Margins in design – review of related concepts and methods

Citation for the original published paper (version of record):

Brahma, A., Ferguson, S., Eckert, C. et al (2024). Margins in design – review of related concepts and methods. Journal of Engineering Design, 35(10): 1193-1226.
http://dx.doi.org/10.1080/09544828.2023.2225842

Journal of Engineering Design

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/cjen20

Margins in design – review of related concepts and methods

Arindam Brahma, Scott Ferguson, Claudia Eckert & Ola Isaksson

To cite this article: Arindam Brahma, Scott Ferguson, Claudia Eckert & Ola Isaksson (20 Jun 2023): Margins in design – review of related concepts and methods, Journal of Engineering Design, DOI: 10.1080/09544828.2023.2225842

To link to this article: https://doi.org/10.1080/09544828.2023.2225842

Published online: 20 Jun 2023.

JOURNAL OF ENGINEERING DESIGN
https://doi.org/10.1080/09544828.2023.2225842

Margins in design – review of related concepts and methods

Arindam Brahma [a], Scott Ferguson[b], Claudia Eckert [c] and Ola Isaksson [a]

[a]Division of Product Development, Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden; [b]Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC, USA; [c]School of Engineering and Innovation, The Open University, Milton Keynes, UK

ABSTRACT

Margins are defined as the difference between a design parameter's minimum required value to ensure functionality, and its actual capability. Margins allow engineers to mitigate uncertainties of various kinds. While some margins are intentionally allocated, some others may get included inadvertently in designs or arise from changes to requirements. Although common in use, the concept of margins has not been formalised systematically. This paper offers the first systematic literature review of margins. Concepts related to margins can be found in various interrelated domains with similar underlying principles. However, these concepts have developed in isolation, leading to a divergent and fragmented understanding. This paper brings these strands together by differentiating between margins which may be deliberately added or discovered during a typical product lifecycle and relates this to various domains such as safety, manufacturing etc. The paper discusses approaches to model, size and allocate margins. The thematic analysis presents insights into the importance of systematic use and management of margins and also raises currently observable gaps in the literature.

ARTICLE HISTORY
Received 31 January 2023
Accepted 8 June 2023

KEYWORDS
Engineering design margin; excess; buffer; overdesign; safety factor

Introduction

Engineers often talk of 'keeping something in reserve', 'having a buffer', 'making use of excess' or 'getting rid of overdesign' (Eckert et al. 2020). These phrases reflect the deliberate planning, or discovery, of surpluses or margins that have been incorporated to make the system less vulnerable to the adverse effects of uncertainty (Brahma and Wynn 2020). For the purposes of this review, we define margins as the difference between a design parameter's minimum required value to ensure functionality, and its actual capability (Eckert, Isaksson, and Earl 2019).

Research studies describe how the general concepts of margins are used as means of sharing ideas with their close colleagues (Eckert, Isaksson, and Earl 2019). However, the understanding of margins is often tacit and informal (Eckert, Isaksson, and Earl 2012). Further, the domain of application often shapes the definition – and view – of the term 'margin'. Concepts and principles associated with margins can be found in aerospace

CONTACT Arindam Brahma brahma@chalmers.se Hörsalsvägen 7A, 412 58 Göteborg, Sweden

(Thunnissen 2004), ship-building (Levine and Hawkins 1970), plant and factory infrastructure (Takamatsu, Hashimoto, and Shioya 1974), civil construction (Jones and Eckert 2017a), and manufacturing (Cao, Liu, and Yang 2018) domains, as examples. The resulting proliferation of this term is that a formal underpinning of how to describe, manage and model [the different kinds of] margins throughout the product development process is missing.

This paper addresses a significant gap in the literature by undertaking a holistic review of margins throughout the product development process. Margins influence multiple aspects of engineering design, as shown by the numerous definitions listed in Table 1, yet non-standard terminology and concepts hinder shared learning across communities. By looking at the various concepts of margin, we distinguish between those that are deliberately incorporated during design versus those that are discovered during redesign. We also explore the application of margins in response to known or unknown uncertainties and map margin-related concepts to their application throughout the product development process.

Further, we highlight the gaps in understanding and identify opportunities for learning from well-established practices. For example, there is an established practice for describing, managing, and modelling tolerances. Tolerances are one way of responding to variability and uncertainty in the production process. We highlight the need for a similarly systematic treatment of margins, as an over-cautious or haphazard allocations of margins can result in overdesigned systems, products, and components that incur unnecessary productions or use costs (Al Handawi et al. 2021, 2021a).

In the next section, we briefly discuss the scope of this paper and the research methodology adopted. This is followed by a brief history of margins, which is then followed by a discussion about uncertainty and how margins are used to mitigate against them. In the fifth section, margins, as found in the literature of related fields is discussed. The discussion is based on margins mapped onto a typical design process. The sixth section discusses margin modelling and sizing approaches. The paper ends with a discussion and concluding remarks.

Research scope and methodology

As the focus of this review is to assimilate concepts that have developed in silos and work toward a holistic unification, decisions were made about what to include. These decisions were guided by several focused discussions by the authors and two workshops in 2022 with various industry and research experts having experience in margins. A five-step process was used:

(1) An initial proposal for the review was generated by drawing on the authors' prior knowledge of the research area (Eckert et al. 2020). The bibliographies of four recent publications by the authors of this paper were considered as a starting point. 51 references from Brahma and Wynn (2020), 56 references from Eckert, Isaksson, and Earl (2019), 55 references from Cansler et al. (2016) and 46 references from Tackett, Mattson, and Ferguson (2014) were combined which resulted in 171 individual references. Any paper that related to margins and topics such as flexibility, evolvability, modularity, resilience, change propagation, uncertainty etc were retained, resulting in 104 core papers.

Table 1. Consolidated list of margin-related concepts in the literature, adapted from Eckert et al. (2020) and Brahma and Wynn (2020).

Publication	Term/concept	Context of margin-related terminologies
Lusser (1958)	Contingency Margin	Kept in reserve in case identified contingencies, or a combination of them, occur in service.
	Scatter Margin	To account for inherent variation of strength.
Levine and Hawkins (1970)	Service Margin	Margin of performance added to compensate for environmental and deteriorative factors reducing a ship's ability to maintain speed, considering a specified period of time.
Takamatsu, Hashimoto, and Shioya (1974)	Design Margin	To compensate for undesirable effects of uncertainties.
Gale (1975)	Design/Construction Margin	Allowance for uncertainties in estimating techniques, for unknowns when estimations are made, and potential minor changes in specifications. Intended to be eliminated prior to design completion.
	Future Growth Margin	Allowance for additions to a system (ship) once in service.
Hockberger (1976)	Assurance Margin	To sustain a specified level of performance under environmental uncertainties, and to offset degradation.
Hammer (1980); Möller and Hansson (2008)	Safety Reserve, or Safety Factor	Strength to resist loads and disturbances exceeding intention. Ratio of min. strength to max. stress. Multiplicative.
	Safety Margin	Difference between min. strength and max. stress. Additive.
Swanson and Galvin (1984)	Overdesign Factor	Ratio of the actual design capacity to the capacity calculated to be required in the absence of uncertainty.
Martin and Ishii (2002)	Headroom	To accommodate future changes in specification values.
Thunnissen (2004)	Design Factor, or Margin	Added to account for uncertainties when rigorous uncertainty mitigation/propagation is unavailable.
Dawson, Fixson, and Whitney (2012)	Design Factor/Reserve Factor	Ratio of allowable stress to actual or calculated stress.
Iorga, Desrochers, and Smeesters (2012)	Safety Margin	Added to increase reliability.
Eckert, Isaksson, and Earl (2012)	Margin	The extent to which a parameter's value exceeds what is needed to meet its functional requirements.
Tilstra et al. (2015)	Excess storage or importation	To enable design evolvability
Watson et al. (2016)	Excess system capability	To accommodate future changes in a product.
Eckert and Isaksson (2017); Lebjioui (2018)	Margin added to requirements	To accommodate future growth and safety requirements.
	Margin added to design	To handle uncertainty related to design, manufacturing and assembly.
	Margin that changes over time	Occurs because of different teams working on different parts of a design leading to duplication or reduction of margins.
Newcomer and Bierbaum (2017); Grover (2021)	Performance margin	Difference between actual and required performance when inputs and environment are within requirement.
	Design margin	Difference between maximum or minimum inputs where component works as intended.
Jones, Eckert, and Gericke (2018)	Overdesign	Capacity above requirements
Guenov et al. (2018)	Margin, or Reserve	Placed on variables to account for uncertainties expected to affect their accurate prediction. Can provide flexibility for evolving requirements or can account for model uncertainty.
Eckert, Isaksson, and Earl (2019); Lebjioui (2018)	Buffer	Account for uncertainties in a component and its use.
	Excess, or Contingency	Range that can be used to redesign or make a change.
Brahma and Wynn (2020)	Deliberate Margin	Margin that is deliberately included to ensure reliability, upgradability and/or to address regulatory, safety, or life requirements, to mitigate the potential risk of rework during design due to change in specifications, and to enable the use of one part in other product variants.

(*continued*).

Table 1. Continued.

Publication	Term/concept	Context of margin-related terminologies
	Excess Margin	Margin that is included without deliberate analysis while accounting for uncertainty during the design process. Margins that emerge as a by-product of sub-optimisation or due to the use of off-the-shelf or platform parts.
McPherson and Ogawa (2008)	Reliability Margin	Range between the application stress to the strength for reliable operation over a given time period considering degradation rate of material or device.
del Rosario (2020)	Margin	An adjustment to a requirement which considers epistemic factors.

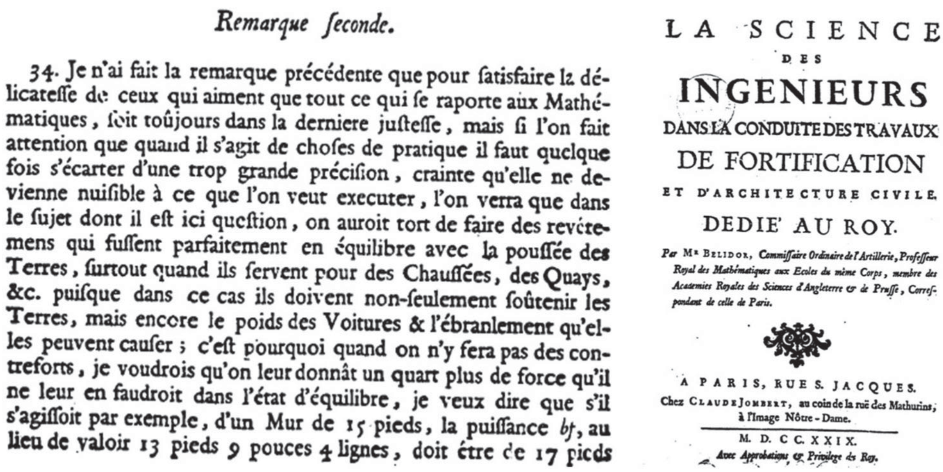
(2) Citations of seminal papers such as Clarkson, Simons, and Eckert (2004) and Eckert, Clarkson, and Zanker (2004) (who briefly discuss margins) were analysed.
(3) Reviews mentioned in recent PhD dissertations on the topic such as by Brahma (2020), Lebjioui (2018) and Touboul (2021) were also considered.
(4) A keyword-based search was employed in Scopus and Google Scholar to find papers which may have been missed in previous steps. The keywords used were 'Margin', 'Margins', 'Design Margins', 'Safety Margins', 'Safety factor', 'Factor of Safety', 'Excess', 'Buffer', and 'Overdesign'.
(5) Additional searches were undertaken to gain a historical perspective on margins.

The scope of the paper was restricted based on the following considerations:

- Domain: Margins only in the context of engineering design were investigated. This included mechanical engineering, civil/structural engineering, and process engineering. Chemical, software, electronics, biology and business or commerce-related topics were kept out of scope.
- Only product margins: Margins are also highly relevant in terms of process planning and management in terms of time buffers, however, this paper largely focusses on the products and services and not the process of designing them.
- Related terms: Consideration was given to topics which may not explicitly state the term margins but may have ideas which are principally similar or have common origins or effects.
- Research Focus: The following aspects of margins were considered; (a) Definitions, taxonomy and ontology, (b) margins throughout the design life cycle, (c) modelling approaches and (d) tools and methods of sizing margins.

Margins throughout the ages

The early history of margin is rooted around uncertainty mitigation in the name of safety. This was especially true in cases where the calculation of requirements proved difficult or the underlying mathematics had not yet been developed. Elishakoff (2017) traces the idea of margins back to the code of Hammurabi, a Babylonian king from 1792–1750 BCE. In this code, the builder is held liable for the collapse of a building. This liability encourages the inclusion of margin with the aim that 'the structure becomes immune to failure and will survive indefinitely'. More direct evidence of margins is found much later in the works of



Remarque ſeconde.

