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Safety Margins and Design Margins: A Differentiation between Interconnected Concepts

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Abstract

The life cycle of complex products is subject to multiple uncertainties. Designers include margins into the product to cater for these uncertainties: safety margins, which is typically included in the requirements against the uncertainties of use and design margins against the uncertainties of design, such as changing requirements or engineering change. In practise the terms design margins and safety margins are sometimes used interchangeably. At the end of the design process, a product might include considerable overdesign, which can increase the initial cost as well as the running cost of many complex systems. Late discovery of both overdesign and lack of safety margins are also expensive to deal with in late phases. This paper explores the role of safety margins and design margins in the design process based on two case studies in truck design and jet engine component design. The paper shows that margins are added both to the requirements and the design parameters, so that companies run the risk of duplicating margins throughout the process without different teams being aware of it. This paper argues that a clearer and common description of design margins can reduce undesired iteration in development processes arising from misconceptions and aggregation effects in the development of complex systems.

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1. Introduction

Safety and the avoidance of risk is a major concern in the design of many complex products. Not only the health and wellbeing of human users and operators are major concerns, but also assuring that the product or system can operate reliably for its intended life are decisive in the design. At the same time companies need to deliver their products on time and on budget. One of the main reasons for delays in product delivery lies in engineering changes needed due to updated requirements or knock-on effects of other changes, unless components or systems have margins to absorb them [1]. Engineers safeguard against both safety risks and potential engineering changes by keeping a “margin” or “reserve” on key parameters. Drawing on a case study of truck design and the second author’s professional

experience in aerospace design this paper discusses the relation between safety margins and design margins. While the term “margin” seems intuitive at first sight and many engineers were able to provide definitions of margins, these definitions and accounts differed within a single organization and engineers were not aware of the margins that others had added and the reasons for doing so. This paper looks at the literature on margins where there are also a multitude of concepts referring to margins and shows how they stack up.

The paper argues that safety factors or safety margins are added to requirements to handle known risks, whereas design margins are added to design parameters to deal with uncertainties. However, such distinction is not consistently

applied as in some cases safety factors are put in place to handle unspecific uncertainties and design margins handle clearly known risks. However this is not just a question of terminology, it can also lead to overdesign across the products as margins are added several time which can compromise the performance of the products and increase cost. Different engineers working on the same product using the notation of margins too loosely is a risk itself.

Nomenclature	
R	Requirement: the values parameters must satisfy.
Const	Constraints: values a parameter must fulfil or not exceed, which can be intrinsic or extrinsic to the problem.
Cap	Capability: the values a parameter could reach regardless of specific constraints or requirements
B	Buffer: The portion of parameter values that compensates for uncertainties.
E	Excess: The value over- and above any allowances for uncertainties
D_M	Design margin
N	Need: The value expressed by the customer or business, that can reliably be reached

Both safety margins and design margins cater against risk of some kind. Risk itself is a rich concept which covers multiple related meanings which are reflected in the usage of the term safety margin in different communities [2]. Qualitatively risk can refer both to an unwanted event and to the cause of an unwanted event, for example engine failure is a major risk for truck drivers and low temperature is a risk in operating trucks in northern countries. Quantitatively risk is the term used for different degrees of specificity from risk as a probability (the risk of the driver forgetting to refuel) to a statistical expectation value (the risk of not finding a petrol station in a sparsely populated area after the low tank indicator has come on) to a known and accepted probability (a decision is taken to accept a risk of 0.0x% of not finding a petrol station).

The safety community is more likely to speak of risk, which might or might not be objectively measurable as they are concerned with the likelihood of an adverse event occurring as well as the impact this might have on product or its users. While the likelihood of an adverse event occurring is in practice rarely known, safety engineers often work with models with explicitly stated assumptions. Designers often speak of uncertainties to reflect that neither the nature of the source of uncertainty might be known, but designers still have to be prepared to meet them. Uncertainties can arise from within the sphere of influence of an organization (e.g. change due to test results) or be external to it (e.g. changing legislation or changes in travel behavior of the public) [3] and can both refer to uncertainty in the data and uncertainty in measurement. Many uncertainties are at least in principle known at the beginning of a design process, however some fall in the famous category of the unknown unknowns.

