Components margins through the product lifecycle

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Abstract

Engineering change is ubiquitous throughout the product lifecycle to meet new requirements or deal with emerging problems in the product.. Components have a certain capacity to buffer the impact of changes before they pass changes on to other components. These buffers are margins on the components which exceed the current requirements. Typically these margins are designed into a product at the beginning and eroded in the course of the design process or during future upgrades. Fundamental design decisions are being taken based on an understanding of the margins available when considering design alternatives. This paper argues that the knowledge and understanding of these margins is the key to managing engineering changes through the product lifecycle. By tracking key product margins a company can assess when an engineering change could lead to costly knock-on effects.

Introduction

Design is an iterative process. Many decisions have to be revisited and changed throughout the design process. This often involves changes to components that are considered finished. However, engineering change is not confined to design processes. It occurs through the entire life cycle of the product. Fricke et al. (2000) estimate that 30% of all work arises from changes of one form or another. Changes arise either from external factors, such as new requirements or advances in technology or are the result of other changes or problems with the state of the design. A change only needs to be made, if the existing design cannot meet the new requirements.

Most components or systems have the ability to absorb some degree of change. This arises from incorporating margins. These are added by different stakeholders for a variety of reasons. However how these margins are introduced and how they work in design have not been addressed in a unified manner in the context of managing change. After a discussion of relevant literature the paper introduces the concept of margins, defines key terms and types, and shows ways to model margins. The paper is set in the context of recent studies on engineering change such as Eckert et al. (2004) and Pasqual & de Weck (2011). It addresses the role of margins at different phases of product development and through product lifecycle.

Background

One way to avoid problems with engineering design changes, is incorporating flexibility and adaptability into a products in the first place. This section provides a brief overview of the literature on design for flexibility and engineering change.

Design for flexibility

Product flexibility can be defined as "the *degree of responsiveness (or adaptability) for any future change in a product design"* (Ross and Hastings, 2005). Qureshi et al. (2006) propose 17 different strategies to achieve flexibility in a product, grouped into four types: a modular approach, a special approach, an interface decoupling approach and an adjustability approach based on the principle of TRIZ (e.g. Altshuller, 1998), Martin & Ishii (2002)). The 17th of Qureshi et al's strategic principles, referred to enabling "the device to respond to minor changes, by controlling the tuning of design parameters". Both Qureshi et al. (2006) and Muir Wood et al. (2010) advocate assessing the flexibility of a product by systematically anticipating and rating the potential changes to 'future proof' the design. Ross and Hastings (2005) advocate assessing the changeability of a system by mapping out the tradespace, i.e. the range of possible parameter values that provides potential solutions. Where the design sits within this tradespace, defines the product margins.

Engineering Change

Changes are ubiquitous through the product lifecycle of a design (see Figure 1 and Eckert et al. 2007 for a more detailed discussion). Almost all complex products are designed by modification from an existing product, so that engineering change starts right at the beginning of design processes and continues.throughout the process as adaptations are made to existing components until parts of the designs are frozen. The process of preparing a product for manufacturing typically also leads to frequent changes. Once a base product is produced, orders are placed for other versions of the product or requests are received for customisation. This may be covered by options from a defined set of configurations, but change to the underlying design might also be required. Products in operation and use are subject to changes through product upgrades.

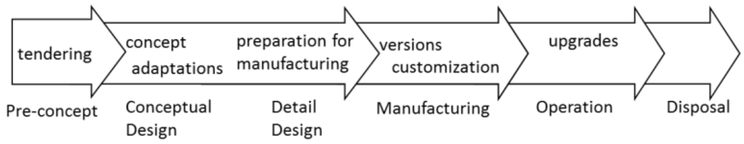

Figure 1: Changes throughout the product life cycles

Engineering change has been looked at from several perspectives. Jarratt et al. (2012) present a review. The processes of handling change and the challenges that arise from change propagation are similar regardless of the cause of the change or the phase of the design project (Eckert et al., 2004). The impact of changes is not limited to the product itself, but can affect the rest of the organisation through shared resources and interlinked processes (Ariyo et al. 2006; Shankar et al. 2012). Change is difficult to predict, because it is inherently not deterministic, and involves people making decision about how to respond to the need for change (Earl et al. 2005). Various tools have been developed to assist predicting the impact of change, through anticipating changes (Cohan et al. 2000), probabilistic links (Clarkson et al., 2004) and network analysis (Pasqual & de Weck, 2011).

