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PRODUCT PROPERTY MARGINS: AN UNDERLYING CRITICAL PROBLEM OF ENGINEERING DESIGN

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ABSTRACT

Engineering change occurs throughout the entire product life cycle. Change propagation can lead to unexpected effort and the objective of this paper is to help manage these changes. Propagation depends on the margins for change allowed in individual parameters. The paper examines these parameter margins for components in complex aerospace products. The main objective is to understand how margins are managed in a design process both within a single product development but across product generations within and outside platforms. The results indicate that parameter margins appear in different forms and are only understood by practitioners to a limited extent. This paper shows the critical importance of parameter margins in understanding, managing and predicting changes, both for engineering and for long term product planning, where sequences of changes are considered over generations of the product and associated product platforms. A main conclusion is to propose that design methods use a 'classification' of margin/change types when defining design concepts. Interfaces and associated dependencies are then classified with respect to change sensitivity in order to enable better predictability of effects when changes are made. This offers one route to embodying the 'good judgment' of experienced designers into design methods. This approach represents a design technique tailored to synthesis rather than analysis.

KEYWORDS

Engineering change, change prediction, product planning, margins, tolerances

1. INTRODUCTION

The goal of many design optimization activities is for design companies to meet their requirements with respect to several sets of requirements, such as performance, quality, or reliability, for example, but not to exceed them. They can make components at lower cost not only directly through reducing material or manufacturing costs but also indirectly though affecting other parameters, such as weight which can make products cheaper to build, run or maintain. Actual parameter values for a component in a design may differ from those values which would ideally or theoretically enable that component to provide its required function within the whole design. These boundary values for component parameters are not unproblematic because of necessary variations through manufacturing tolerances and service wear as well as uncertainties with respect to risks of failure. However, in some appropriate sense, each component parameter will lie within its boundary.

With connected components and associated dependent functions, the boundary may encompass several parameters simultaneously in a surface or general 'multidimensional' boundary. In an applied context, this situation is typically found in many design problems, where there may exist principally different approaches to solutions. An increased physical (or temperature) load condition within a jet engine can be solved either by selecting a material with better properties (an integrated solution) or by a de-coupled design solution where the tougher load conditions can be met by topological re-design, alternative configurations or cooling techniques. On the one hand, sensitivity to tolerances and variations may cause only local effects, whereas on the other hand it may trigger an (often unforeseen) chain of effects.

How well a development organization is able to understand the margins of their design concepts is crucial in successfully dealing with changes and disruptions that occurs throughout the development process. Inability to manage margins is perhaps one of the most critical problems causing late and costly re-designs and inconvenient disturbances for the company and subsequently its customers.

The difference between the boundary values that a design parameter needs to have in order for the associated component and product to meet its requirements and the value it actually has is referred to as the margin on the parameter on that component. The goal of this research is to analyze the role that these parameter margins play in designing products that are changed throughout the design process or over several generations of incremental design. If a margin is exceeded, that is a boundary is violated, the design will have to be changed. If the requirement for future changes can be anticipated the margins can be planned in, so that change can be absorbed and would not propagate in a significant way. Understanding the state of the margins on component parameters, together with managing the ways that requirements are met as a product is developed, are important aspects of product planning.

This paper will develop a detailed description of these parameter margins including an analysis of why they may be difficult to specify. Alongside parameter margins a component will present associated behaviour margins which indicate the extent to which a component exceeds required behaviour. While there are good reasons to keep parameter margins to a minimum, finite and distinct margins can be extremely useful in all phases of the product lifecycle especially to cope with uncertainties in conditions of use or in parameter values (arising from manufacture or wear, for example). This paper investigates the roles of margins in different design situations throughout the entire design. It argues that understanding, documenting and managing the network of interrelated parameter margins can play a significant part in strategic product planning at the beginning of a design process , as well as in engineering change throughout the product life cycle.

One of the reasons why margins are included in a product is robust design which aims to improve the quality of a particular product by minimizing the effects on performance which arise through both variation in external noise factors as well as control factors (ie design variables) of the product (e.g. [6]). However, this paper looks at margins from the perspective of engineering change and attempts to control change propagation (see section 2.3), which is at the heart of assuring flexible products that can meet new requirements (see section 2.2). The paper proposes to think of changes explicitly in terms of the key margins that are included by a company during product development to mitigate propagation of changes in future generations of the product. The long term view is to improve change prediction tools.

2. BACKGROUND

In incremental products, planning is about the changes that are required to reach new design specifications. Product planning is often very closely linked with the design of a product platform and the flexibility that is designed directly into the platform. Flexibility has also been addressed from the view point of individual designs to make sure that a new product will be flexible. This research focuses on engineering design and addresses how changes can be carried out to a given design. In this paper we argue that margins are a common theme underlying research on engineering design change

2.1. Product planning

Very few companies are purely responsive to customers who approach them. Instead they plan their product offering over the medium and long term, due to the lead time and effort required to develop and mature the necessary technologies. Understanding when they will offer which functions or features to the market allows companies to develop their product offering incrementally. This reduces the risk to both the company in terms of time and cost of the product development process, and the

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user who has a product which in many respects has been tried and tested. Product planning requires an understanding of trends in the market [19], as well as an understanding of the current product and future products as they evolve. Companies aim to control the amount of innovation required for a new product [24] and assess the risk associated with the planned innovations [25]. The same authors are using a DSM-based approach to model the differences between generations of product to assess the risk and therefore the potential benefit of technology infusion [26]. This is a way to mitigate against "emergency innovation", where companies are forced to come up with innovative solutions late in the design process [11].