2. Margins in the literature

While design and safety margins are related concepts they have been looked at separately in the literature.

2.1. Safety margins

The concept of safety margins is discussed in a number of community from cancer care to nuclear power plants with little references to each other. Responses to safety risk can be classified in four distinct categories [4]:

- Inherently safe design, which removes the source of the safety risk for example by replace a flammable liquid with a non-flammable liquid;
- Safe fails designs, which minimizes the impact of any failure, e.g. by containing flammable material in a non-flammable container;
- Safety reserves, which involve an element of over-dimensioning;
- Procedural safeguards, which aim at human processes such as training that counteract the safety risk.

Safety reserves are added against specific risks and can be classified into safety factors, which express a ratio between maximum load and expected load and safety margins, which is a value that is added to a parameter [4]. To manage safety effectively it is important to articulate the risk or safety goal precisely so that a suitable safety margin or safety factor can be calculated [5]. However in practice it can be extremely difficult to do and unknown unknowns are often neglected and in consequence lead to accidents or severe budget overruns if they are detected during the development process [6]. They point to a “can-do” culture, which underestimates risks. They identified the following factors as drivers: general design factors (Complexity involving the interfaces between different elements of the system; Scaling beyond the domain of knowledge; fundamentally new technology or fundamentally new application of an existing technology); organizational (Priorities not focused toward safety and reliability. Hierarchical management style, Distributed responsibility without adequate oversight) and programmatic (Pressures to meet schedule and budget constraints). This shows the link between safety factors and design, which we will address further in this paper.

Much of the research on safety margins is concerned with calculating the appropriate level of safety margin given the known and unknown risk that the product is subject to (for example [7]). This is part of a wider attempt to create reliable and at the same time optimal products, where probability distributions are created to understand the distribution of risk and then optimized (e.g. [8]). In some industry sectors such as in construction, safety factors are routinely added to the calculated requirements to deal with uncertainties arising during the building process. For example load are regularly doubled and energy provision can often be 25% above what is required [9]. Safety margins and safety factors play a huge role in the certification and licensing of products. “The ultimate objective is to establish a reasonable margin to account for the difference between known risks and actual risks in attempting to validate compliance with a probabilistic

safety threshold or goal” [6]. The aerospace industry distinguished between performance margins and safety factors on structural components, which are predefined by the regulation authorities and performance margins. For example a fuselage of a civil aircraft needs to be loaded to 150% of the expected maximal wind load and is tested to this value in the physical tests as a part of the certification programme. The performance margins are partially safety margins for the performance of the aircraft in extreme conditions, but also a type of reserve for different future load cases. It is common to plan certification of the aircraft system, in a way that expected upgrades can be covered.

Another effect that drive engineers to introduce margins, is the “proven in flight” reasoning. Solutions that have proven flight worthy in previous products are generally seen as more credible than new, yet unproven, solutions. Although Technology Readiness Levels (TRL’s) are used to assess the confidence in design solutions this may be misleading since “proven” designs will be used in new contexts and therefore cannot be assumed to be completely understood [10]

2.2. Design Margins

The concept of design margins first appeared in the academic literature in the context of ship building, where Gale [11] drew a distinction between design margins, which are allowance for uncertainties during the design process and future growth margins, which are allowances made for future adaptations of the system to new customer needs. Hockberger [12] added assurance margins as an additional category as a “key element in the probability of a system being able to perform to requirements; that is, to attain a specified level of performance under specified conditions”. These cross the boundary between design and safety margins as they explicitly consider different use conditions.

The concept of margins is also considered in the aerospace industry, where the term is commonly used in design discourse [1] in the context of managing engineering change, e.g. keeping a margin on the load capability of key components such as the fuselage to accommodate changes in load being requested by other component teams. Due to (1) the complexity of aircraft systems and (2) the high degree of functional and physical integration, the loads governing the design and sizing of component contain a significant degree of uncertainty long into the design process. Therefore experienced engineers argue for keeping margins early, in excess of what sometimes are called for in specifications and requirements.

