating environmental damage costs in Environmental Load Units (ELUs), defined to represent ecological damages in euros. All materials and processes have associated environmental costs, and an EPS assessment is made in a similar way to an economic calculation. This enables the designer to directly respond to an environmentally expensive material by either choosing another or assuring efficient recycling. It also allows trade-offs against other issues expressed in economic terms.

RESULTS

The result of the study is an updated version of RD&T with a built-in environmental impact assessment tool. This section describes the software and functionality, as well as the use of the tool when performing multi-objective design optimization of an automotive part.

Integrated tool: RD&T with EPS

The software integration is based on an interface designed in the existing RD&T program, which communicates with an external database file containing EPS information as process flows and ELU values. This enables an efficient assessment of the total environmental load for the product life cycle, including production, use, and end-of-life phases, using geometric data from the simulation model itself. Prior to analysis, the users should define system boundaries such as a functional unit and the lifecycle phases to account for. For the production phase, materials are assigned to each part, and the manufacturing processes and amounts of production waste are defined. The use phase calculation relies on an estimate of the lifespan of the product as well as the quantities of energy and material inputs that are required for operation. For the final, end-of-life, phase, the user defines disposal or recycling scenarios in different fractions. Once these inputs are set, the software can report the lifecycle environmental load in ELUs alongside the results of the RD&T variation analysis.

Case study: Design optimization of a sustainable automotive part

The software implementation is demonstrated for the design of the d-pillar of a first-generation Volvo XC90, shown in Figure 1. The d-pillar is the part on each side of the vehicle connecting the roof to the lower frame, between the rear-side window and the rear windshield. This particular model is comprised of two stamped sheet metal components that are welded together, and the prescribed tolerances are located at the mating surface of the parts (t_1) and at the support points (t_2). The critical dimensions are the coordinates of the top-left corner of the part, which should be flush with the other roof supports and the side window.

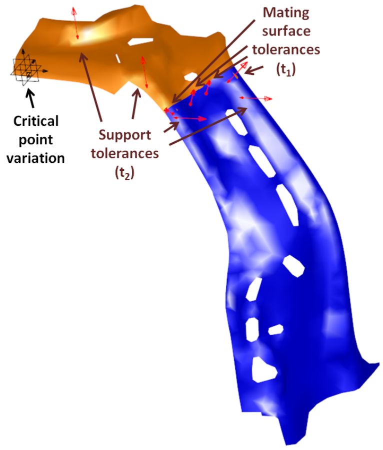

Figure 1. Model of left-side d-pillar

The model was analyzed for variation propagation 3,600 times with different input tolerance values using an exhaustive full-factorial sample, each analysis consisting of a 5,000-point Monte Carlo simulation to determine the distribution of output critical dimension variation. With the allowed variation set to 1 millimeter, the output is interpreted as a percentage of faulty parts, φ, as a function of the inputs, t_1 and t_2. For input values between the sampled points, spline interpolation was used to form φ into a continuous function of the tolerances.

The value of φ influences both economic costs C as well as ecological impacts E, due either to making replacement parts or manual re-work. C is also a function of tolerances t_1 and t_2, as higher precision is associated with higher manufacturing costs. Multi-objective optimization was conducted with four material options following the optimization formulation in Equation (1), where C is in Euros, E is in ELUs, and E_{max} is a varying upper limit on E. Solving with a number of E_{max} values yields a Pareto, or trade-off, curve for each material (Deb 2001).

$$\begin{array}{ll} \min_t & C\,(t_1, t_2, \varphi(t_1, t_2)) \\ \text{subject to} & E(\varphi(t_1, t_2)) \leq E_{max} \end{array} \qquad (1)$$

Figure 2 shows these Pareto sets under two strategies for managing faulty parts, where the length and height of the boxes reflect the optimal values of t_1 and t_2, respectively; i.e., a larger box corresponds to a wider tolerance. The optimal solutions for when the objective is the simple sum of *C* and *E* are highlighted in yellow. Here, the system boundaries are different for the economic and environmental assessment, as the economic cost only covers production while the environmental impact spans the full lifecycle.

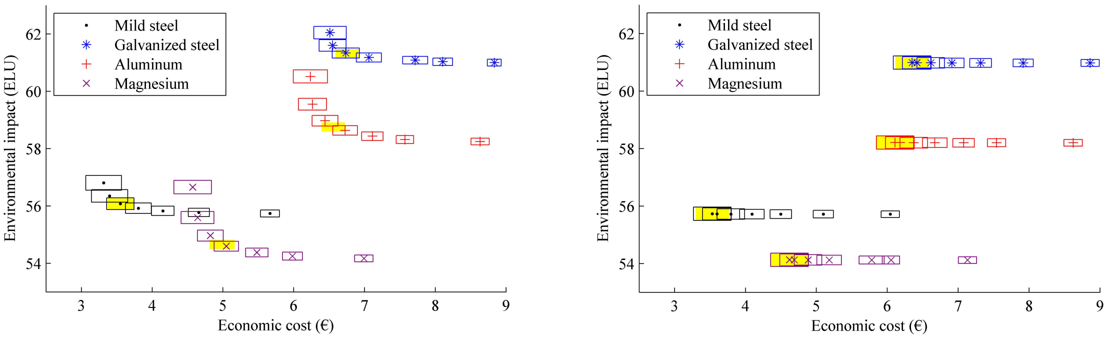

Figure 2. Trade-off curves, *(left)* discarding faulty parts and *(right)* re-working faulty parts

DISCUSSION AND CONCLUSIONS

The example shows simultaneous analysis and design optimization accounting for variation propagation and ecological impacts. The d-pillar scenario in which faulty parts are discarded shows a significant trade-off, where lower ecological impacts can only be achieved at higher economic costs, shown on the left of Figure 2. In this case, mild steel is the lowest-cost material alternative, but if the manufacturer places enough value on environmental impacts, magnesium may be better. This trade-offs within material options are much less evident in the scenario where faulty parts are re-worked, shown on the right of Figure 2, as the ecological impacts of faulty parts are much lower in this case; however, re-working defective parts may not be implemented in companies since it requires labor that is not always available.

This new tool and approach can facilitate sustainability-focused design by making designers more aware of ecological consequences with minimal extra investment in LCA. Since tolerances have been shown to influence aesthetic quality, functionality, and product life, this work provides a new user-friendly way to manage and understand the interrelations between variation and ecological impacts. Such a capability is of benefit to designers and strategists for making knowledgeable decisions toward sustainable product development.

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