Most companies cannot plan their products in isolation, but have to consider implications across an entire product platform. As Simpson argues in his review paper, [27], optimising a platform is the key to profit and viability of an entire product offering. Understanding engineering change lies at the core of product planning.

2.2. Design for flexibility

Product planning has to be seen in the context of the flexibility that is designed into a product, providing a product with the ability to withstand future changes. Product flexibility can be defined as "the *degree of responsiveness (or adaptability) for any future change in a product design"* [29]. Qureshi et al. [21] propose 17 different strategies to achieve flexibility in a product grouped into a modular approach, a special approach, an interface decoupling approach and an adjustability approach based on principle of TRIZ [1] and work by Martin and Ishii [18]. One of their strategic principles, the 17th, referred to enabling "the devise to respond to minor changes, by controlling the tuning of design parameters". Both [21] and [18] are advocate assessing the flexibility of a product by systematically anticipating and rating the potential future changes to 'future proof' the design. However, this is to some extent problematic owing to the uncertain nature of engineering change. Ross and Hastings [30] advocate assessing the changeability of a system by mapping out the tradespace, i.e. the range of possible parameter values that provides potential solutions.

2.3. Engineering change

Change is a fundamental part of all design processes throughout a product's life cycle. Eckert et al. point out in [9] that processes of handling change and the challenges that arise from change propagation are very similar regardless of the cause of the change or phase of the design project. New products are often designed by modification from existing ones. Designs are changed throughout the design process as new requirements come from the customer or the business and problems and inconsistencies with the emerging design appear. As suppliers are selected and manufacturing processes become clear further modifications are often required. After a core product has been released, different variants might have to be generated. Complex products, such as aircraft are also upgraded to incorporate new technologies (see [10]).

Drawing on interviews with engineers and managers from 13 companies in 7 industries, Fricke et al [13] estimate that 30% of all work in these companies arose from changes of one form or another. According to a survey of 50 German manufacturing companies carried out by the Technical University of Munich [7], 56% of all changes happen after the initial design phase and of these, 39% were considered avoidable. The implications of change go beyond the product itself. A study by the Aberdeen Group [3] showed changes that cause "scrap, wasted inventory, and disruption to supply and manufacturing", but only 11% of all companies were able to assess the impact of a change on a product properly and were able to "provide a precise list of items affected by a change", while only 12% were able to assess the consequences of changes on the lifecycle of the product.

Change is not only critical, but also difficult to manage. It is hard to predict where and when change will be required, as it is often driven by the emerging needs and problems of customers; or by problems in procurement. Once a change is initiated it has a tendency to propagate through the product. Empirical studies ([28], [9], [23]) have highlighted how changes can lead to unexpected knock-on effects in other parts of the product. If the changes snowball or avalanche this can pose a serious risk to process plans and budgets, making it difficult to plan the resources required to deal with the change. If the resources are not available to handle the change the need for change must be resolved in a different way. For example a change that was intended to be carried out internally, might be passed on to a supplier, or the resources pulled from other design tasks. Therefore the effect of changes can spread across organisations [2].

Change is difficult to predict, because it is inherently not deterministic. Eger et al. [12] point out, that designers need to make explicit decisions about how to implement a change, but many change prediction issues arise from limited understanding of connectivity in products [14] and the state of individual components (2.4 below). Various tools have been developed to predict the impact of change, through linking parameters [20] anticipating changes [5], and probabilistic links, ([4], [15]). Fricke et al. propose in [13] five generic strategies to reduce the adverse effect of change on design processes: *Prevention* of errors or changes which lead to follow on change; *Front-loading* to identify changes as early as possible (see also [16] or [28]), *Effectiveness* of changed based on cost/benefit analysis for each proposed change, as not all changes need to be implemented; *Efficiency* in terms of time and cost for those changes that are carried out; and *Learning and reviewing* from past changes.

2.4. The state of components

Whether a change will propagate to another component or system, depends both on the exact nature of the change and the current state of the component or system that is being changed. Each proposed change can be expressed as changes to one or more parameter of the component or system. Each component is associated with various parameters, which might become critical in the sense that small required changes (or combinations of changes) initiate significant changes in behaviour in components with linked parameters (Figure 1).