The state of components

Whether a change in one component (or system) will propagate to another component, depends both on the exact nature of the change and the current state of the component that is being changed. Each proposed change can be expressed as changes to one or more parameter of the component. Various parameters are associated with each component .These can become critical in the sense that small required changes (or combinations of changes) initiate significant changes in behaviour in components with linked parameters (Figure 2).

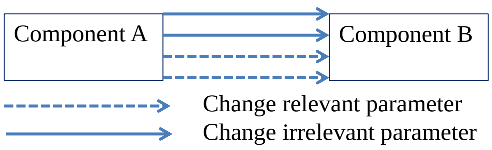

Figure 2: Parameter links between components

Eckert et al (2004) argue that components either act as (i) change *absorbers*, receiving change without passing it on, (ii) change *carriers* passing the same degree of change on as they have received, or (iii) change *multipliers*, which pass more changes on to others parts of the system, which in turn will need to be redesigned.

Change becomes problematic when change absorbers turn into change carriers or change multipliers and critical when changes cause an avalanche creating more and more potential changes. Often the changes can be brought under control given sufficient design resources and time, but companies might need to abandon these projects. From the perspective of an individual change, there might be several knock-on effects. Some can be dealt with directly and others require detailed analysis. This leads to ripple effects. Pasqual & de Weck (2011) studied change requests for a complex product over many years, observing ripple patterns, with the number of change requests increasing towards deadlines.

A generic model of margins

Margins occur in many guises through the lifecycle of a product. This section introduces a base definition before relating margins to other phenomena. For the purpose of this paper we define a margin as: *"the extent to which a parameter value exceeds what it needs to meet its* <u>functional</u> *requirements regardless of the motivation for which the margin was included".*

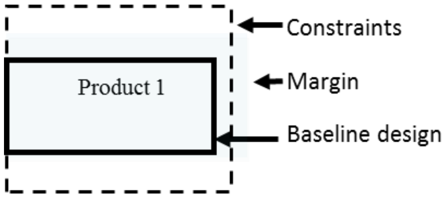

Figure 3: Requirements, margins and constraints.

Figure 3 illustrates the relationship between the base line parameters (heavy black outline) that are required and the actual component parameters (the grey shape with margins in several parameters). In addition the component might be subject to constraints. Note that the margined product exceeds constraints in the figure and is a non-viable design. Viable margined products sit within constraints.

Each component or subsystem of a product can be conceptualized along three dimensions: form (internal structure and configuration of features), function and material. By form we are referring both to external shape and internal (possibly micro) structure. The component carries out a specified function in the product, which is usually described in terms of performance parameters and other target parameters reflecting the component's role in the product. For the third dimension, a component is constructed from a particular material or combination of materials with their own inherent properties. The combination of these three dimensions creates a working component, and the parameters arising from each of the three dimensions are required to describe the component. Parameters in each dimension have their own type of margin, Individual parameters can be traded off against each other across the three categories (Figure 4) and margins allow this tradeoff.. The closer a component gets to its margins the less flexibility it has to absorb a change and make tradeoffs (Figure 5).

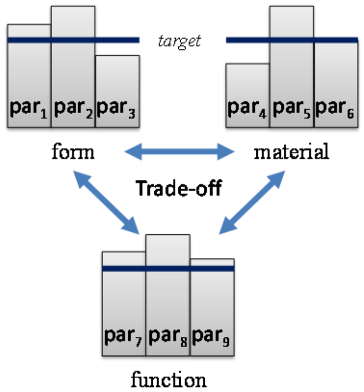

Figure 4: Trade-offs among form, function and material.

Margins do not only reside with individual components, but also apply to subsystems and systems in a way that is not deduced from the margins on specific parameters of individual components. These system margins on system parameters, allow changes in response to changes in other system parameters or in the operating conditions and uses of the product. The margins to absorb different operating conditions and uses does not relate to the margins of individual components in a linear and predictable way. For example a change in the ambient temperature in operation can require direct changes to the product, like the introduction of isolation material, but can also affect the behaviour of individual components, e.g. through heat expansion.