34. Je n'ai fait la remarque précédente que pour ſatisfaire la délicateſſe de ceux qui aiment que tout ce qui ſe raporte aux Mathématiques, ſoit toûjours dans la derniere juſteſſe, mais ſi l'on fait attention que quand il s'agit de choſes de pratique il faut quelque fois s'écarter d'une trop grande préciſion, crainte qu'elle ne devienne nuiſible à ce que l'on veut executer, l'on verra que dans le ſujet dont il eſt ici queſtion, on auroit tort de faire des revêtemens qui fuſſent parfaitement en équilibre avec la pouſſée des Terres, ſurtout quand ils ſervent pour des Chauſſées, des Quays, &c. puiſque dans ce cas ils doivent non-ſeulement ſoûtenir les Terres, mais encore le poids des Voitures & l'ébranlement qu'elles peuvent cauſer; c'eſt pourquoi quand on n'y fera pas des contreforts, je voudrois qu'on leur donnât un quart plus de force qu'il ne leur en faudroit dans l'état d'équilibre, je veux dire que s'il s'agiſſoit par exemple, d'un Mur de 15 pieds, la puiſſance *bf*, au lieu de valoir 13 pieds 9 pouces 4 lignes, doit être de 17 pieds

LA SCIENCE
DES
INGENIEURS
DANS LA CONDUITE DES TRAVAUX
DE FORTIFICATION
ET D'ARCHITECTURE CIVILE.
DEDIE' AU ROY.

Par M. Belidor, Commiſſaire Ordinaire de l'Artillerie, Profeſſeur Royal des Mathématiques aux Ecoles du même Corps, membre des Academies Royales des Sciences d'Angleterre & de Pruſſe, Correſpondant de celle de Paris.

A PARIS, RUE S. JACQUES.
Chez Claude Jombert, au coin de la ruë des Mathurins, à l'Image Nôtre-Dame.
M. D. CC. XXIX.
Avec Approbation & Privilege du Roy.

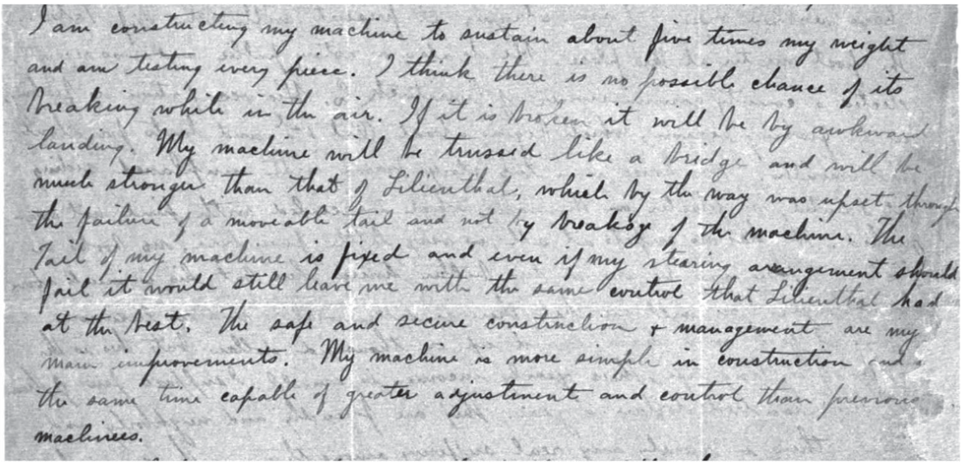
Figure 1. Cover page (left) and extract (right) from Bernard Forest de Bélidor's 1729 – La science des ingénieurs, page 35, second remark. Source gallica.bnf.fr / Bibliothèque nationale de France, reproduced under the non-commercial reuse criteria.

French civil engineer Bernard Forest de Bélidor, (de Bélidor 1729), who suggests increasing wall thickness by 'a quarter' to account for unknowns. An extract is presented in Figure 1.

Beginning in the mid-late nineteenth century, the term 'Factor of safety' started being used. For instance, Rankine (1872) suggests a multiplication factor in the context of bridges and tunnels. Wilson (1874) provides guidance on selecting a proper 'coefficient' or 'factor of safety' in boiler design against uncertainties such as defects, wear and tear. The concept of a factor of safety was driven by serious boiler explosions in the late 1800s and the early 1900s, resulting in formal discussions on measures to prevent boiler accidents (Peters and Pham 2018). As the aircraft industry became established, such factors became a part of the aircraft design process. Wilbur Wright comments in a letter that he is constructing his machine to sustain about five times his weight and considers the ramifications of a crash landing (See an excerpt from the letter in Figure 2). Shanley (1962), when tasked with rationalising U.S. civil-airworthiness requirements in 1932, introduced a 1.5 'ultimate factor of safety' (Muller and Schmid 1977) and a 'load factor' of about 6 for a typical aeroplane. Shanley's notes reveal that these numbers are not 'sacred' but were generated by considering the properties of prior aircraft that had 'good service records' (Shanley 1962).

The importance of margins in different design considerations

As our representations of the design process have become more formal, and our ability to model and analyse a system has improved, so too has the use of margins. Without a holistic perspective of margins, existing margins may not be fully utilised or may be included inadvertently (Brahma and Wynn 2020; Eckert, Clarkson, and Zanker 2004). For instance, in a collaborative setting, it has been observed that teams unnecessarily add their own margins without knowing what other teams have done or assumed (Eckert and Isaksson 2017; Gil et al. 2005). This lack of coordination may lead to duplication, or stacking of margin (Jones, Eckert, and Gericke 2018). Further, a lack of transparency may lead to the unnecessary accumulation of margins when standardised, modular or off-the-shelf components



I am constructing my machine to sustain about five times my weight and am testing every piece. I think there is no possible chance of its breaking while in the air. If it is broken it will be by awkward landing. My machine will be trussed like a bridge and will be much stronger than that of Lilienthal, which by the way was upset through the failure of a moveable tail and not by breaking of the machine. The tail of my machine is fixed and even if my steering arrangement should fail it would still leave me with the same control that Lilienthal had at the best. The safe and secure construction & management are my main improvements. My machine is more simple in construction and the same time capable of greater adjustment and control than previous machines.

Figure 2. An excerpt of a letter from Wilbur Wright to his father dated Sept 23, 1900, where he describes overdesigning his aircraft for safety (Wilbur and Orville Wright Papers, 1900). Reproduced under fair use and the U.S. Copyright Office Circular 15a.

are used, as these components have their own margins (Brahma and Wynn 2020; Meyer 2002).

Two general principles – the frame by which margins are found and the uncertainty associated with operating conditions – can help establish the role (and define the consideration) of margins. The first distinction is between margins deliberately set in the design process and margins that are discovered through investigations. In the second dimension, margins can be used to mitigate uncertainties that are determined, nominal and specified by bounding conditions (Determinate Conditions). On the other extreme, margins can be used to mitigate uncertainties that cannot be specified a priori (Indeterminate Conditions). Various reasons for the presence and incorporation of margins, as found in the literature, are mapped onto these dimensions in Figure 3.

Classifications of uncertainty

Uncertainty is an inherent part of engineering design, found in many of its aspects (Earl, Johnson, and Eckert 2005) and is described to be at the core of complexity in design (Suh 1999). Most commonly, uncertainties are classified into Aleatory and Epistemic (Der Kiureghian and Ditlevsen 2009). While aleatory uncertainties are associated with the inherent randomness of a phenomenon, epistemic uncertainties are associated with a lack of knowledge. Earl, Johnson, and Eckert (2005) distinguish between two dimensions of uncertainty, as shown in Figure 4.

- Known and unknown uncertainty: The variability of known uncertainties is based on past experience, while unknown uncertainties are events that could not have been anticipated.
- Uncertainty in descriptions; including the selection of element, the scope etc., and uncertainty in data; which include accuracy of data, the accuracy of measurement etc.

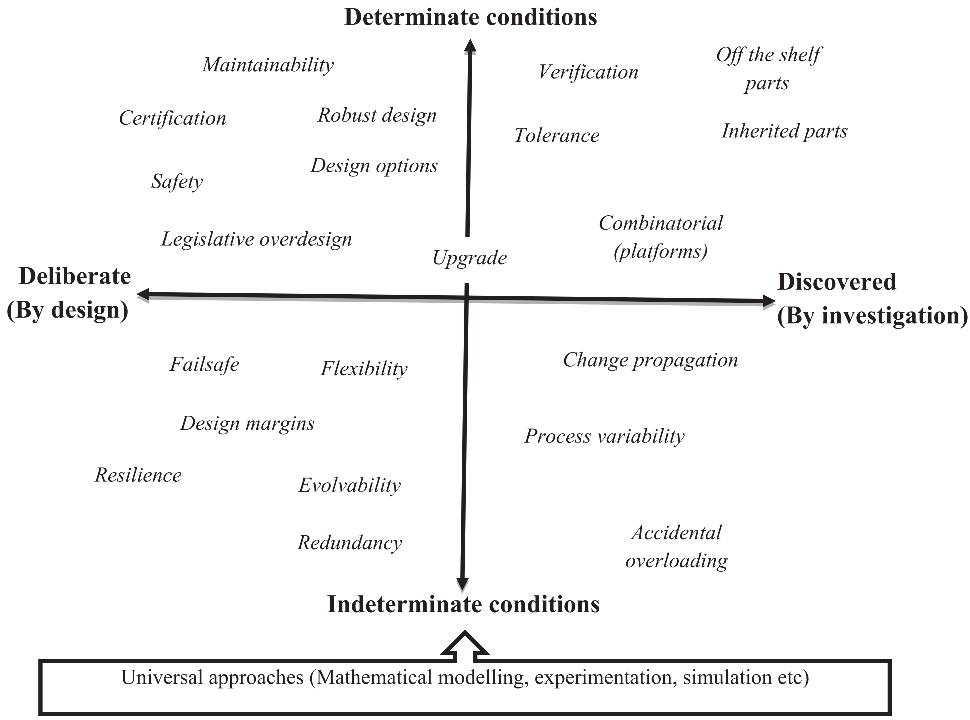


Figure 3. Map of issues where margins are important in product development.

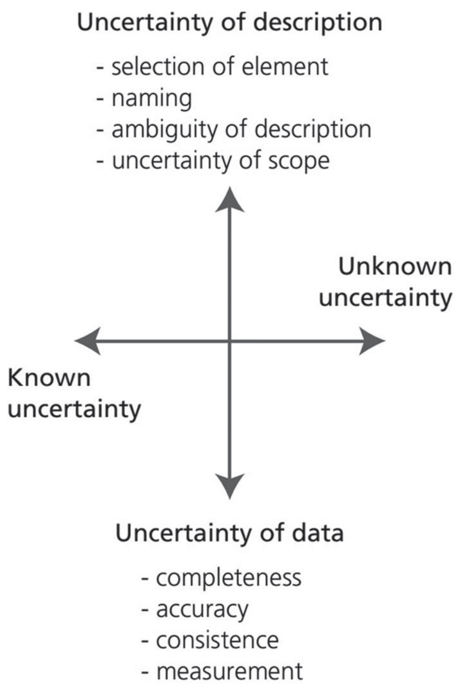


Figure 4. Types of uncertainty in engineering design as described by Earl, Johnson, and Eckert (2005). Reproduced with permission from Springer Nature.

A similar distinction is also introduced by Hastings and McManus (2004), where uncertainties are classified into five types: lack of knowledge, lack of definition, statistically characterised variables, known unknowns, and unknown unknowns. In their definition, lack of knowledge refers to the facts that are not known or are known with a limited degree of precision. Lack of definition is defined as the aspects of a design that are yet to be decided or specified, and therefore are in an uncertain state. These two definitions are similar to Earl, Johnson, and Eckert (2005)'s 'uncertainty of description'. The third uncertainty type is the statistically characterised variables, similar to Earl, Johnson, and Eckert (2005)'s 'known uncertainties'. However, Hastings and McManus (2004) further classify 'unknown uncertainty' into known-unknowns and unknown-unknowns. Known unknowns are things that may be identified qualitatively but cannot be statistically quantified (such as the performance of a future technology). Literature in economics and business describes unresolvable uncertainties, which make defining future states inherently difficult because historical data provides limited insight into future outcomes (Fenton-O'Creevy and Tuckett 2022; Kay and King 2020). Unknown unknowns are completely unanticipated (such as an accident or a natural calamity).