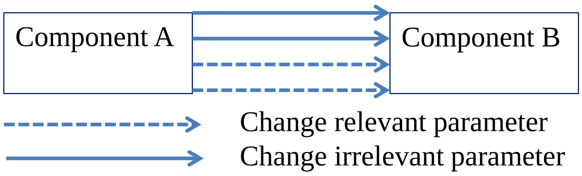

Figure 1 Parameter links between components

Eckert et al [9] argue that components either act as (i) change *absorbers*, receiving change without passing it on, (ii) as change *carriers* passing the same degree of change on as they have received, or (iii) as change *multipliers*, which pass more changes on to others parts of the system, which will in turn need to be redesigned.

Change becomes problematic when change absorbers turn into change carriers or change multipliers and critical when changes 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 that can be dealt with directly and others that require detailed analysis. This leads to ripple effects with the volume of change decreasing over time. Pasqual & de Weck [21] studied change requests for a complex product over many years, observing ripple patterns, with the number of change requests increasing towards deadlines.

2.5. Freeze

One way of protecting an organization against the adverse effect of change propagation through exceeding margins is to freeze the components or the critical parameters early in the design process allowing no further change to them [12]. However, the freeze will need to encompass a set of dependent components otherwise changes in related components may cause significant changes to what a frozen component is required to do and its behaviour margins could be exceeded. For a ‘fully frozen’ component the design task is to ensure that variations in other components are made in such a way as not to exceed margins on the frozen component. Knowledge of margins on frozen components becomes critical.

3. METHODOLOGY

3.1. Empirical studies

This research is based on several large scale empirical studies carried out by the first author on engineering change [9], [14] as well as a series of interviews carried out with a leading truck

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manufacturer on product planning. After several discussions with the head of the product planning team, six semi-structured interviews ranging between one and two hours were carried out by the first author and her students. The interviews included three members of the product planning team, who were working on a ten to fifteen year time horizon, an engineer engaged in the research on the use of alternatives fuels and engines and a trend analyst who focused on, long term trends in transport. One interviewee represented construction equipment and spoke about planning several generations ahead. This was followed up with a visit to the construction equipment team to discuss how changes to system architecture emerge. These interviews were recorded and partially transcribed to supplement detailed notes from the interviews.

3.2. Margins in previous case studies

In the first set of empirical studies, carried out on helicopter design [9], the issue of margins was highly prominent in the discourse of the participants, and the importance of margins in upgrading and customizing these complex engineering designs was clearly revealed. However, during a second, consecutive, empirical study on diesel engine design [14], the issue of margins was rarely mentioned, even though several interviewees were asked about it. When the lead participants were challenged on these issues in the context of a study on freeze [12] the enormous importance of their tacit understanding of margins was revealed. When these interviews were carried out in 2005 the conceptual design of new generation engines was developed by a small team of led by an engineer with over 30 years of experience, who was able to visualize the entire engine and trade off parameters against each other. He was well aware of how close key components were to their limit. These components were either redesigned or frozen very early. In this way parameter values were deeply embedded in the sequence of subsequent decisions. In the meantime this knowledge has been formalized in mathematical models, which allow the company to carry out a requirement cascade. The conceptual design engineer has taken on the role of a system architect and inputs his knowledge about margins as constraints into the requirement cascade.

3.3. Example: margins in incremental jet engine design

To illustrate these issues a simplified jet engine design problem is used derived from the third author's professional practice. His company acts as a second tier supplier to the aerospace industry of structural components for jet engines. Their components are often subject to changes during the development processes due to changes to the basic design of the engine. During the course of a development project it is common that the loads and dimensioning conditions for the engine component change. The example shows how an increase in mechanical and thermal loads at a engine system level requires a change in the design solution of the particular engine component. The profile of margins for the alternative design solutions are used to analyse the impact of the change.

4. SAFETY MARGINS FOR PRODUCTS

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. 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.

As a product is used it often becomes clear whether particular safety margins are necessary. A systematic analysis of this is often carried out as part of an FMEA at the beginning of the design of a new product. This allows a company to identify critical margins that could cause failure in service, but also to reclaim margins for the design of the next product generation.

5. DESIGN MARGINS

The concept of a margin occurs in several contexts in design processes and is referred to by a variety of names. It is addressed from a design viewpoint through planning in margins that could be taken away in future design decisions. From a manufacturing and performance viewpoint it is addressed through margins adopted for a particular product. For the purpose of this paper we define margin as:

"the value a parameter has above and beyond the what it needs to meet its functional requirements regardless of the motivation for which it was included".

The functional requirements imposed on a parameter arise from a variety of sources: the usual design requirements for the specific product and requirements arising from the manufacturing and assembly process. An overall margin is the value that exceeds all the requirements, however the margins can be greater for particular requirements. For example a stiffening element in an engine needs a certain strength to carry a required load, but might be stronger, because it carries out an additional structural function. A simple, yet practical situation, is where the eigenfrequences of the element are designed so that they are not aligned with the rotor frequencies to avoid resonance. Dimensions need to be adjusted not only for strength, but also to take account of its interactions with other parts of the engine.

In addition to these requirements companies might 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.