Besides engineering change and product flexibility margins are discussed from the view point of negotiation. The term “information bias” is used to refer to the buffer or margin that designers add to their own estimated values in negotiations between design teams in complex systems design, [14] Canbaz et al. [15] use an agent based approach to model design convergence through negotiation between design agents in collaborative complex systems design. A similar idea is also picked up in set based design [16] where design options are represented through ranges of parameters that are narrowed over the course of a product

development process. Dawson et al. [17] talk about the amount by which properties, such as strength, exceed their requirements, which they see as a means to mitigating against misalignment between the product architecture and the organizational structure. They state that “safety factors, sometimes called design factors or reserve factors, are an important set of metrics in structural engineering, including for aerostructures”; and thereby highlight the confusion around the terminology.

Margins also contribute to the adaptability of a product to new requirements in the future. Ross et al. [18] and Qureshi et al. [19] advocate assessing the flexibility of a product by systematically anticipating and rating the potential future changes to “future proof” the design, which will inevitably introduce a degree of redundancy into the product. In [18] this assessment is achieved through mapping out the tradespace, i.e. the range of possible parameter values that provides potential solutions. Where the design sits within this tradespace indicates margins on the product. De Neufville et al. [20] introduce design options as a form of deliberate planning for a small number of potential changes that will be carried out to the product including calculations of the cost of planning in these options and the savings made in using a design option as opposed to making a change from scratch.

Another perspective is how a given design can be upgraded by identifying margins in terms of excess, as the “the quantity of surplus in a system once the necessities of the system are met” and capacity as “the ability of a system to meet future performance objectives using existing system excess” [21]

A design margin is defined as “the extent to which a parameter value exceeds what it needs to meet its functional requirements regardless of the motivation for which the margin was included” [22].

3. Methodology

Eight interviews were carried out in October 2013 with ten design engineers from a Swedish truck manufacturer. They included four designers from their chassis team, a test engineers, three simulation engineers, platform and brand representatives as well as experts from product planning. The engineers had between 4 and 40 years of professional experience and were selected by the head of the chassis team to provide a range of perspectives on design margins. The interviews last between 45 minutes and an hours were transcribed. In the analysis of the transcripts we looked at both the answers to the question of margin and other responses which pointed to margins. Initial results were presented back to the interviewees in December 2013. After a further study of the literature an in depth study of margins on a particular system the classification discussed in this paper, was again presented to the participating designers. Additional interviews were held in the aero engine company with three senior engineers, who were questioned on their use of margins and also asked to comment on the diagrams presented in this paper.

4. Margins in design practice

Our case study on truck design revealed that designers through the entire design processes added margins to both the requirements for a product and the key parameters of the solutions that they are designing to meet these requirements. In the interviews the designers were asked where and when margins were added. The terminology used by the designers was very inconsistent. For example they referred to margins in requirements, which assure that the product works safely under all expected use conditions as “safety margins”, however they also used the term “safety margin” for margins they added to the design to make sure they can handle changes to their components during their design process. The test engineers who also are part of writing the requirements for components, assured us that they looked at worst case scenarios and added safety margins to the requirements so that these were covered. However, design engineers also commented that they added margins to the component above the requirements to allow for different uses of the truck. Later in the design process, the company looks to optimize the product to produce the safe cost in production and operation, where they redesign oversized components to make them cheaper. Here margins are seen as negative, because they can be a potential cause of excessive cost which needs to be tracked down systematically. By contrast many designers see margins as positive as a means to reduce the risks arising from changes.

The following analysis separates the different concepts of margin by the main rationale for putting the margins in. Each of these concepts existed in the organization, however the organization had not put them together systematically before.

4.1. Margins to Requirements

At the beginning of each new product generation the product planning team needs to make a judgment where new needs can be met with existing technologies. Unless the update has been preplanned they aim to reuse an existing component or make small changes to it. If this is not the case for a component or system and a new design needs to be generated or a new technology needs to be chosen, this is typically not just targeted at the present generation, but includes a margin to allow *room for growth* for future generations, for example empty electrical port might be specified to allow for new electronic features. This enables companies to manage the risks associated with new technologies across product generation in a systematic technology infusion process [23]

The case study company covers multiple brands with different characteristics, who operate in different markets but aims to maximize communality across and within the brands. This leads to some components being highly overspecified for applications [24]

While room for growth is an internal requirement, safety requirements come from the use of the product and are to a certain extent legislated by regulators. For trucks this

involves handling multiple use applications and handling the accumulation of multiple adverse use conditions are captured in so called worst case scenarios which encapsulate the range of conditions the product operates under. *Safety margins* are set to assure that the product operates reliably under all use conditions for the target live time and beyond; and cover potential misuse by the customer. While companies are increasingly able to track what their customers are doing with their product and therefore know when the warranty would be compromised, they want to avoid any design failures that would endanger people or the environment or reflect badly on the performance of their products.