Another uncertainty classification based on their source of origin is proposed by De Weck, Eckert, and Clarkson (2007) (i.e. endogenous or exogenous). Endogenous uncertainties are directly related to the product and therefore to a certain extend under the control of the designers, such as design-related technical risks, unmodelled interactions, etc. Whereas exogenous uncertainties are outside the system boundaries of a product on which the company may not have direct control such as how a product is operated, uncertainties related to the market dynamics, and political and other socio-cultural uncertainties.

Margins to counter uncertainties

Early definitions of margins were highly context specific. One of the earliest efforts comes from a 1958 report by Lusser (1958), who relates margins in the context of military equipment reliability to applied loads and the strength of a designed structure or machine. Lusser distinguishes between margins used to handle occurrence(s) of identified contingencies and margins that allow for variation in material properties (e.g. strength). Levine and Hawkins (1970) propose a similar concept in the context of a ship's operational performance. They define a 'service margin' specifically related to a ship's power and speed, added to the design, that accounts for variations in future operating conditions. The uncertainties, in this case, are characterised by the unpredictably deteriorating weather conditions that typically have an adverse effect on a ship's ability to maintain speed over time. Margins targeted at uncertainties can also be found in Takamatsu, Hashimoto, and Shioya (1974) who define design margins in terms of parameter uncertainties in process plant designs, and Gale (1975) and Hockberger (1976) who specify design or construction margins to account for design information-related uncertainties in early phases of design. Hockberger (1976) introduces assurance margin, a concept similar to the service margin found in Levine and Hawkins (1970), as shown in Figure 5.

The discussion of margins, since these publications in the 1970s, has been further refined into how margins can mitigate uncertainties during the design phase, e.g. frequent change in requirements (Al Handawi et al. 2021; Watson et al. 2016b), versus those uncertainties that must be mitigated along the product's lifecycle such as considering operational

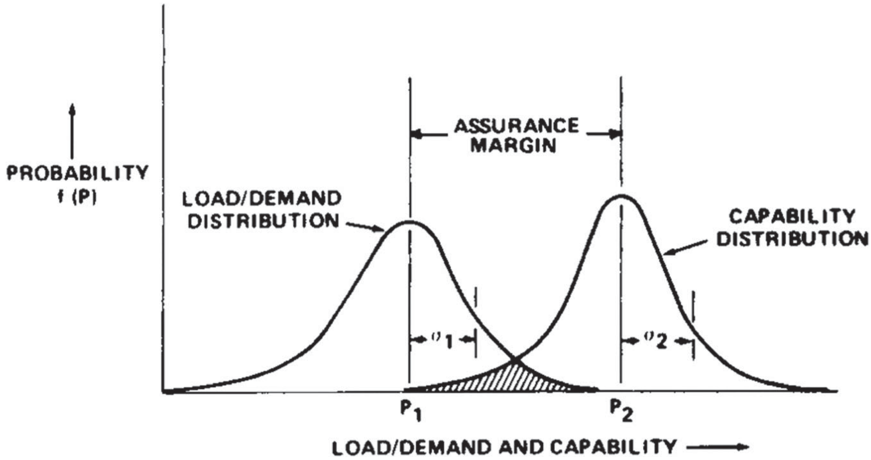


Figure 5. Relationship between assurance margin and probabilistic load/demand and capability as described by Hockberger (1976). Reproduced with permission from the American Society of Naval Engineers.

considerations (Fisher, Doherty, and Douglas 1985; Gimenez, Schlamp, and Vertullo 2002) and use related issues (Hockberger 1976; Morse et al. 2018; Zhu and Ting 2000). While margins used for managing uncertainty during the design phase can be consumed or eliminated once the design is matured, margins incorporated for the use phase must be retained. This establishes a distinction between margins as discussed in Eckert and Isaksson (2017) and the assurance (service) margins described by Gale (1975), Hockberger (1976) and Levine and Hawkins (1970). Gale (1975), for example, describes 'future growth margins' as one type of assurance margin that is intended for future modernisation additions to a ship. These future growth margins reduce the need for significant changes to the existing design, while simultaneously assuming that these margins will be consumed during the lifetime of operations. Similar definitions are provided by Tilstra et al. (2015) and Watson et al. (2016), where margins are defined (and consumed) in the context of system evolvability. System evolution is modelled as changes made to an existing system after it has been fielded in response to known or unforeseen changes in future operating requirements. These works advance the 'options' research of (Neufville, Scholtes, and Wang 2006). Analogous to the concept of 'real options' in finance, a small number of potential changes are pre-planned into the system – requiring margin incorporation during the design phase – which can be exercised as needed at a future date.

When addressing uncertainty arising from thermal systems in aerospace components, Thunnissen and Tsuyuki (2004) classify margins into three categories. These margins span different aspects of product development: (a) Uncertainty Margin aimed at parameter uncertainties; (b) Qualification Margin, used in prototype testing when modelling the maximum and minimum temperature ranges; and (c) Protoqualification Margin, used when demonstrating the reliability of actual flight hardware in a protoflight testing situation. Cansler et al. (2016) present four types of margins, deterministic excess, epistemic excess, aleatory excess and consequent excess. Out of these two are aimed at known uncertainties: Deterministic Excesses are aimed at operational uncertainties; Epistemic Excess are margins used to account for known risk. Aleatory excess on the other hand is aimed to handle future needs and consequent excesses are a result of using off-the-shelf/standardised parts.

Safety margins and safety factors are perhaps the most discussed margins in practice. Yet, these are often significant sources of misunderstanding (Musto 2010). Möller and Hansson (2008) argue that safety is handled according to four principles: (1) Inherently safe design, which designs-out the source of failure, (2) Safety reserves, which can buffer a potential problem (3) Safe fail, which assures that the design can withstand the failure mode and (4) Procedural safeguards, which mitigate a failure mode in operation. Safety reserve is a margin added in the design phase, while the rest are ways of making a design safe, especially when in operation. A procedural safety margin is a difference between the parameters at which the product is supposed to operate and the point where failure occurs (Boyack et al. 1990; Schulz and Gruner 1990).

There is an important distinction between safety factors and safety margins. Safety Factor is the ratio of the required minimum strength for an application and the component's failure strength (Dawson, Fixson, and Whitney 2012; Hammer 1980), while Safety Margin is the difference between the two, i.e. a value (also see Rasky et al. (2003)). Consequently, one has an additive effect and the other has a multiplicative effect on the design (Möller and Hansson 2008). This becomes especially important when they accumulate. An interrelated concept is that of redundancies in systems, implemented primarily to ensure reliability even in the event of a failure (Chen and Crilly 2014). Typically, redundancy may be achieved by implementing multiple instances of vital components, all of which can perform the same function, independent of each other. In case one component fails, the other, which is at times identical, takes over to prevent a total failure of the system (Hein, Jones, and Eckert 2021; Jones and Eckert 2017b). Requirements of redundancy are often enforced strictly in many safety-critical industries such as aerospace and civil aviation (Eckert, Isaksson, and Earl 2019).

Lusser (1958) also talks about the 'factor of ignorance', which is intended for use against contingencies which are not known and can be as high as a factor of 10. These include unknown-unknowns, such as 'acts of god' like asteroid strikes, earthquakes, tsunamis, and hurricanes (Wisch 2006) or other factors, such as accommodation for technologies not yet invented in long-life products. Some authors argue that it is possible to draw from experience and reduce these types of uncertainties to statistically characterised variables (Hastings and McManus 2004).

Intentionally and unintentionally included margins

Margins have primarily been included as a mitigation strategy against recognised uncertainties and applied based on experience. Recent research has attempted to address the lack of formal definitions, acknowledging that margins are added for different reasons and often under unique labels. Some margins in engineered products get inadvertently incorporated or arise as a by-product of other decisions (Brahma and Wynn 2020). For instance, margins may appear in a design as a result of sub-optimisation (Eckert, Clarkson, and Zanker 2004). This may occur, for example, because of deliberately stopping optimisation when the cost of optimisation goes beyond the benefit gained. A conservative mindset of design

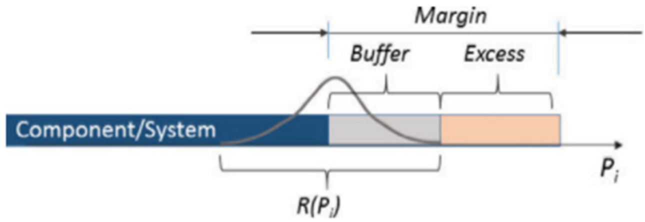


Figure 6. Buffer and Excess (Eckert, Isaksson, and Earl 2019). Reproduced under a CC BY-NC-SA 4.0 licence.

engineers may also lead to the inadvertent inclusion of margins in design (Jones, Eckert, and Gericke 2018). Multiple teams in the design of complex products may add their own margins in an uncoordinated way resulting in duplication or multiplication of margins (Eckert and Isaksson 2017). Margins may also get included when off-the-shelf (Brahma and Wynn 2020; Cansler et al. 2016) or platform parts are used (Isaksson, Lindroth, and Eckert 2014). Off-the-shelf parts often have their own margins, and these margins are not always disclosed to the designers who use them, as suppliers work to manage their own organisational risks and protect trade secrets (Eckert et al. 2020).

Regardless of why margins are included (Eckert, Isaksson, and Earl 2012), the result is a difference between the required and actual parameter value of the design (Brahma and Wynn 2020). Eckert et al. (2020) look at this from the perspective of what the margins on a product are at any given time. They define margins as the difference between a parameter's minimum required value and its actual capability. Margin allocation is also subject to requirement and constraint conditions imposed on the parameter. As illustrated in Figure 6, they conceptualise that margin can be decomposed into two elements, 'Buffer' and 'Excess'. Buffer is incorporated in response to uncertainties while excess can be repurposed. This implies that to increase the margins that can be used to meet an increased or different requirement, either the capability needs to be increased or the uncertainty reduced. This can be accomplished through testing or firming up requirements.

Brahma and Wynn (2020) focus on margins based on what is intended and what is not, distinguishing between Deliberate margins and Excess margins (without intent). Touboul (2021) distinguishes between what is required and demanded (demand margins) and the final margin when the product is in use (effective margins). Note that the definitions of Excess diverge between Eckert et al. (2020), who argue that every margin regardless of its purpose can have an element of excess whereas Brahma and Wynn (2020) see excess as a type of margin. Brahma and Wynn (2020) argue the margins are added deliberately to handle uncertainty and to reduce the design effort. Deliberate margins are therefore added to:

- increase reliability, address regulatory, safety or life requirements,
- mitigate potential rework during design,
- absorb large changes in specifications,
- be resilient to changes arising in the design process,
- ensure upgradability or future growth,
- ensure commonality between product families or platforms.

Excess margins can be added inadvertently:

- without deliberate analysis such as over-conservative decisions or assumptions,
- as an undesirable by-product of sub-optimisation,
- because of the use of off-the-shelf parts,
- reuse of parts from previous generations.

Margins throughout the lifecycle of a product

Concepts related to margins in engineering design span a wide range of applications. For instance, ship builders may think of margins as a measure to ensure performance over a long period of time (Levine and Hawkins 1970), while nuclear plant engineers may think of margins as a metric of safe operating conditions (Schulz 2006). Cimino and Filiopoulos (1997) and Meyer (2002) categorise margins according to the phases of a ship-building project and use terminology related to naval ship design. In their categorisation, margins in the preliminary/contract design account for inaccuracies of the preliminary design model while design and build margins account for parameter changes during detailed design. They also introduce categories for margins in government-furnished material, margins to account for potential contract modifications and modifications during the service life of a ship. Eckert et al. (2020), in the context of truck design, distinguish between margins on requirements (divided into margins for future growth and safety margins) and margins added to the design (allocated to changes of requirements in the design process and margins which are added to make the design robust). While many such examples of classifications can be found in literature (thematically discussed throughout the paper), they reflect the use case/context or specialisations within a field. These works provide evidence that margins are relevant to designers in all phases of design.

As uncertainties affect design at every stage of the process, so do margins that are put in place in response to these uncertainties. When faced with uncertainties, designers look for margins as they adjust or optimise the design. Both the deliberate and the discovered margins mapped onto a typical design process representation are shown in Figure 7.

Margins in design planning and concept development

Margins become relevant very early in the design process when eliciting requirements. Designers add margins to requirements, and correspondingly, the way margins are handled can also create margins in the design (Eckert et al. 2020). Engineering products in many sectors have to abide by codes and standards that govern specific requirements (Rangan, Maddux, and Duwe 1994). Margins may also be added to satisfy legal or statutory requirements such as crash performance in vehicles (Eckert et al. 2020), bridge design safety (De Santis and de Felice 2014), and nuclear plant safety (Schulz 2006). Other margins are dictated by life and performance requirements stipulated in the governing codes and standards. For instance, API RP 14E (API 1991) – a recommended practices document for the oil and gas piping industry – stipulates a specific corrosion allowance to be added to the pipe thickness. The allowance is calculated based on process parameters such as pressure, flowrate and the type of fluid being carried.