In the design of a product platform the different products place different requirements on the platform element. A component has different margins with regards to the different products it is placed into. **Error! Reference source not found.** illustrates this in an abstract form. The component that is offered (the lighter box) has room to accommodate future changes already planned in. Market and brand set constraints which the current design meets. The lower box shows the same component pushed much closer to the edge of its margins. This component now has little redundancy, and its capacity to absorb more change is limited.

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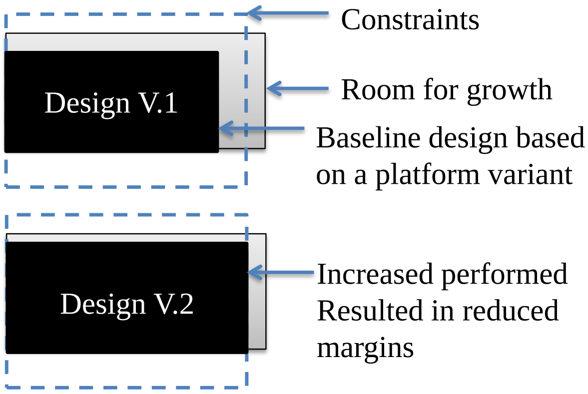

Figure 2 Margins, constraints and room for growth

As the changes are introduced after the development has been initiated, a common situation is that the actions necessarily induce changes that force the design solution to be optimized or modified compared to the initial baseline design. Margins are reduced, and sensitivity to changes increases.

A second complicating factor is that as a design progressively matures the dependencies at the boundaries increase in either complexity or sensitivity, and the likelihood of induced changes impacting other parts of the design increases. In other words, the changes tend to become change carriers or change multipliers whereas at earlier stages they acted as, and were treated as absorbers. This is reflected in practice where it is well known that late changes carry significantly increased cost.

Further, it is possible to make broad timescale distinctions about types of margin and the scenarios in which they are introduced. Some margins may be assigned to components specified early in product development in order to accommodate possible changes or uncertainties of other components later in design. In a helicopter design case [9] the conceptual design engineers planned a margin into key components, sometimes up to a third of the parameter value. These margins were eroded in the course of the design process as requirements arising from dependencies of components and systems become apparent. A simple example is clearances between two components, to provide insulation for

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heat or vibration, for example. These clearances are marked on plans and often used to run cables through the product, which are not necessarily planned at the same time as the geometric layout of the components. While the space can accommodate a certain number or size of cable, at some point the core functionality of the intercomponent spacing may be compromised if running cables is used beyond capacity. As many design decisions can impact a single margin keeping track of how design decisions affect margins proves extremely difficult. The last designer who happened to be the one to push a parameter beyond its margin was likely to be blamed for any problems. In the helicopter case the margins were also intended to accommodate future customization of the helicopters for different customer needs. This shows the link between product planning and product design. Before the conceptual design, the designers required some awareness of future changes. This situation is the target of design for flexibility or design for changeability approaches. Managing margins is one way to assure flexibility.

Exceeding margins lies at the heart of turning change absorbers into change multipliers. Many designers don't find it very difficult to think about the effect that special changes have on each other. If a clearance is used up then a component needs to be moved or resized, which in turn can push it up against another. It is challenging to think through the effects of different types of parameters have on each other. For example as a component becomes hotter, the insulation between it and its neighbour might no longer be sufficient and the neighbouring component becomes hotter, expands so that it touches one of its neighbours, perhaps causing vibration. For these chains of events to occur multiple dimensional and temperature margins must be exceeded. To predict this risk, designers would need to know exactly where the margins lie with respect to the various components.

In a requirement cascade it is possible to set margins as constraints in mathematical models for key performance parameters. However, this requires being aware which margins are critical. Requirement cascades deal with critical margins on key components, but are unlikely to reach those parameters which are only addressed during detail design. Further, requirements cascades cannot handle the indirect effects on components

During the design process, components with critical margins can be frozen to assure no further change is possible. In the companies studied, components were also frozen for other reasons, namely long lead time manufacturing and the structure of internal decision making processes. It was difficult for other engineers to see that components were frozen because of critical margins, so that the pressure to change them remained.

The impact of changes on individual components goes beyond implications on the immediate product behaviour to the performance through life. For example increasing the load on a component might decrease its certifiable life. Change also affects manufacturing and procurement processes, which in turn have their own margins, both in terms of the tolerance that can be achieved and the degree of change possible without changing the process fundamentally. Design margins need to be addressed in conjunction with the manufacturing margins to guarantee a safe product. In selecting among design alternatives designers have to trade all these issues across alternatives.