The company combines the room for growth requirements and the safety margins into specific target values or ranges of values as requirements to the design team. At the end of this process the requirements for a component and system can be described in terms of the minimum or maximum value that a parameter should have. Some of the reasoning processes are communicated to the design teams, however the details are often not clear.

4.2. Margins to design

Designers add *design margins* to their parameter specifications to handle design uncertainties. These arise either from changes in the requirements, for example as new design options are being considered, from the effects of other design decisions, such as material decisions which affect the weight of the product or as part of a convergent iteration cycle. Design margins play a very significant role in responding to engineering change and generating engineering change. Design margin can absorb change, so that no action is required or if they are exceeded can multiply the change, so that many other components or system need to be changed in consequence [1].

In the following section we will argue that the margins can be split into a buffer against uncertainties and a genuine *excess*, which is the overdesign which is not required to allow for uncertainties in the design process, and can be used in the next product generation or variant. The excess that exists once most of the design uncertainties are resolved can be optimized out.

Margins are also added from a manufacturing and assembly point of view by a manufacturing team to ensure that a product will be safe and reliable for a given manufacturing variability. This is considered in robust design. *Tolerances* can be considered as margins to accommodate manufacturing variability and are typically much smaller than design margins. However when margins become critical during a design process, tolerances might be affected by design margins.

4.3. Margins changing over time

Figure 1 shows an overview of the changing margins in the course of the design process, starting from the top. As the requirements go up, margins are reduced, but they can also be released by reducing uncertainty. Each team has

good reasons to add margins or take them away, but they might not be aware of the rationales of their colleagues so that the margins can be either be duplicated or carefully planned margins are reduced. Both could add significantly to the cost of a new product version or product generation.

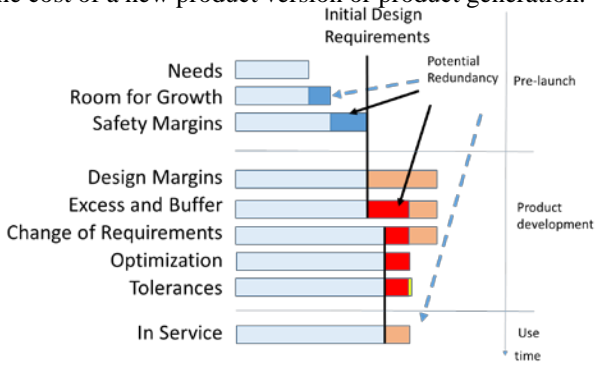


Figure 1 Margins in the design process

5. Formulation of margins

Design margins are the difference between requirements and the capability of the component or system. Margins can refer to simple parameters p or vectors of parameters $\mathbf{P} = \langle p_1, p_2, \dots, p_n \rangle$. Therefore the margin can be expressed as

$$D_M(\mathbf{P}) = Cap(\mathbf{P}) - R(\mathbf{P})$$

However in practise margins are subject to constraints that they need to meet therefore it is not always possible to take advantage of the full margin.

$$D_M(\mathbf{P}) = Cap(\mathbf{P}) - Const(\mathbf{P}).$$

$$D_M(\mathbf{P}) = Const(\mathbf{P}) - R(\mathbf{P}).$$

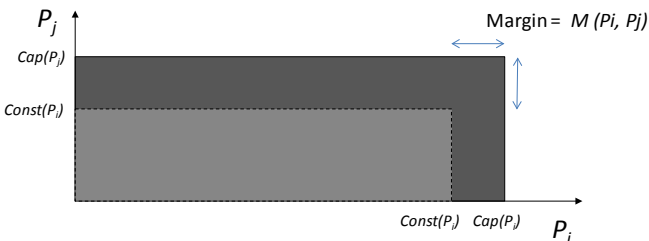


Figure 2 Margin between constraints and capabilities

To decide whether a margin can be used in a design it is useful to distinguish between an element of the margin that acts as buffer against uncertainties and an excess that can be repurposed or if necessary taken away in an optimisation exercise.