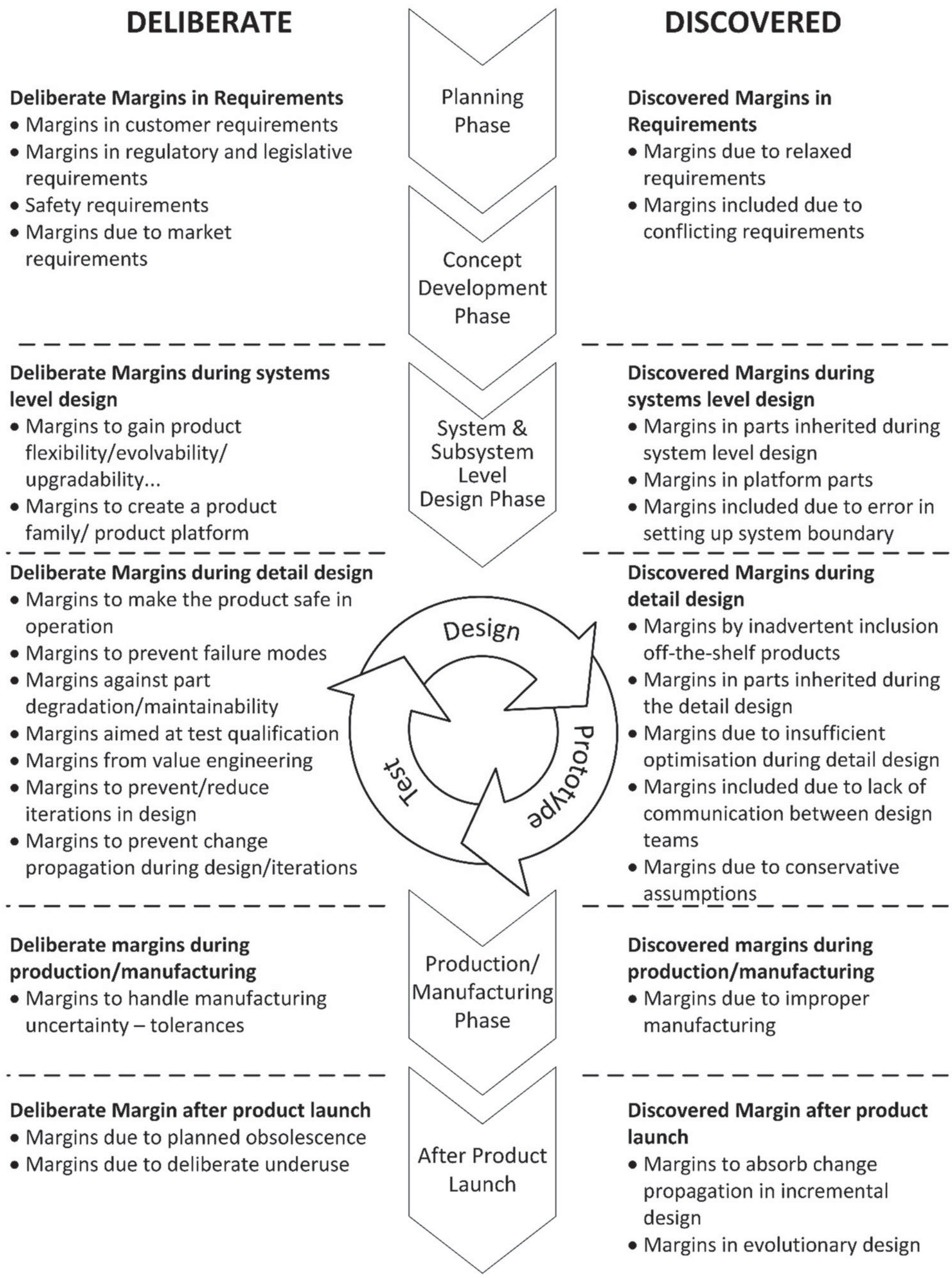


Figure 7. Margins of various kinds mapped onto a typical product development process (Based on the descriptions of Pahl et al. (2007), Mattson and Sorensen (2020) and Ulrich, Eppinger, and Yang (2020)). Discovered margins are shown on the top, deliberate margins are shown at the bottom.

While margins in the form of safety factors are often defined as a relative factor, they can also take on an absolute value. For example, Garbatov and Guedes Soares (2018) analysed corrosion in ships and found a 0.48 mm corrosion of the deck plate, regardless of part thickness. Non-regulatory requirements may also dictate design margins such as the requirement to have space for future growth, reliability or potential rework. Some of these future needs may never be realised, or an 'option' may never be exercised, leading to an overdesigned product (Coman and Ronen 2010). Further, requirement change is typical in most design processes, the result of which may create margins when requirements are relaxed and overcapacity becomes present in the design (Cansler et al. 2016). Requirements may also conflict, and a solution that satisfies all requirements may result in margins located in certain parts/components that may not be required to function at the highest requirement (Erens and Verhulst 1997).

Margins during systems-level design

Margins can also arise from a product's architecture. Companies often want their products to be flexible and use concepts such as modularity and standardised interfaces (Baldwin and Clark 2000) or platforms-based product development, such that multiple products share common parts. Interface designs, therefore, must be compatible with a large range of mating modules (Blackenfelt and Sellgren 2000). Since part combinations are often not uniquely designed to work together in an optimised way, some module variants may be overspecified (Durand, Telenko, and Seepersad 2010; Kamrad, Schmidt, and Ulku 2017).

Similarly, for platform-based products, parts and modules shared between product variants (or inherited from a previous generation) must be designed for the variant that demands the highest specifications (Krishnan and Gupta 2001). Modules must therefore be designed to meet the requirements of the most demanding application, potentially leading to very large margins for the products where the module's requirements are relaxed (Isaksson, Lindroth, and Eckert 2014). In the case of a product family, this leads to significant margins being present in the 'low-end variants' (Fisher, Ramdas, and Ulrich 1999). While researchers argue that overdesign can be advantageous (Allen et al. 2019) and that the overdesign cost can usually be overcome by the advantages gained by parts standardisation, flexibility, and/or by creating product platforms (Krishnan and Gupta 2001), case studies have also shown the contrary (Jones, Eckert, and Gericke 2018).

Margins in detail design – safety and reliability

Margins play an important role in the steps designers take to make a system more reliable. Safety and reliability engineering (RAMS) deals with failure modes and measures to prevent or minimise them (Birolini 2014) throughout the product life cycle. This includes considering the transient behaviour of a product in its use-cycle, such as wear-and-tear and general performance degradation rates (McPherson and Ogawa 2008). Uncertainties that affect product reliability (or failure) must be modelled using quantification (Kang et al. 2016). The traditional design approach has been to first identify design-basis accidents[1] (i.e. the worst case on which the design is based) and then to design safety measures mitigating the potential consequences (Ahn and Kwon 2006; Zio 2009). Designers accomplish this by adding margins or adding redundant systems (Apostolakis 2004; Chen and Crilly 2014). We argue that redundancy can be conceptualised as a margin. Such approaches are often motivated by the assumption that designing for the worst case subsumes preventive measures against all possible failure modes. As many margins are based on legacy or heuristic decisions based on experience from past designs, the result can be large margins and highly conservative designs (Zio 2009).

The quantification of margins in the context of safety and reliability is influenced by a number of factors. These factors may include how precisely parameters and behaviours can be defined, the severity of consequences of failure, and operating conditions (Collins, Busby, and Staab 2009). One limitation of these approaches is that the understanding of failure modes may be difficult, particularly at the systems level, although they are well developed when it comes to individual machine elements (Brahma and Wynn 2020). Additionally, the factors influencing margin quantification may not be equally important and require a weighting scheme so that a suitable safety margin requirement can be determined (Iorga, Desrochers, and Smeesters 2012).

A somewhat related topic in this field is procedural safety margins, quite commonly used in process plants. The International Atomic Energy Agency, IAEA (2003) for instance, defines the safety margin of operating reactors as 'the difference or ratio in physical units between the limiting value of an assigned parameter the surpassing of which leads to the failure of a system or component, and the actual value of that parameter in the plant' (IAEA 2003). These types of margins are generally established to ensure safe operation by ensuring that critical parameters always remain below desired limits. Although these safety margins relate to operation, they are primarily incorporated during the design of the system (Boyack et al. 1990). For critical systems such as nuclear power plants, these are often based on anticipated operational occurrences (AOOs) and design basis accidents i.e. the worst case on which the design is based. For these sorts of margins, it is not only important to know the amount of margin available, but also their sensitivity, i.e. the rate at which they may deplete when a failure occurs or is about to occur (Schulz and Gruner 1990). While procedural safety margins are important in highly safety-critical operations such as power plants, boilers etc., they are often used as an excuse for overdesign. This is especially the case in building services as observed in multiple case studies of hospital buildings by Jones and colleagues (Jones and Eckert 2017a; Jones and Eckert 2019; Jones, Eckert, and Garthwaite 2020), where requirements are often not worked out properly while using reliability and resilience as an excuse.

Margins during iterations in product development

While iterations are inevitable in design (Wynn and Eckert 2017), the margins in a design may heavily influence the amount of rework required (Wynn, Eckert, and Clarkson, 2007; Eckert, Isaksson, and Earl 2014). Design engineers often deal with incomplete or interdependent information at the beginning of the design phase (Brinkmann and Wynn 2020; Grebici, Goh, and McMahon 2008), for example, because the information has not been required in the bidding stage (Meyer 2002). To handle this, designers usually make assumptions to move the design forward (Brahma and Wynn 2021) or put off less critical decisions for a later stage (Erens and Verhulst 1997).

When decisions are made based on assumptions the iterations associated with product development can be influenced in two ways. First, if an assumption underestimates the final requirement or needed capability, not enough margin will be included. In such scenarios, changes may propagate (Brahma and Wynn 2021) and a high amount of rework will be required (Wynn and Eckert 2017; Wynn, Eckert, and Clarkson, 2007). The relationship between margins and change propagation is discussed in more detail in a later section. Second, and in contrast to the first scenario, if assumptions are made that overestimate the final requirement or needed capability, more margin will be included than is necessary. This too can lead to a number of unnecessary iterations being required to converge the design (Eckert, Isaksson, and Earl 2014).

As the design process moves forward and more information becomes available, the margins within a system may be refined. Designers then have a choice between tailoring the margin in a system or retaining the existing margin as an 'insurance policy' against unforeseen future changes. Factors influencing this decision include design complexity and trade-offs between the margin cost and the cost to eliminate it, as examples (Eckert, Clarkson, and Zanker 2004; Eckert, Isaksson, and Earl 2019).

Although the strategy of selecting one concept and iterating over it is the most commonly used approach, methods such as set-based concurrent engineering (SBCE) argue against it (Ward et al. 1994; Sobek et al., 1999). In SBCE, sets of feasible alternative design solutions are maintained throughout the design process instead of selecting one design solution, and initial requirements are sets rather than point values. These are refined as more information is gathered throughout the project's development and the detail of the solution, therefore, increases (Sobek et al., 1999). In other words, the design space is identified and reduced gradually by identifying limits and constraints in advance of selecting concepts and solutions. Margins are directly related to the size of the sets themselves and provide a means for controlling uncertainty (Riaz, Guenov, and Molina-Cristobal 2017; Al Handawi et al. 2022)

Margins during production – tolerance management

One special case of margins is tolerances. Tolerances account for uncertainty related to the manufacturing and assembly process. Unlike other types of margins, which might lead to overdesign and therefore an increase in the overall cost, larger tolerances are usually less costly from a manufacturing point of view (Lee and Woo 1990), yet can cause problems in the assembly process (Söderberg, Lindkvist, and Dahlström 2006). Further, unlike traditional margins which are usually over and above the requirement (Eckert, Isaksson, and Earl 2019), tolerances are defined as a range between which a specific dimension is permitted to vary (ASME 2018) and therefore can be on both sides of the nominal value. One of the primary areas of research in tolerance management is the stack-up of tolerances (Cao, Liu, and Yang 2018) arising from the insight that locally added ideal tolerances to individual components may not lead to an ideal global tolerance at the assembly level (Lee and Woo 1990). A stack-up in the positive direction leads to overdesign whereas a negative stack-up may lead to an increased susceptibility to failure. Manufacturing variability and the resulting overdesign can have a direct impact on the environment and cost of the product (van Grootel et al. 2020). Research in tolerances and their management has led to methods and tools widely used in industry where research continues to widen their applicability and generalisability (Morse et al. 2018). Tolerance analysis and management is an example of where, well worked out mathematical methods and definitions have impacted practical utility.