6. MARGINS IN PRODUCT PLANNING

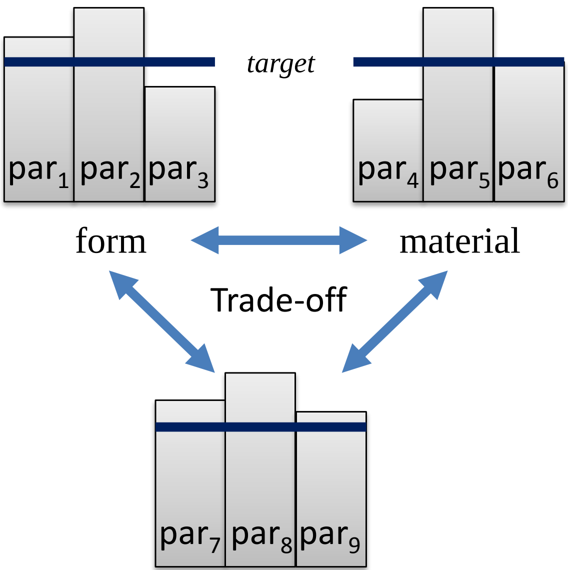
Product planning is focused on the changes that will be required over generations of the product. In complex products risk can be reduced by minimizing the amount of change between generations of products, with very different designs achieved through a sequence of incremental steps. Knowing the margins on a component means that the designers can plan how much change it can absorb without major design change. To have a picture of the margins designers also need to predict the knock-on effect of the changes that they are proposing. For example if the weight of an engine exceeds a limit then mounting brackets need to be redesigned. If the designers know that a component needs to be redesigned as a knock-on effect of change they can also plan other changes for this component. Designers can bundle changes and as major redesign of a component constitutes a planning opportunity, knowing margins can inform the entire product planning process.

Knowing when components are close margin is one of the key factors in planning a product platform, because it provides the basis for understanding the longevity of a components and thus the volume they can be produced. Components with significant margins can be deployed in different products with minimal changes. The closer a component is to its specification and requirements the less flexible it is likely to be. However there is a limit to the amount of redundancy a product can have without compromising its functionality. Redundancy can carry a significant cost. For example in helicopter design, the designers reckoned on a cost of £10 000 for each additional kilo of weight. The added weight requires also more fuel, thus increasing running and environmental costs. Trading these factors off against the cost and ease of future design processes is a key problem for process planners. Many products are highly optimised for their specific requirements, which makes them susceptible to the effects of change. As margins are exceeded, the proportion of new design required is higher with associated higher risk to designer, manufacturer and the customer.

Over generations of a product the status of component margins become less clear as the link to the original requirements it lost. Testing is typically carried out to assure that a product meets its own requirements, rather than to understand how much more each component could achieve. However, as most new products are analyzed through simulation, explicit analysis of margins on individual components is possible as is modelling the dependencies among margins.

7. A GENERIC MODEL OF MARGINS

Each components or subsystem of a product can be conceptualized along three dimensions: form or structure, function and material. In form we are referring both to external shape and internal (micro) structure. For example a turbine guide vane has an external shape and might be designed with an internal structure with cooling channels. The form and the structure can be described with geometric parameters, which are captured in the CAD description of the component. The component carries out a certain 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.



These are usually set by requirements and validated in tests. In a turbine guide vane maximum temperature or cooling flow rates are examples of performance parameters. For the third dimension, a component is constructed from a particular material or combination of materials with their own inherent properties. For example at material of the guide vane has a certain melting point.

Only the combination of the three dimensions creates a working component, and the parameters required to describe the component arise from each of the three dimensions. Parameters in each of these dimensions have theirs its own types of margins, Individual parameters can be traded off each other across the three categories. For example if a turbine guide vane needs to operate over higher temperatures, which is a functional requirement, designers can change form/structure for example by introducing cooling ducts or they can look for a different material which can operate at higher temperatures. In deciding between these options, the designers trade off margins in these three dimensions, see Figure 3.

However, the organizational structure of many companies tends to places the expertise concerning

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these three dimensions of margins in different departments, so that experts in each group are not aware of the margins a component has in the other categories. Only those engineers with an integrative role can make those tradeoffs.

8. CASE STUDY: CHANGES AFFECTING MARGINS IN DESIGN OF A STRUCTURAL JET ENGINE COMPONENT

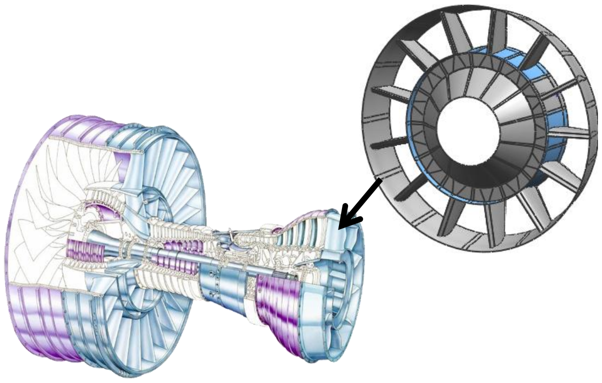

Figure 4 A structural jet engine components

A jet engine is technically an integrated system, optimized to provide efficient power to the aircraft. Since weight is costly in aerospace applications, there is a continuous push to find an optimal balance of all constituent parts of the system. From a systems perspective, this implies that there are many sensitive dependencies within the engine.

The structural engine components are critical within the architecture of a jet engine. They have to withstand structural, dynamic and thermal loads, while meeting objectives of cost, producability and maintainability. Two different situations are studied – the Product planning situation and the Product Design situation. Both situations rely on good understanding of margins and their behavior when subject to changes.