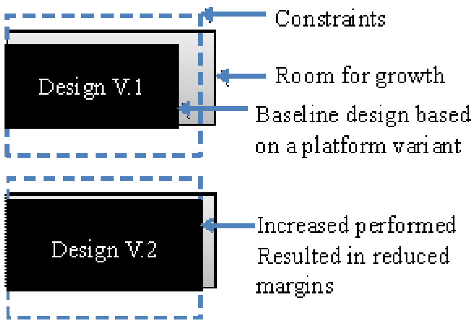

Figure 5: Reduced margins for change

Changes can rarely be addressed in isolation and display complex interactions. For example a component might expand in the heat while at the same time the isolation material takes up some of the expansion space. The challenge lies in identifying these interlinking changes and managing them together in a coordinated way. Giffen et al. (2008) map out the relationship of change requests illustrating both how change requests to specific components are repeatedly rejected and how changes to specific components multiplies repeatedly across the system. A particular challenge arises when the same margins is affected by seemingly unconnected changes carried out in parallel.

Margins across the product lifecycle

Product margins need to be considered even before a specific design process starts. As companies aim to control the amount of innovation required for a new product (Suh et al., 2008) and assess the risk associated with the planned innovations (Suh et al., 2010), they need to plan when major changes to the design are to be carried out and therefore where margins are required. This helps avoid unplanned changes. It requires a detailed understanding of the dependency between components and systems, to estimate when knock-on changes are likely to force significant redesign and thereby unplanned innovation. The is complemented by a deliberate design for flexibility approach (see Ollinger an Stahovich 2001).

Planning product changes over longer periods of time is particularly critical in the context of platform design, as the margins of each component are different with regards to different products in the platform, as illustrated in Figure 6.

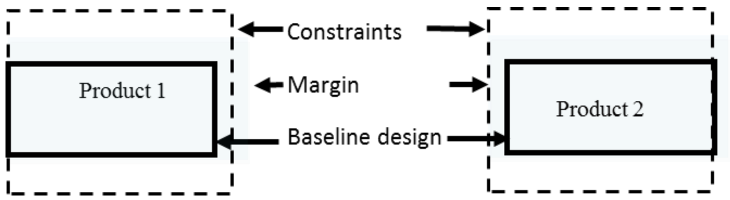

Figure 6: Margins in platform components

Margins are added or identified in the product in different forms through the design process, as illustrated in Figure 7. The evaluation of the starting design stands at the beginning of many ‘new’ design processes. This evaluation can refer to the existing test data as well as use and warranty data, which allows the designers to understand the actual parameter value of a component. This is used to access which components need to be redesigned and thus how much effort is involved in the new design. At the beginning of the design process companies identify the requirements for different parameters and often plan in *room for growth*, i.e. parameter margins which accommodate further changes to the requirements for an emerging design or design changes in future generations or upgrades. These margins are used up as the design process progresses, often without the company having a clear picture of the margins still available on a component. This is particularly an issue when multiple components need to make use of the same margin and the designers may not be aware of their colleagues' decisions.

During the design process, testing begins with the aim of assessing whether a product can meet its requirements, rather than understanding exactly the extent of margins exist in a component. In some cases companies test products to destruction and thereby determine the actual margins on components. Virtual testing, i.e. computer simulation of test conditions on analysis models can also reveal the actual component margins. Test results require a certain degree of post-processing to ascertain the parameter margins. This appears to takes place rarely.

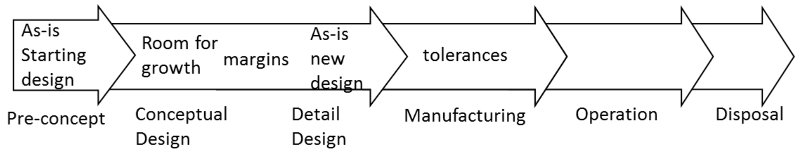

Figure 7: Margins throughout the product life cycles

Margins are often thought of as *tolerances* or associated boundaries designed into a component to accommodate variability in manufacturing and assembly. This is typically the angle on margins picked up in robust design, which is concerned with assuring the quality of a specific product in service (see Chen et al. 1996). To reduce the risk of product failure in service it is necessary to understand the manufacturing variabilities or set them as hard requirements for suppliers. Products also require safety margins to cater for extreme working environments, for example cold weather and the potential misuse of the product by customers. To a certain extent this can be covered by certifying a product for a specified range of conditions and behaviours or by imposing warranty conditions on the product. However companies still want to be sure that their product is robust to potential misuse, because doing otherwise might compromise the integrity of their brand. Design margins are essentially the residue when these tolerances have been accommodated.