Margins in change propagation

Design changes often lead to propagation, where changing one component leads to changes in many other components (Brahma and Wynn 2023). This occurs when a component's margins are exceeded, meaning that the component cannot absorb the change in requirements (Brahma and Wynn 2021; Eckert, Clarkson, and Zanker 2004). Prediction of how changes propagate is important. One of the most well-known methods for modelling change propagation is the Change Prediction Method (CPM) by Clarkson, Simons, and Eckert (2004). This method considers the likelihood of propagation steps occurring, and their potential impact, to calculate the risk of changes propagating between components or subsystems in a design. Hamraz et al. (2013) extend CPM by considering the margins in the interface between two subsystems. This allows for an understanding of how much margin is present at an interface and how robust the design is to a change. When the change propagation probability is low, it is likely that high design margins exist between two subsystems and vice-versa (Lebjioui 2018). Quantification of margins, therefore, can be used in a direct prediction of the probability of change propagation, provided that the uncertainty (e.g. variation in input specification) is also known (Brahma, Wynn, and Isaksson 2022).

Conversely, overdesigned components may act as shock-absorbers and prevent further propagation (Chua and Hossain 2012). Careful margin allocation can reduce the severity or probability of change propagation (Brahma, Wynn, and Isaksson 2022) and reduce the costs associated with changes (Long and Ferguson 2019). Brahma and Wynn (2020) argue that when allocating margins, it is important to identify margins that limit the utilisation of other margins, i.e. 'bottleneck margins'. Such bottleneck margins in a design are consumed first (and lead to a failure), preventing other margins from being used. Incorrect margin allocation may not only lead to un-utilisable margins, but also to deteriorating performance (Robertson, Mavris, and Zweber 2012). Other authors suggest allocating margins in the form of extra design features, called 'resilient objects', which are specifically designed to absorb multiple kinds of changes, thereby creating resilience to future changes (Fernández, Panarotto, and Isaksson 2022). These objects are placed between parts where propagation of change is most likely. The authors explain this by using an example of a flexible coupling between a motor and a gearbox, which enables the absorption of vibrations, misalignments, and heat transmission. It also enables partial changes to the system when a new requirement arises. Excess capacity in a system therefore may not just be in the form of margins added to existing parts, but also in the form of additional parts which are functionally responsible for absorbing uncertainties.

Margins during the use of a product – planned obsolescence and underuse

After the product is put in operation, the usage pattern may determine the availability of margin. For instance, a product may deliberately be underused to prolong its life, such as the throttling of a mobile phone's processor to prolong battery life (Sahin and Coskun 2015). In other cases, the available margin may be dictated by the performance characteristics of the product. The most efficient point of performance may not be the product's highest capability, for instance in motors and pumps. Further, conditions surrounding usage may also dictate how much margin is consumed or remains in a system. For instance, in corrosion allowances for process pipes (API 1991) the allowance (margin) is consumed based on variable usage patterns. These usage patterns are often dictated by extraneous conditions, and peculiar usage patterns may also cause a unique erosion pattern of margins. Examples could include tyre wear, which is dependent on the usage pattern of a car, including braking behaviour, environment of use etc.

Geometrical tolerances, as a special case of margins, support the monitoring and planning of product and machinery use and remaining life in Digital Twins (Söderberg et al.

2017). In digital twins, the behaviour of existing products is measured and used together with simulation on the digital twin to make predictions that enable e.g. condition-based maintenance. Predicting a product's remaining life (e.g. Thomsen et al., 2017) is an area benefitting from uncertainty management. Terminology and definitions for margins in this context will be useful, as it is expected that variation and life cycle uncertainties will receive more attention as business interest in concepts like the Circular Economy becomes more prevalent (Bocken et al. 2016).

Methods for sizing, modelling, and allocating margins

General modelling of margins

Margins can be modelled mathematically in different ways. Eckert, Isaksson, and Earl (2019) modelled margins in terms of three fundamental concepts in engineering design, i.e. Requirements (R), Constraints (Const) and Capability (Cap), see Figure 8. A Requirement is the value a parameter is required to reach for it to be acceptable. A constraint is imposed on a parameter as a 'must reach' or 'must not exceed' criterion. Capability is the value a parameter would assume regardless of specific constraints or requirements. Four cases based on combinations of whether the requirements and constraints must or must not be exceeded by the margins can be identified, as shown in Figure 8.

Brahma and Wynn (2020) express the decision dependencies in a design using a visual dependency graph called the margin analysis network (MAN). For example, Figure 9 shows a section of the MAN where a motor is being selected. P_{M2} represents the bare minimum amount of power required from the motor (target threshold). Based on this value a selection is made (large diamond marked D1) to select the next higher size of motor available from a manufacturer's catalogue. If the motor has the capability of delivering power P_M (defined as the 'decided value'), then the margin for the motor can be calculated by comparing the target threshold and the decided value in a margin node (shown as a hexagon marked as E_1).

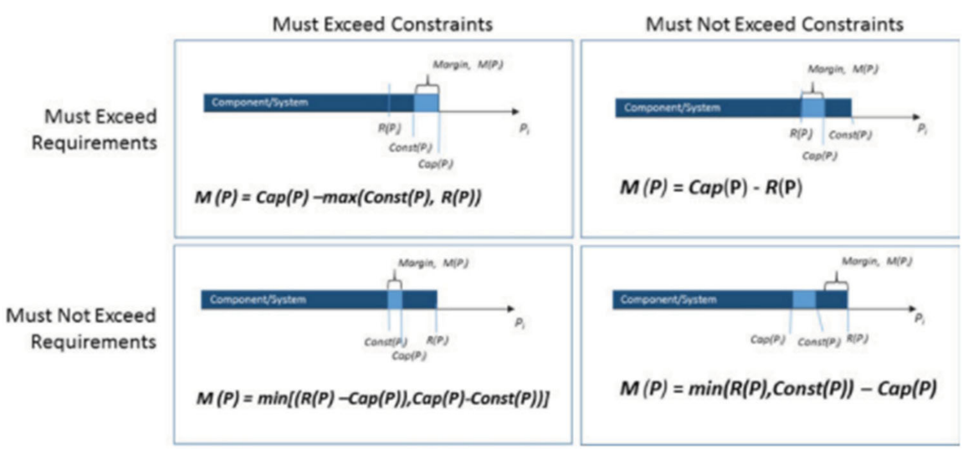


Figure 8. Mathematical formulation of margins as presented by Eckert, Isaksson, and Earl (2019). Margins are shown in light blue for various requirements and constraint conditions. Reproduced under a CC BY-NC-SA 4.0 licence.

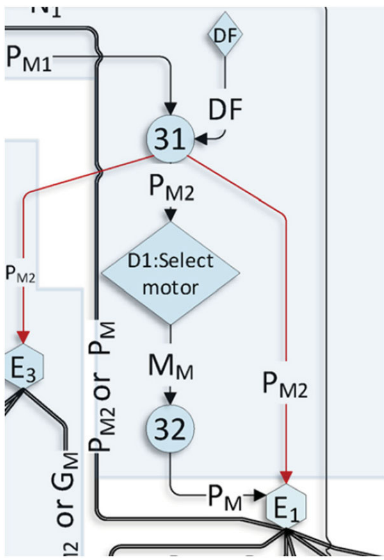


Figure 9. Extract from Brahma and Wynn (2020)'s margin analysis network of a belt conveyor design. The figure shows the selection of a motor and the margin node associated with it. Reproduced with permission from Springer Nature.

To allow a comparison between different potential solutions, the margin is calculated as a ratio unlike the absolute value proposed by Eckert et al. (2020).

$$Excess_m = \frac{decided_m - threshold_m}{threshold_m}$$

Cansler et al. (2016) also proposed a block-diagramming method for early design phases, which focuses on components and associated flows of signal, material, and energy. Component flow diagrams are used to identify interactions between components which are then used to quantify the current operating values and the tolerable upper limit. The difference

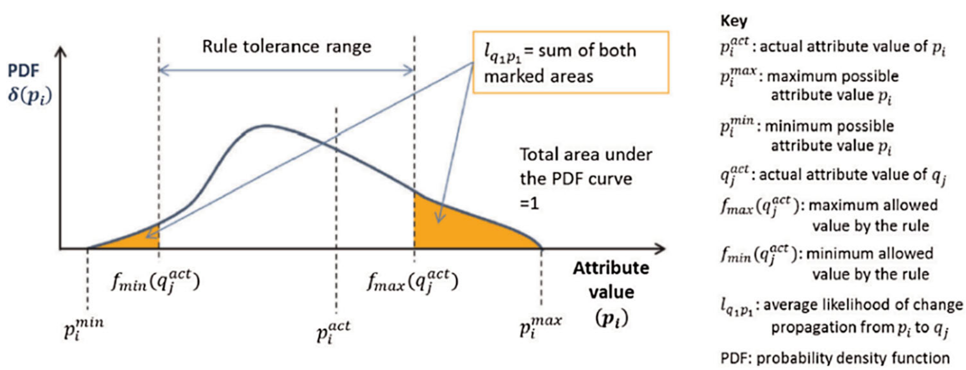


Figure 10. Definition of rule tolerance margin as presented by Hamraz et al. (2013). Reproduced based on STM guidelines.

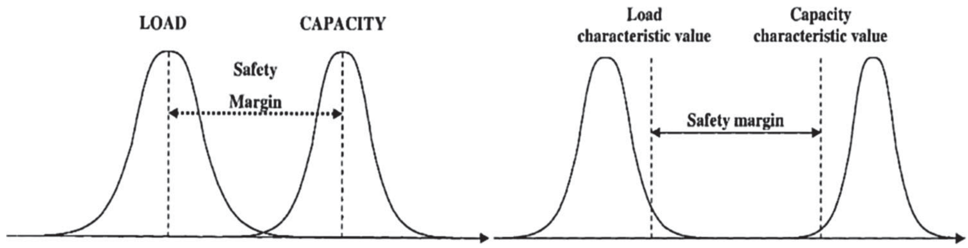


Figure 11. (Left) Definition of safety margin as presented by Pagani (2004). (Right) shows a more conservative interpretation. Reproduced under fair use permission from MIT Library.

Table 2. Generalised margin modelling techniques that accommodate various levels of architecture representation.

Publication	Technique for modelling margin
Pagani (2004)	As the difference between the median values of distributions corresponding to the capacity and actual load
Hamraz et al. (2013)	As probabilistic values by defining the lower and upper tolerance limits between attributes of the mating ports.
Cansler et al. (2016)	As values associated with the flow of signals, materials, and energy between component interfaces, supported by a block-diagramming method called a component flow diagram.
Eckert, Isaksson, and Earl (2019)	As a value by considering requirements, constraints, and capability in a mathematical formulation.
Brahma and Wynn (2020)	As a ratio by considering 'decided' and 'threshold' values whose values are supported by a visual dependency graph called the margin analysis network.

between the two can be used to analyse future changes and their effects on the overall system.

As previously discussed, margins also play an important role in the interfaces of a product's subsystems. In Hamraz et al. (2013)'s work on CPM, margins are modelled probabilistically in the interface as the lower and upper tolerance limits between attributes of the mating ports (Figure 10). Change propagates from one port to the other if the attribute value falls outside the predetermined range, i.e. the margin. Some researchers term the gradual absorption of changes until change propagation occurs as 'margin erosion' (Ariyo, Eckert, and Clarkson 2004). Probabilistic modelling of margins can also be found in fields such as reliability engineering. For instance, Pagani (2004) models margins as the difference between the median values of distributions corresponding to the capacity and actual load (Figure 11 left). They also suggested a more conservative interpretation (Figure 11 right) where the characteristic value of the load and the capacity are in the upper and lower percentiles of respectivetive distributions.

A summary of the generalised margin modelling techniques is presented in Table 2.

Methods of sizing margins

Several methods to size margins have since been developed which look at margins at a much more granular level of the design. If safety factors (safety margins) are considered, a single standardised method of determining suitable margins may not exist, as margins are contingent on the condition of use, regulatory requirements, life requirements etc. which vary from product to product (Brahma and Wynn 2020). Since a plethora of case-specific approaches exists, we only consider a few examples here:

- Pagani (2004) determines safety margins by calculating the probability of functional failure associated with them in nuclear plants.
- Ghosn and Moses (1986) used field measurement datasets to project the maximum loading a bridge would experience in a lifetime. They use statistical methods on the data to derive suitable design margins and associated design recommendations.
- Mohammed et al. (2016) quantify the safety margins in a ship hull design starting with a probabilistic analysis of the most extreme combined loads due to waves the structure might experience. They then establish the margin of safety by comparing the load-carrying capacity of the structure with the ultimate capacity.
- Collins, Busby, and Staab (2009) compiled a list of eight factors which must be considered individually for every use case, which Iorga, Desrochers, and Smeesters (2012) rate according to the risk from uncertainty and severity of outcome to develop a formula for estimating appropriate safety factors.