From a product planning view, the EIS (Entry Into Service) point of time is decisive since it is when the product has to be completely defined, certified and in production. In general, the EIS date represents the time when market needs and expectations need to be met by the product and its constituent technologies. It also indirectly sets the date for when the design and development efforts are completed.

In Figure 4 a typical structural components, where the rear components (to the right) are exposed to high temperature combustor exhaust gases.

From a planning point of view, it is critical to understand the dimensioning situations for the component to assess what technology that has to be used. The difficulty is that such situations depend on the evolving systems design. The consequence is changes in planning prerequisites must be taken into account.

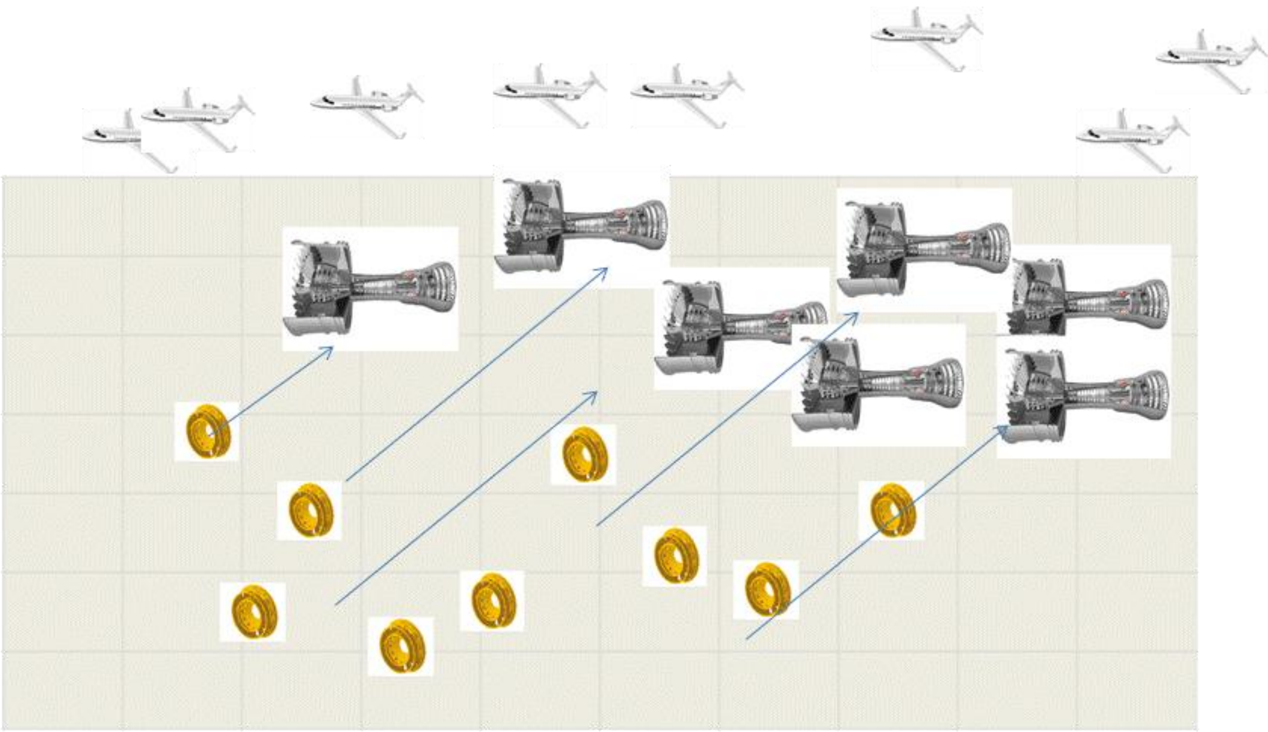

Figure 5 A schematic view of a product plan

Once into the actual component design phase, the details of the dimensioning circumstances must be known, and due to the desire to optimally design the product, materials and design solutions are typically close to their limits. Changes and updates in loads may need (late) re-designs and different design strategies.

8.1. The product view

The component used as an example is the rearmost engine structure in the engine, see figure 4.

The component has a range of functions to provide to the engine system such as controlling the gas flow path, rear attachment point to the aircraft and hosting a number of secondary systems. Two functions are considered in the case situation, namely {*Gas Temperature Resistance*, *Load Transfer to Aircraft*}. Such functional requirements need to be met by relevant product designs, and require technologies such as appropriate materials.

Each function can be realized by different design solution elements. These *design solution elements* rely on capabilities of technology, such as a materials capability in strength, temperature resistance and ease of production.

The design work is to combine these design solution elements into an integrated design that meets the functional requirements. Initially there are several potential ways of realizing the design, whereas the

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degree of completeness increases as the development process progresses. Each of the alternative design approaches has unique characteristics for design and has, consequently, different behavior from a margins point of view.

8.2. The product planning view

There are many different drivers for launching new aircraft, and the market expectations of new aircraft are constantly shifting. Careful, yet responsive, planning is necessary since changes in market information, such as when the aircraft should enter the market and what operational conditions it is intended to serve. Such information has consequences on what technologies and products can be developed and delivered.