Products are designed to operate under a given range of conditions for a target life time, which is specified in the product warranty. In practice products are often used for different purposes than intended or for a much longer period than anticipated. How products behave after the end of their target life also plays an important part in brand reputation. In the past products have often exceeded their target life by many years, because the products were overdesigned with large margins and the excess cost could be passed on to customers. As mathematical analysis tools have been improving, companies now have a handle on these excess margins and can optimise the products for a particular situation. Optimised products are both cheaper and have better performance, but are more susceptible to negative effects of engineering change, as they have lower, or potentially no, margins to absorb change.

To date, consideration of margins does not systematically capture or analyse margins. However, the information to do so exists to some extent in companies. Those responsible for the last changes affecting a particular margin, usually have a good understanding that a margin could become critical, but on the other hand do not have a means to flag this up. To capture margins systematically companies would need to capture the results from testing with regards to margins. If a test fails, companies it is necessary to determine exactly what contributed to the failure, i.e. which margin was exceeded. To gain a more detailed understanding the companies would need to engage in physical (or virtual) destructive testing.

Example

The design of a rear turbine structural frame for an aircraft jet engine clearly displays the problem with design margins (Eckert et al. 2012). The function of the component is partially to ensure mechanical load transfer, structural stability and integrity of the turbine section, whilst contributing to aerodynamic performance (low drag and gas-flow control) of the gas passing through the section. Weight and cost targets are important, so the final design solution typically follows a design optimization effort.

The margins on the metal temperature are critical. Making the turbine frame out of a well known and understood material may be a cost efficient way to produce, but has a narrow upper boundary of allowable metal operating temperature, Since the performance of the new engine is often expected to be higher than that of previous designs, the gas temperature may increase. The margin to ensure structural integrity using the well known material consequently reduces and may vanish entirely.
The design team then faces several design options: (A) use another material, capable of withstanding the new gas temperature, which might be more expensive, and costly to produce and maintain. (B) alter the actual design, e.g. to select a cooled version of the turbine frame, and maintain the "simpler" material.

Comparing (A) and (B) reveal different behaviour from a design margins point of view. Alternative (A) can be made without too much interaction with other parts of the engine system, but still has a definite upper bound in thermal resistance and the material itself may be quite expensive. Alternative (B) impacts the engine system design to use cooling air (expensive), but uses a known and less costly material. From a margins point of view the upper boundary of thermal resistance may be less definite. If the gas temperature turns out to be higher that first expected – the solution may be possible to manage without changing material.

In reality change in conditions happens throughout the development process. Preconditions such as operating design gas temperature are uncertain, and often sub-

ject to change. Alternative (A) may initially seem to be a wise choice, whereas alternative (B) is more adjustable from a design perspective.
This simple – yet realistic – example reveals several aspects of margins.

1. The need to represent margins of principally different design alternatives (material up-grade vs. alternative cooled design solution).
2. The need to manage dependencies between design components (the turbine frame) in a system (the jet engine)
3. The need to strategically analyse and predict consequences of change in loads and pre-requisites.

The third aspect is crucial to make informed design decisions, and requires that the underlying design information actually contain information about margins. Today, the analytical ability to make such design simulation is limited, and often handled qualitatively using FMEA and FMECA type approaches for risk analysis.

Conclusions

Margins play important roles in engineering change processes under different guises, which, although related, are typically considered and modelled separately. These roles include:

- helping to predict the knock-on effects of changes;
- assessing uncertainty concerning the properties and behaviour of the product and conditions of its use;
- evaluating flexibility regarding the use, manufacture and assembly of the product;
- tolerancing for manufacturing and assembly and the robustness implications.
- Building in adaptability for future products

To manage margins efficiently, the ability to model margins and eventually assess consequences of changes, first requires a sound understanding and adequate representation of underlying margins. Further, the relations and couplings between design components and system with regards to margins needs to be identifiable.

Further research is currently being conducted in several case studies on product planning and platform development to (a) see how industry is handling margins in practice and (b) explore the role of margin models in change predication. The goal of this research is describe margins in a suitable language and model margins in a way that can be linked to existing product representations. The objective is to use margins directly in change prediction.

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