Stochastic approaches are used to determine appropriate safety factors by calculating the intersection of probabilities relating to use and failure (Peng and Li 2021) use. High intersection indicates the need for larger margins to ensure that the probability of failure remains below acceptable levels (Juvinall and Marshek 1991). Factors of Safety (FoS) appear in codes and standards. These can be very broad; e.g. ASME B31.3 stipulating all pressure piping to be designed to sustain 1.5 times the design pressure in testing (Becht 2009), or very specific; such as requirements of appropriate corrosion allowances to be added to process pipes (API 1991). The recommendations are often developed based on empirical evidence and tend to be conservative (often leading to overdesign) as they are often specified for a generalised use and do consider specific conditions (Levine and Hawkins 1970; Snape et al. 2005).

In Quantification of Margins and Uncertainty (QMU) in reliability engineering, margins in a design are related to the uncertainty absorption capability in parameters (Shah, Hosder, and Winter 2015). QMU was first developed as a framework to assess the risks and reliabilities of nuclear weapon stockpiles and has since been applied to other complex systems (Wallstrom 2011). Similar to design for changeability (Martin and Ishii 2002), QMU first identifies and quantifies sources of uncertainty, which are then propagated through a modelled system to determine whether the margins are enough to prevent failure (Helton 2011; Pilch, Trucano, and Helton 2011). This enables the comparison of the system's response under uncertainties against the expected or required performance (Urbina, Mahadevan, and Paez 2011). Some methods in QMU also suggest the calculation of a confidence metric which is the ratio of the available margin and the uncertainties (Pepin, Rutherford, and Hemez 2008). A confidence metric greater than 1 shows safe and reliable conditions (Shah, Hosder, and Winter 2015).

Multi-disciplinary optimisation (MDO) has also been used significantly in sizing and allocating margins. Takamatsu, Hashimoto, and Shioya (1974) consider in the context of chemical design multiple design parameters for margin allocation while optimising the system's performance objective. They assume the uncertain parameters to be continuous but

Table 3. Margin sizing techniques developed for specific design scenarios.

Publication	Method for establishing margin size
Ghosn and Moses (1986)	Bridge maximum loading projections based on statistical methods informed by field measurement datasets.
Pagani (2004)	Functional failure probability calculation for nuclear plants.
Collins, Busby, and Staab (2009)	A list of eight factors for each use case.
Wallstrom (2011), Helton (2011), Pilch, Trucano, and Helton (2011), Urbina, Mahadevan, and Paez (2011), Shah, Hosder, and Winter (2015)	Quantification of Margins and Uncertainty (QMU) framework based on risks so that system response can be compared against expected/required performance. The original context was the reliability of nuclear weapon stockpiles.
Iorga, Desrochers, and Smeesters (2012)	Modelling the risk caused by uncertainty and the severity of outcome.
Mohammed et al. (2016)	Extreme combined structural loads calculated by considering waves.
Peng and Li (2021)	Calculation of probability intersection when considering use and failure.

bounded variables without a specified distribution, The performance parameters are modelled as first-order linear approximations around their nominal values; and each constraint is evaluated. This method was further advanced by Dittmar and Hartmann (1976) to consider non-linear systems. An MDO-based case study of a hybrid engine considered margins along with the performance objectives. The MDO traded off design performance requirements against individual component performance capabilities and showed that robust designs can be achieved by adding additional margins while only suffering slight deterioration in the performance (Tan 2017; Tan, Otto, and Wood 2016). Bianchi et al. (2018) aimed to maximise the probability of constraint satisfaction while using uncertainty quantification and optimisation techniques. The authors traded the 'cost of uncertainty' off against the 'price of reliability' and demonstrate that empirically derived safety factors may be uncompetitive and produce overly conservative designs.

The examples provided in Table 3 describe advances for specific design scenarios.

Margin allocation

Margins are either allocated based on past experience (e.g. Wisch (2006); Meyer (2002); Meyer and Whitcomb (2004)), or an a-priori analysis of uncertainties to obtain a probability distribution function (PDF) (Chen 2017). Thunnissen (2004) see margins as a response to risk, which is measured against the mean system performance. The method starts with an identification of tradable system-level parameters from three categories: those under the engineer's control, those beyond their control and predetermined requirements. Multicriteria selection is used to generate probability distributions for the tradable parameters. The method then compares the results with the required risk tolerances to determine the available margins in the design.

Zang et al. (2015) start by allocating margins first to sizing and performance parameters. Then probabilities of success are calculated based on constraint satisfaction. The target probability of success can then be manipulated by considering trade-offs against performance indicators such as Take-Off Gross Weight. Strategies to do such trade-off studies could include exploration of large design spaces and then down-selecting based on sets of margin performance combinations (Cooke et al. 2015).

Guenov et al. (2018) introduce a concept analogous to design space called margin space to trade margins against various design parameters. The method requires the creation of a network of parameters and their interaction augmented by PDFs which represent the uncertainty, absorbed by the allocation of margins. Similar to constraints in design space

Table 4. Problem formulation strategies for margin allocation.

Publication	Performance objective
From a robustness perspective:	
Takamatsu, Hashimoto, and Shioya (1974)	Minimising the deviation of a performance index within a limit of output variable deviation.
Dittmar and Hartmann (1976)	
Thunnissen (2004)	Mean system performance within defined risk tolerances.
Guenov et al. (2018)	Trade-off between design performance and robustness
From a performance trade-off perspective:	
Dec and Mitcheltree (2002)	Optimisation using Monte-Carlo approaches
Molina and Finzi (2006)	
Tan (2017)	Trade-off between design performance requirements and individual component performance capabilities.
From a constraint satisfaction perspective:	
Zang et al. (2015)	Probabilities of success based on constraint satisfaction.
Bianchi et al. (2018)	Maximising the probability of constraint satisfaction by trading off 'cost of uncertainty' against the 'price of reliability'
From a decision-support perspective:	
Cooke et al. (2015)	Down-selection using sets of margin performance combinations.
Brahma and Wynn (2020)	Three metrics that define a node's margin, the impact on performance, and the ability of each node to absorb change.

exploration, constraints are used to determine the regions of the margin space which are feasible. A design of experiments-based methods then generates combinations of design parameters and margins, which are then used to trade-off design performance and robustness against the given uncertainties. The inputs can be specified by the user and the outputs, which relate to the performance of the system can be explored through parallel coordinates plot. The margin value method (MVM) by Brahma and Wynn (2020) requires the modelling of the decisions. The method then requires the calculation of three metrics i.e. (a) the local excess margin which is the quantity of margin in each margin node (b) the impact, which calculates the deteriorating impact each margin node has on the performance parameters and (c) absorption, which calculates the ability of each margin node to absorb changes in the specification parameters such that the overall design does not change i.e. the change does not propagate.

Monte-Carlo simulation-based approaches can also be used to size margins. For instance, Molina and Finzi (2006), show how reduced multicriteria selection (MCS) models can also produce accurate margin quantification instead of using detailed models which may be computationally intensive to run. Dec and Mitcheltree (2002) describe an MCS to calculate the thickness margin required to handle the uncertainties, which they demonstrate to be significantly less than the traditional worst-case approach.

To summarise, researchers have proposed different problem formulation perspectives, covering robustness, system and component performance, constraint satisfaction, and decision-support, as shown in Table 4.

Discussion

While the concept of margin is not new, the lack of a unified view has resulted in the parallel development of margin concepts. The concept of margin is a fundamental and overarching concept which can be (and has been) applied to many fields, through various topics. Figures 3 and 7, for instance support this argument and present two ways of looking at such topics through the 'lens of margins'. In contextual domains where margins have been defined and community-based formalisation has occurred (Safety regulations, tolerances, etc), margins are widely adopted and used in practice. Understanding, managing and actively designing with margins helps ensure functionality, manufacturability, and performance. Further, the economic incentives for effective margin management are significant. The review of literature presented above describes how margins are used to manage uncertainty, either by intent (deliberate) or by discovery (by investigation). It is further recognised that once margins have been defined, mathematical modelling and problem-formation strategies for margin allocation are enabled. Yet, this review also highlights how the definitions proposed and used for margins differ within (and across) communities.

A common element across all work is the acknowledgement that margins need to be documented, modelled and systematically managed. Perhaps more importantly, and not always described in the literature, is that the need for margin must also be systematically captured. Such documentation is necessary for planning, life cycle support and upgrades, and setting acceptance levels for suppliers. Documentation also helps designers capture and manage their experience with designing the system and describing how they envision possible future states of the system.

Designers would benefit from tracking margins throughout the product life cycle to understand whether a design can be used to meet different requirements, can be changed or can be a starting point for the next product generation. Formalised documentation would also enable designers to record critical margins and stop others from adding their own margins in haphazard (and perhaps duplicative) ways. Cues could arguably be taken from fields such as requirements management or tolerance management, which have had significant advances.

Many domains and areas of engineering design research leverage the notion of margins without systematically or formally acknowledging the term. Relevant research at different levels of maturity and acceptance where margins play a role is highlighted in Figure 12. The observations are based on reviewing notable works on the topics. For instance, Safety

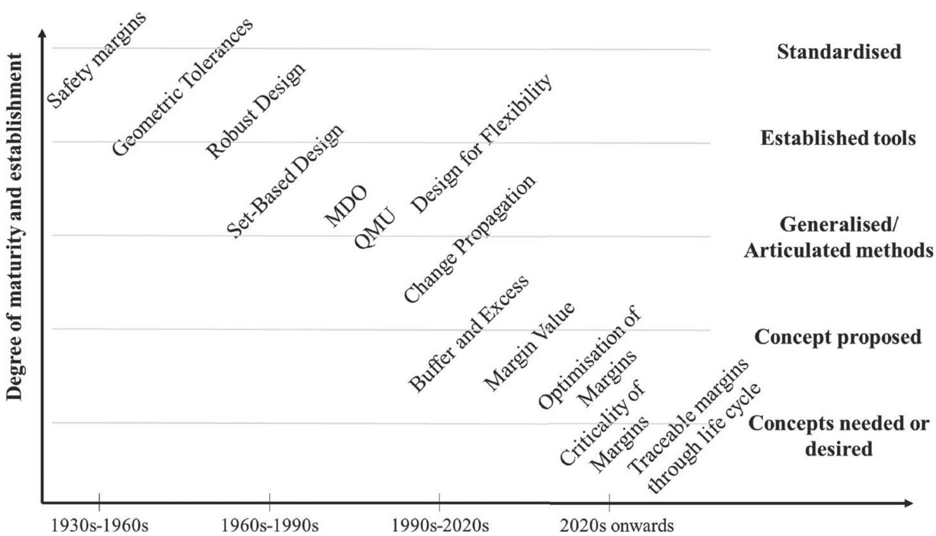


Figure 12. The establishment of selected design margin concepts.

margins, in particular, have been developed to a high degree of maturity over the past 90 years. This is visible from the large number of design and operational standards in the field. Similarly, tolerances and robust design have been researched since the 1940s and 1950s respectively (Taguchi and Phadke 1989; Wilks 1941). Other topics such as set-based design (Ward et al. 1994) and MDO (Sobieszczanski-Sobieski 1995; Martins and Lambe 2013) saw an uptake in the 1980s and the 1990s and now have established tools and well-articulated methods. Some other fields emerged in the early 2000s such as Design for Flexibility (Saleh et al. 2003; Rajan et al. 2003) and Change Propagation Analysis (Clarkson, Simons, and Eckert 2004) are well established in the academic literature, but still wait to be embraced at a large scale by industry. Other ideas are new and emerging concepts.