The example here, illustrated in Figure 5, visualizes the case of technology necessary for the structural component in the engine, and the consequences that a change within the product plan may have on technology level. The place in plan and nature of change to component that is needed to respond to market requirements are difficult to assess and a margin model of product can provide the room for manoeuvre within margins and when step changes and radical redesign are necessary. The development of jet engines requires extensive engineering efforts- typically involving several design teams both within the OEM organizations and at development partners. Taking into account that the engine is an integrated unit, there are several tight dependencies between the system components. Thus the consequences of changes to the engine system often have impact on the components, and vice versa.

Product planning view

In a product planning view the EIS - Entry Into Service – is one key factor, in determining what technology to select for implementation, that creates problems in performance. A change in EIS date, has a direct impact on what technologies are available to realize the functions to be provided. A change in EIS also has an impact on the expectation on performance from the market. If EIS is pushed to the future, there is time to validate more capable technologies, whereas if EIS is set to an earlier date – necessary technologies may not be available for the development program. An example is the use of novel advanced materials which have to undergo significant validation programs to reach enough maturity to use. We consider such technology to be an example of a *Design Solution Element*, that requires validation (time, cost) in order to be available directly for product development.

The situation illustrated in Figure 6 is that of a change in EIS, where *design solution elements* are available. The parameter (out of several) selected in the illustration is the state of maturity of the needed technology, and the practical case is material used for the gas channel of the component. The state of maturity is judged using the Technology Readiness Scale [17].

The dependency is thus between (a) {EIS, Performance} as governing parameters and (b) the *design solution elements* to meet the market situation. The Material has an operational temperature restraint, e.g. Material A: $T_{operatiional}$=T=760 Degrees whereas Material B: $T_{operational}$= T=820 Degrees.

The parameter that is impacted by the EIS date is the time (t) and effort (c) required for the material to be ready to put into development (at least Technology Readiness Level (TRL) = 6). Material A has T760, TRL 8 at present and can be used in a development project starting now. Material B has T820, but is only mature to a level corresponding to TRL5 at present. The cost and time to raise the TRL level for Material B is known.

If there is a change in EIS – pushing the date earlier - the use of material A may be sufficient to meet the market expectations. If, conversely, the EIS is pushed to a date in the future, material B may be necessary to meet expectations. Pushing the EIS even further may increase the level of expectations even further,

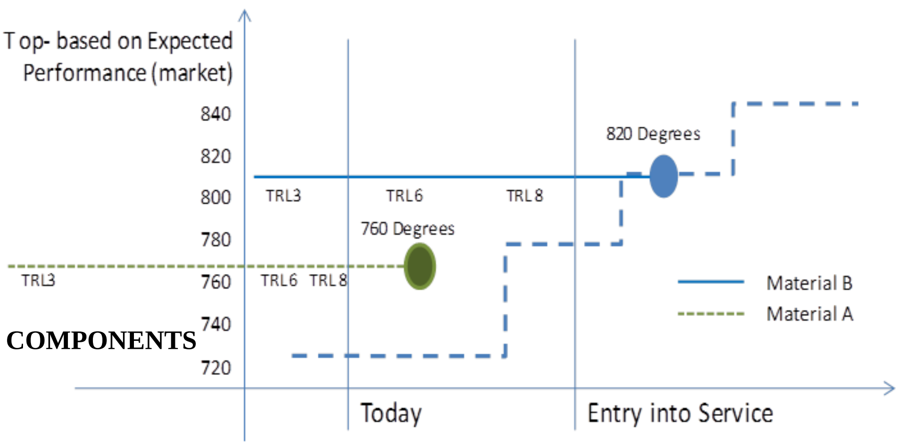

Figure 6 Entry into service verses market expectations and maturity of materials

where the margins of using material B vanishes, and may even become insufficient.

The margin of the Materials Design Solution Element is consequently discrete in nature representing a range of alternatives. The availability of these alternatives for development programs depends on time and cost to reach enough maturity.

The ability to quickly assess, and predict the effects of changes in the market plan is decisive for taking the correct measures for any company, and the illustrative scenario addresses the issue that margins be applicable to capabilities as well as "traditional" product parameters.

Product and Conceptual Design view

The second situation is when the product is in the conceptual design phase, where the design space (identified and "agreed") in the product planning phase has to be met. The work is to define the design solution elements to meet the functions offered. Still