$$D_M(p_j) = B_D(p_j) + E_D(p_j)$$

To obtain usable margins it is either possible to increase the capability of a component or system or importantly reduce the uncertainty, as it releases part of the buffer to become excess. Analogously we can define safety margins as

$$S_M(\mathbf{P}) = R(\mathbf{P}) - N(\mathbf{P})$$

When defining the requirements the distribution of risk needs to be assessed before the design is created. To cater for unknown risk safety margin often have an additional buffer build in. As is the difficult to estimate the buffer for unknown risk, product might also have a certain excess

$$S_M(\mathbf{P}) = B_{SK}(\mathbf{P}) + B_{SU}(\mathbf{P}) + E_S(\mathbf{P})$$

Where SK stands for the known uncertainties and the SU

for the unknown uncertainties.

When the product is evaluated at the end of the design process the risks are better known and the actual capability of the design is known. At this point design margins and safety margins could be accessed together. As many uncertainties will be better known, it is possible that in a practical design is excess greatly exceeds what is expected, as there is a buffer and excess element to both the safety margins and the design margins.

6. Discussion

The term margin in general and safety margin in particular is used very loosely in industry referring to several concepts each of which lead to a higher (or lower) specification of a value. While individual teams might understand the rationale for margins and the distributions of risks that they mitigate, this is rarely shared across different design teams. However, the teams themselves are rarely sure of margins, because they can be difficult to measure.

The capability of components, systems and products is often not known, because the effort in testing is placed at meeting the requirements. Only destructive testing would reveal the true capability of the product, however this could be simulated. Virtual test data is also available earlier in the development process, so that it is possible to consider buffers and excesses earlier in the design process. Even virtual testing is limited by the number of the scenarios that can be tested. It is only possible to test against known unknown, therefore there is also a residual risk remains.

Companies need to set an acceptable risk level to cater for unknown risk. Highly safety critical system might require additional buffers in the safety margins which handles those risks that cannot anticipated. The safety buffers should be reassessed when the product is designed, since they depend on the capability of the product. Test for the actual capability could reveal buffers, which would allow companies to optimize the product further.

Understanding the relationship between design margins and safety margins is particularly important for platform products, where very large margins can exist for particular applications. For some standard applications the risk might be very well understood, so that safety buffers for unknown risk can be kept at a minimum.

We therefore suggest that companies adopt a clear definition of safety margins (or factors) in an organization to describe the margins added to the needs and to use design margins for margins in the design process. These can be captured systematically at different stages in the design process. The safety margins could be included explicitly in the definition of requirements that are handed over to the designers. Design margins can be tracked through different gateways, where a formal evaluation of the design and associated risks takes place. To achieve this companies need to change the requirements for reporting from simulations and test procedures throughout the design process. At present companies simulate and test products to see whether they are meeting the requirements that are specified in the requirement documentation [25]. Running

simulations routinely to the point of distraction would yield useful insights to margins at little additional cost.

The literature on safety margins does not usually consider the order of decision making in the design processes and proposes safety margins set based on assumptions made about the product prior to its design.. Similarly the literature on design margins does not consider safety margins and an additional range or uncertainty in values they are considering to cater for safety issues. However both would benefit from being seen as a joint up decision making process.

The lack of transparency might lead to margins being added several time for the same reasons across the design process. In particular between safety margins and design margins and the between the room for growth planned in at the beginning of a design process and the excess left at the end once the product has entered service and the buffers against design uncertainties are no longer needed.

7. Conclusions

While the concept of margin is used informally across the design process by both the designer and safety experts, neither group has a clear definition and the two type of margins are not looked at together. Therefore there is a risk that margins are added both to the requirements and the design implementation. Greater awareness of the margins added across the design process can lead to more efficient change processes and avoid optimization steps where excess is taken out. Further work will quantify the margins in case studies and analyze the extent to which margins are duplicated.

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