Several research gaps remain, particularly when margins are considered at the system level:

- Margins at multiple levels of hierarchy: The margin of a system is often that of its most optimised component. Yet, other components within the system each have their own margins (of which some may be quite large). The hierarchy of margins is not well understood, and there is likely hidden excess in each component that could be repurposed. Further, as different levels in a product hierarchy are often owned by different organisations, a shared conception of margins and the ability to communicate margins across organisational boundaries is necessary.
- Margins across interfaces: Designers often work within silos bound by the interface definitions within a system. This leads to 'margin hogging' where designers may build in the largest possible margins for themselves rather than systematically resolving issues. This may lead to margins being added by different people to the same parameter. Changes in organisational culture are needed and must be supported by advancements in engineering design tools so that decisions about different parts of a system can be traded off.
- Tracing margins across the product life cycle: As requirements change through the design process, the resulting margins also change. These could be traced and visualised systematically, and critical margins could be flagged. The ultimate goal becomes a complete modelling of margins. In this environment, margins could be shown in the product specifications (such as CAD) so that designers can make informed decisions.
- Margin identification and consumption during design modifications: Designers tasked with modifying a system are likely not the original designers of the system architecture. Modifying a system in ways that minimise change propagation requires the identification of margins that exist, and that can be consumed, during a redesign. Currently, there is minimal understanding of how humans engaged in the act of designing to identify whether margins are present or how they make use of the margins that are present.
- Unified understanding of margins: As new technologies, often from different domains, need to be integrated into a product architecture the communication of margins becomes challenging. There is a need for formalised, generic representations of margins for system functionality that are understandable by (and communicable to) product developers from different domains.

A systematic treatment of margins has the potential to impact many areas of engineering. An exhaustive discussion goes beyond the scope of this review paper, however,

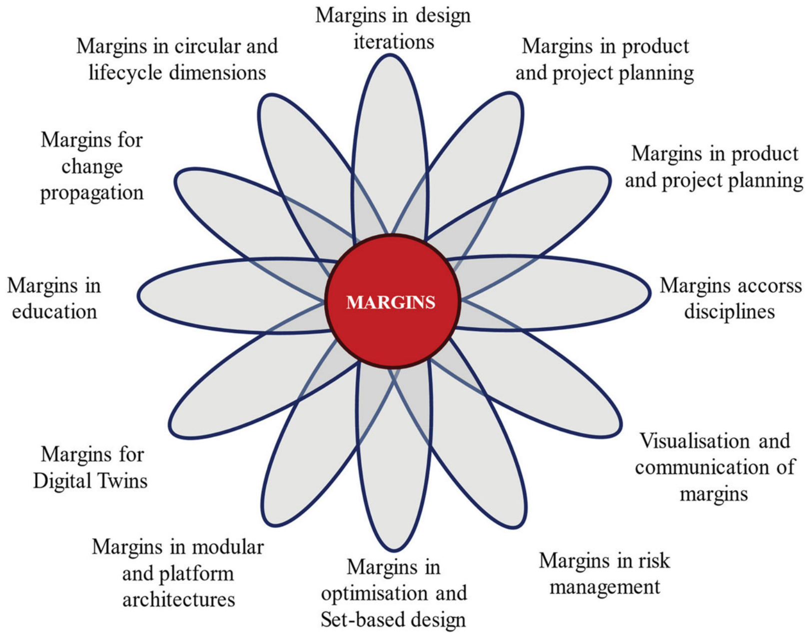


Figure 13. Potential areas of application of margins.

Figure 13 indicates the possibilities. For example, it can be argued that margin allocation is inherently linked to design optimisation. New methods are required to optimise the margins on parameters rather than only the parameters themselves. Similarly, methods that systematically capture the hidden excess in platform components can have profound effects on the way product platforms are designed and evolved.

Well-formulated and generalised representations of margins across product architecture hierarchies will allow for the systematic development of design tools that enable margin modelling, simulation, visualisation and communication. Such generalised models are likely to be generic, and to some extent abstract, meaning that they still need to be contextualised. The advantage is that a generalised representation of margins would enable general-purpose support tools that would be beneficial in vastly different contexts. Introducing general margins theory and representation in engineering curricula would further enable synergies.

Concluding remarks

Margins in design is an important topic which influences multiple aspects of engineering design. Margins as a concept have been used by designers for a very long time, much of which however has been based on an intuitive understanding. Practitioners have used a variety of terms to describe different aspects of margins However, most research on margins is being done in isolation and is topic specific. This paper has touched upon various topics surrounding the product development process and shows how the underlying principles fundamentally relate to design margins. The paper also discusses various approaches being developed to size and model margins which reflect the state of the art in the field.

Given that modern products span a range of technological areas and have significant influences from uncertain customer needs, and financial and legislative uncertainties, methods and tools have to be developed from a holistic perspective for them to be of utility. As societal and industrial development address domain (topic) bridging problems, such as sustainable development, or co-designing products and systems that rely on digital and physical infrastructure synergies, the necessity to share the understanding of margins across domains is likely to gain increasing attention.

Note

1. Design basis accident as defined by the U.S. NRC: 'A postulated accident that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to ensure public health and safety.' Design-basis Accident | NRC.gov.

Acknowledgements

We acknowledge the support from Area of Advance at Chalmers for partially funding this project. The authors also wish to extend their sincere appreciation to all the participants of the two workshops held in May and June 2022, who shared their expertise and experience on the topic with us.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Arindam Brahma http://orcid.org/0000-0003-0365-0394
Claudia Eckert http://orcid.org/0000-0002-2201-3828
Ola Isaksson http://orcid.org/0000-0003-0373-3720

References

Ahn, J., and Jang-Hyuk Kwon. 2006. "An Efficient Strategy for Reliability-Based Multidisciplinary Design Optimization Using BLISS." *Structural and Multidisciplinary Optimization* 31 (5): 363–372. https://doi.org/10.1007/s00158-005-0565-6.

Al Handawi, Khalil, Petter Andersson, Massimo Panarotto, Ola Isaksson, and Michael Kokkolaras. 2021. "Scalable Set-Based Design Optimization and Remanufacturing for Meeting Changing Requirements." *Journal of Mechanical Design* 143:2. https://doi.org/10.1115/1.4047908.

Al Handawi, Khalil, Massimo Panarotto, Petter Andersson, Ola Isaksson, and Michael Kokkolaras. 2021a. "Optimal Allocation of Design Margins in Additive Remanufacturing." *Paper Presented at the ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*.

Al Handawi, Khalil, Massimo Panarotto, Petter Andersson, Ola Isaksson, and Michael Kokkolaras. 2022. "Optimization of Design Margins Allocation When Making Use of Additive Remanufacturing." *Journal of Mechanical Design* 144: 1. https://doi.org/10.1115/1.4051607.

Allen, Jeffrey D, Phillip D Stevenson, Christopher A Mattson, and Nile W Hatch. 2019. "Over-Design Versus Redesign as a Response to Future Requirements." *Journal of Mechanical Design* 141 (3): 031101. https://doi.org/10.1115/1.4042335.

API. 1991. *Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems (RP14E)*. Americal Petrochemical Institute.

Apostolakis, G. E. 2004. "How Useful is Quantitative Risk Assessment?" *Risk Analysis* 24 (3): 515–520. https://doi.org/10.1111/j.0272-4332.2004.00455.x.

Ariyo, O. O., C. M. Eckert, and P. J. Clarkson. 2004. "Tolcerance Margins as Constraining Factors of Changes in Complex Products." *Paper Presented at the IPD 2004, Proceedings of the 5th Workshop on Integrated Product Development, Magdeburg, Germany, 22–24 Sep 2004*.

ASME. 2018. *Dimensioning and Tolerancing*. New York: ASME.

Baldwin, Carliss Y., and Kim B. Clark. 2000. *Design Rules: The Power of Modularity*. Cambridge: MIT Press.

Becht, I. V. Charles. 2009. *Pressure Testing*. New York: ASME. doi:10.1115/1.802861.ch14.

Bianchi, Davi, Tarik H. Orra, Carlos Silva, and Flavio J. Silvestre. 2018. "Optimization Under Uncertainty: Rethinking Margins at the Conceptual Design." *Paper Presented at the 2018, Multidisciplinary Analysis and Optimization Conference, Atlanta, Georgia, USA, 25–29 June, 2018*.

Birolini, Alessandro. 2014. *Reliability Engineering*. Berlin: Springer Nature.

Blackenfelt, Michael, and Ulf Sellgren. 2000. "Design of Robust Interfaces in Modular Products." *Paper Presented at the ASME 2000, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Baltimore, Maryland, USA, September 10–13, 2000*.

Bocken, Nancy M. P., Ingrid de Pauw, Conny Bakker, and Bram van der Grinten. 2016. "Product Design and Business Model Strategies for a Circular Economy." *Journal of Industrial and Production Engineering* 33 (5): 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Boyack, B. E., I. Catton, R. B. Duffey, P. Griffith, K. R. Katsma, G. S. Lellouche, S. Levy, et al. 1990. "Quantifying Reactor Safety Margins Part 1: An Overview of the Code Scaling, Applicability, and Uncertainty Evaluation Methodology." *Nuclear Engineering and Design* 119 (1): 1–15. https://doi.org/10.1016/0029-5493(90)90071-5.

Brahma, Arindam. 2020. *Engineering Design Change Propagation and its Mitigation Using Margins*. University of Auckland. http://hdl.handle.net/2292/53413.

Brahma, A., and D. C. Wynn. 2020. "Margin Value Method for Engineering Design Improvement." *Research in Engineering Design* 31 (3): 353–381. https://doi.org/10.1007/s00163-020-00335-8.

Brahma, A., and D. C. Wynn. 2021. "A Study on the Mechanisms of Change Propagation in Mechanical Design." *Journal of Mechanical Design* 143 (12): 121401. https://doi.org/10.1115/1.4050927.

Brahma, Arindam, and David C. Wynn. 2023. "Concepts of Change Propagation Analysis in Engineering Design." *Research in Engineering Design* 34 (1). https://doi.org/10.1007/s00163-022-00395-y

Brahma, A., D. C. Wynn, and O. Isaksson. 2022. "Use of Margin to Absorb Variation in Design Specifications: An Analysis Using the Margin Value Method." *Proceedings of the Design Society* 2: 323–332. https://doi.org/10.1017/pds.2022.34.

Brinkmann, J. T., and David C Wynn. 2020. "Assessing, Aggregating and Visualising Preliminary Design Information Maturity to Support Collaborative Design." *Proceedings of the Design Society: DESIGN Conference* 1: 1225–1234. https://doi.org/10.1017/dsd.2020.65.

Cansler, E. Z., S. B. White, S. M. Ferguson, and C. A. Mattson. 2016. "Excess Identification and Mapping in Engineered Systems." *Journal of Mechanical Design* 138 (8): 081103. https://doi.org/10.1115/1.4033884.

Cao, Y. L., T. Liu, and J. X. Yang. 2018. "A Comprehensive Review of Tolerance Analysis Models." *The International Journal of Advanced Manufacturing Technology* 97 (5-8): 3055–3085. https://doi.org/10.1007/s00170-018-1920-2.

Chen, Xin. 2017. "Enablers for Uncertainty Quantification and Management in Early Stage Computational Design. An Aircraft Perspective." http://dspace.lib.cranfield.ac.uk/handle/1826/14328.

Chen, Chih-Chun, and Nathan Crilly. 2014. "Modularity, Redundancy and Degeneracy: Cross-Domain Perspectives on Key Design Principles." *Paper Presented at the 2014, IEEE International Systems Conference Proceedings, Ottawa, ON, Canada, 31 March 2014–03 April 2014*.

Chua, D. K. H., and M. A. Hossain. 2012. "Predicting Change Propagation and Impact on Design Schedule Due to External Changes." *IEEE Transactions on Engineering Management* 59 (3): 483–493. https://doi.org/10.1109/TEM.2011.2164082.

Cimino, Dominick, and C. Filiopoulos. 1997. "Weight and KG Margin Analysis of Naval Surface Ships." *Paper Presented at the SAWE 56th annual conference, Bellevue, Washington, USA, May 19–21, 1997*.

Clarkson, P. J., C. Simons, and C. Eckert. 2004. "Predicting Change Propagation in Complex Design." *Journal of Mechanical Design* 126 (5): 788–797. https://doi.org/10.1115/1.1765117.

Collins, J. A., H. R. Busby, and G. H. Staab. 2009. *Mechanical Design of Machine Elements and Machines: A Failure Prevention Perspective*. Hoboken, NJ: John Wiley & Sons.

Coman, A., and B. Ronen. 2010. “Icarus’ Predicament: Managing the Pathologies of Overspecification and Overdesign.” *International Journal of Project Management* 28 (3): 237–244. https://doi.org/10.1016/j.ijproman.2009.05.001.

Cooke, Roger M, Thomas A Zang, Dimitri N Mavris, and Jimmy C Tai. 2015. “Sculpting: A Fast, Interactive Method for Probabilistic Design Space Exploration and Margin Allocation.” *Paper Presented at the, 16t. h AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Dallas, TX, USA, 22–26 June 2015*.