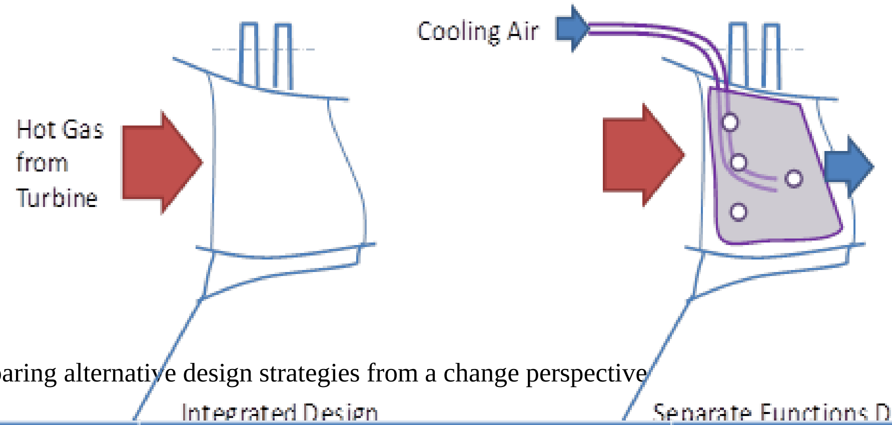

Table 1 Comparing alternative design strategies from a change perspective

	Integrated Design	*Separate Functions Design*
Advantage	*An integrated design may have a simple configuration an allow a single casted variant.*	*Can solve the expectations using Material A.*
Disadvantage	*Require material B to retain some margin.* *Require even more advanced materials if further increases in temperatures are needed.*	*An initially more complex configuration, and impact on a larger portion of the engine system (cooling etc).*
Change perspective	*Changes has to be treated as absorbers. If margins vanishes the consequences may risk the entire system.*	*Initially, design introduces more dependencies to the system, whereas sensitivity to changes may be easier to meet.*

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each design solution element has a limitation (eg Temperature, TRL).

The conceptual design challenge is whether to integrate functions, (that is cast a product in a single piece) or separate functions (example, separate the Gas Temperature Resistance function with Load Transfer to A/C function).

A change in input, e.g. a required increase in gas temperature, gives the designer options. Either the designer can go for the integrated solution, that requires material B since the margin of Material A is unsuitable or go for a design solution with separate functions. The latter may allow using Material A, but introduce a shield or a cooling solution to withstand the heat. This has some impact on the engine system, but will be more scaleable with greater margin and effective design control over the margin

Figure 7 show two principally different approaches to resolving the design situation. Their behavior from a design margins point of view, driven by the temperature load, differs in the way dependencies are entangled with the overall engine system. The situation illustrates how alternative design options may induce different sensitivity to a design strategy, as presented in table 1.

Analyzing and establishing margins for the two alternative conceptual design strategies requires that the descriptions of conceptual design systems are available. The capability to assess the degree of sensitivity to changes by defining margins is a clear advantage. Notably, the definition of margins needs

to apply not only to geometrical properties, such as geometrical tolerances, but to the design properties and their associated dependencies on other properties such as “impact on engine system performance”.

9. IMPLICATIONS FOR RESEARCH / FURTHER WORK

Design margins are one of the key ways of predicting and managing engineering change through the entire design process as well as delivering the right balance between flexibility and the expense of redundancy in the design of product families or product platforms.

To date companies make little effort to track the status of parameter margins through the design process. While there might be some information about the original margins designed into the product, they have little idea of the actual margin a component has. This information could be obtained as a side effect of a testing process. It would be very beneficial, if companies would collect this information systematically and feed it back to product planning or conceptual design teams in a systematic way.

As long as a component is well within its margins designers do not need to be concerned. However, it would be a useful input to their decision making processes to know when a margin is becoming critical. In some cases their colleagues or managers might be aware of this, because the issue has come up in the context of other decisions or previous changes. Flagging up the status of critical parameter in CAD systems or PLM system, which hold the product information might be a useful way to alert designers to potential problems. Alternatively margins could be included as a step in an FMEA analysis, where designers could systematically access the state of key margins and thereby adding them to a risk register.

Building up a picture of the margins would also allow more accurate change prediction. Current methods treat components as units, using aggregate impact and likelihood measures for changes to one component affecting others. Parameters and performance properties that affect multiple components, such as aerodynamics are modeled as links between components rather than as explicit entities. The tools also do not distinguish between the different parameters of a component. The users therefore need to draw their own conclusions whether a particular change is likely to affect a component. By modeling the impact and likelihood that a particular parameter will be affected, a clear picture can be drawn up and designers can be reminded of the nature of different connections that might propagate the change.

10. CONCLUSIONS

The margins of components are critical throughout the life cycle of the product or product family, but are not treated as connected and interdependent characteristics across components and across products. An understanding of the state of components would allow designers to predict the risk of changes more accurately and enable product planner to understand when components need to be changed or upgraded. By understanding this they can use the opportunity to introduce innovation in components that are changed anyway and keep other components constant. Based on current findings, it is recommend to

1) Identify what component design boundaries are critical for the system functions
2) Describe these boundaries and their behavior
3) Identify and describe its relation and dependencies to the system

Such recommendations can be implemented as “design thinking”, and once understood, supported by modeling and simulation tools.

The paper has indicated how design methods use a 'classification' of margin/change types when defining design concepts. Interfaces and associated dependencies are assessed in relation to change sensitivity in order to improve predictability of effects when changes are made. This offers a way to embody the 'good judgement' of experienced designers into design methods. This approach represents a design technique tailored to design synthesis which exploits fully powerful analysis of designs and design spaces.

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