Dawson, Benjamin, Sebastian K. Fixson, and Daniel Whitney. 2012. “Orchestrating Coordination: Reducing Rework in Complex Product Development.” *Technology, Operations & Information Management Working Papers Paper 4*.

de Bélidor, Bernard Forest. 1729. *La Science des Ingénieurs Dans la Conduite des Travaux de Fortification et D’Architecture Civile*. Paris: https://gallica.bnf.fr/ark:/12148/bpt6k856819.image.

Dec, John, and R. Mitcheltree. 2002. “Probabilistic Design of a Mars Sample Return Earth Entry Vehicle Thermal Protection System.” *Paper Presented at the 40th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, USA, 14–17 Jan 2002*.

del Rosario, Zachary. 2020. “Precision Margin: First-principles Margins for Aircraft Design Under Uncertainty.” Ph.D., Stanford University. https://purl.stanford.edu/xy114jv5352.

Der Kiureghian, Armen, and Ove Ditlevsen. 2009. *Aleatory or Epistemic? Does it Matter?*. https://doi.org/10.1016/j.strusafe.2008.06.020.

De Santis, Stefano, and Gianmarco de Felice. 2014. “Overview of Railway Masonry Bridges with a Safety Factor Estimate.” *International Journal of Architectural Heritage* 8 (3): 452–474. https://doi.org/10.1080/15583058.2013.826298.

De Weck, Olivier, Claudia M Eckert, and P. John Clarkson. 2007. “A Classification of Uncertainty for Early Product and System Design.” *Paper Presented at the DS 42: Proceedings of ICED 2007, the 16th International Conference on Engineering Design, Paris, France, 28-31 July 2007*.

Dittmar, R., and K. Hartmann. 1976. “Calculation of Optimal Design Margins for Compensation of Parameter Uncertainty.” *Chemical Engineering Science* 31 (7): 563–568. https://doi.org/10.1016/0009-2509(76)80019-X.

Durand, James, Cassandra Telenko, and Carolyn Seepersad. 2010. “How Does Modularity Affect Green Design?” *Paper Presented at the ASME 2010), International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, ontreal, Quebec, Canada, August 15–18, 2010*.

Earl, Chris, Jeffrey Johnson, and Claudia Eckert. 2005. “Complexity.” In *Design Process Improvement: A Review of Current Practice*, edited by John Clarkson, and Claudia Eckert, 174–197. London: Springer London.

Eckert, C., P. J. Clarkson, and W. Zanker. 2004. “Change and Customisation in Complex Engineering Domains.” *Research in Engineering Design* 15 (1): 1–21. https://doi.org/10.1007/s00163-003-0031-7.

Eckert, C., and O. Isaksson. 2017. “Safety Margins and Design Margins: A Differentiation Between Interconnected Concepts.” *Procedia CIRP* 60: 267–272. https://doi.org/10.1016/j.procir.2017.03.140.

Eckert, Claudia, Ola Isaksson, and Christopher Earl. 2012. “Product Property Margins: An Underlying Critical Problem of Engineering Design.” *Paper Presented at the Proceedings of TMCE 2012, Karlsrube, Germany, 2012/05*.

Eckert, Claudia M., Ola Isaksson, and Chris F. Earl. 2014. “Design Margins as a Key to Understanding Design Iteration.” *Paper Presented at the ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Buffalo, New York, USA, August 17–20, 2014*.

Eckert, C., O. Isaksson, and C. Earl. 2019. “Design Margins: A Hidden Issue in Industry.” *Design Science* 5 (1): e9. https://doi.org/10.1017/dsj.2019.7.

Eckert, C., O. Isaksson, S. Lebjioui, C. F. Earl, and S. Edlund. 2020. “Design Margins in Industrial Practice.” *Design Science* 6 (1): e30. https://doi.org/10.1017/dsj.2020.19.

Elishakoff, Isaac. 2017. *Probabilistic Methods in the Theory of Structures: Strength of Materials, Random Vibrations, and Random Buckling*. New York: World Scientific.

Erens, F., and K. Verhulst. 1997. “Architectures for Product Families.” *Computers in Industry* 33 (2-3): 165–178. https://doi.org/10.1016/S0166-3615(97)00022-5.

Fenton-O'Creevy, Mark, and David Tuckett. 2022. "Selecting Futures: The Role of Conviction, Narratives, Ambivalence, and Constructive Doubt." *Futures & Foresight Science* 4 (3-4): e111. https://doi.org/10.1002/ffo2.111.

Fernández, Iñigo Alonso, Massimo Panarotto, and Ola Isaksson. 2022. "Designing Multi-Technological Resilient Objects in Product Platforms." *Paper Presented at the DS 118: Proceedings of NordDesign 2022, Copenhagen, Denmark, 16th–18th August 2022*.

Fisher, Wayne R, Michael F Doherty, and James M Douglas. 1985. "Effect of Overdesign on the Operability of Distillation Columns." *Industrial & Engineering Chemistry Process Design and Development* 24 (3): 593–598. https://doi.org/10.1021/i200030a013.

Fisher, M., K. Ramdas, and K. Ulrich. 1999. "Component Sharing in the Management of Product Variety: A Study of Automotive Braking Systems." *Management Science* 45 (3): 297–315. https://doi.org/10.1287/mnsc.45.3.297.

Gale, Peter A. 1975. "Margins in Naval Surface Ship Design." *Naval Engineers Journal* 87 (2): 174–188. https://doi.org/10.1111/j.1559-3584.1975.tb03728.x.

Garbatov, Yordan, and C. Guedes Soares. 2018. "Corrosion Margins for Redundant Ship Structures." *Paper Presented at the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, Madrid, Spain, June 17–22, 2018*.

Ghosn, M., and F. Moses. 1986. "Reliability Calibration of Bridge Design Code." *Journal of Structural Engineering* 112 (4): 745–763. https://doi.org/10.1061/(ASCE)0733-9445(1986)112:4(745).

Gil, N., I. D. Tommelein, A. Stout, and T. Garrett. 2005. "Embodying Product and Process Flexibility to Cope with Challenging Project Deliveries." *Journal of Construction Engineering and Management* 131 (4): 439–448. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:4(439).

Gimenez, M., M. Schlamp, and A. Vertullo. 2002. "Uncertainties Assessment for Safety Margins Evaluation in MTR Reactors Core Thermal-Hydraulic Design."

Grebici, K., Y. M. Goh, and C. McMahon. 2008. "Uncertainty and Risk Reduction in Engineering Design Embodiment Processes." *DS 48: Proceedings DESIGN 2008, the 10th International Design Conference, Dubrovnik, Croatia*.

Grover, Myron R. 2021. "A Methodology for Determination of Entry, Descent, and Landing Design Performance Margins of Spacecraft Landing on Planetary Bodies." Ph.D., University of Washington. http://hdl.handle.net/1773/47911.

Guenov, M. D., X. Chen, A. Molina-Cristobal, A. Riaz, A. S. J. van Heerde, and M. Padulo. 2018. "Margin Allocation and Tradeoff in Complex Systems Design and Optimization." *AIAA Journal* 56 (7): 2887–2902. https://doi.org/10.2514/1.J056357.

Hammer, Willie. 1980. *Product safety management and engineering*. Englewood Cliffs, NJ: Prentice-Hall.

Hamraz, B., O. Hisarciklilar, K. Rahmani, D. C. Wynn, V. Thomson, and P. J. Clarkson. 2013. "Change Prediction Using Interface Data." *Concurrent Engineering* 21 (2): 141–154. https://doi.org/10.1177/1063293X13482473.

Hastings, Daniel, and Hugh McManus. 2004. "A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems." *Paper Presented at the 2004 Engineering Systems Symposium*.

Hein, Maria, Darren Anthony Jones, and Claudia Margot Eckert. 2021. "Understanding the Embedded Carbon Challenges of Building Service Systems." *Paper Presented at the Proceedings of the Design Society*.

Helton, J. C. 2011. "Quantification of Margins and Uncertainties: Conceptual and Computational Basis." *Reliability Engineering & System Safety* 96 (9): 976–1013. https://doi.org/10.1016/j.ress.2011.03.017.

Hockberger, William A. 1976. "Ship Design Margins-Issues and Impacts." *Naval Engineers Journal* 88 (2): 157–170. https://doi.org/10.1111/j.1559-3584.1976.tb03821.x.

IAEA. 2003. *Safety Margins of Operating Reactors Analysis of Uncertainties and Implications for Decision Making*. Vienna: International Atomic Energy Agency.

Iorga, Cristian, Alain Desrochers, and Cecile Smeesters. 2012. "Engineering Design from a Safety Perspective." Paper Presented at the 2012: Proceedings of the Canadian Engineering Education Association Conference, University of Manitoba, Winnipeg, Canada, 2012.

Isaksson, Ola, Peter Lindroth, and Claudia M Eckert. 2014. "Optimisation of Products Versus Optimisation of Product Platforms: An Engineering Change Margin Perspective." *Paper Presented at the DS 77: Proceedings of the DESIGN 2014 13th International Design Conference*.

Jones, D., and C. Eckert. 2017a. "Overdesign in Building Services: The Hidden Energy Use." Paper Presented at the Ds, 87–1. Proceedings of the 21st International Conference on Engineering Design (Iced 17), Vol 1: Resource Sensitive Design, Design Research Applications and Case Studies.

Jones, Darren, and Claudia Eckert. 2017b. "Overdesign in Building Services: The Hidden Energy Use." Paper Presented at the DS, 87–1. Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 1: Resource Sensitive Design, Design Research Applications and Case Studies, Vancouver, Canada, 21–25 Aug 2017.

Jones, Darren Anthony, and Claudia Margot Eckert. 2019. "Empowering Decision Makers to Avoid the Oversizing of Building Service Systems." *Paper Presented at the Proceedings of the Design Society: International Conference on Engineering Design*.

Jones, Darren Anthony, Claudia Eckert, and Pam Garthwaite. 2020. "Managing Margins: Overdesign in Hospital Building Services." *Paper Presented at the Proceedings of the Design Society: DESIGN Conference*.

Jones, Darren Anthony, Claudia Margot Eckert, and Kilian Gericke. 2018. "Margins Leading to Over-Capacity." *Paper Presented at the DS 92: Proceedings of the DESIGN 2018 15th International Design Conference, Dubrovnik, Croatia, 2018*.

Juvinall, R. C., and K. M. Marshek. 1991. *Fundamentals of machine component design*. New York, NY: John Wiley & Sons.

Kamrad, B., G. Schmidt, and S. Ulku. 2017. "In Pursuit of Product Modularity: Impediments and Stimulants." *California Management Review* 59 (4): 97–113. https://doi.org/10.1177/0008125617722793.

Kang, R., Q. Y. Zhang, Z. G. Zeng, Z. Enrico, and X. Y. Li. 2016. "Measuring Reliability Under Epistemic Uncertainty: Review on non-Probabilistic Reliability Metrics." *Chinese Journal of Aeronautics* 29 (3): 571–579. https://doi.org/10.1016/j.cja.2016.04.004.

Kay, John Anderson, and Mervyn A King. 2020. *Radical Uncertainty*: Bridge Street Press Decision-Making Beyond the Numbers.

Krishnan, V., and S. Gupta. 2001. "Appropriateness and Impact of Platform-Based Product Development." *Management Science* 47 (1): 52–68. https://doi.org/10.1287/mnsc.47.1.52.10665.

Lebjioui, Safaa. 2018. "Investigating and Managing Design Margins throughout the Product Development Process." The Open University. https://oro.open.ac.uk/56663/.

Lee, W. J., and T. C. Woo. 1990. "Tolerances: Their Analysis and Synthesis." *Journal of Engineering for Industry* 112 (2): 113–121. https://doi.org/10.1115/1.2899553.

Levine, G., and S. Hawkins. 1970. "Comments on Service Margins for Ships." *Naval Engineers Journal* 82 (5): 75. https://doi.org/10.1111/j.1559-3584.1970.tb04362.x.

Long, Daniel, and Scott Ferguson. 2019. "An Excess Based Approach to Change Propagation." *Paper Presented at the ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*.

Lusser, R. 1958. "Reliability Through Safety Margins."

Martin, Mark V., and Kosuke Ishii. 2002. "Design for Variety: Developing Standardized and Modularized Product Platform Architectures." *Research in Engineering Design* 13 (4): 213–235. https://doi.org/10.1007/s00163-002-0020-2.

Martins, Joaquim R. R. A., and Andrew B. Lambe. 2013. "Multidisciplinary Design Optimization: A Survey of Architectures." *AIAA Journal* 51 (9): 2049–2075. https://doi.org/10.2514/1.J051895.

Mattson, Christopher A, and Carl D Sorensen. 2020. *Product Development: Principles and Tools for Creating Desirable and Transferable Designs*. Cham: Springer Nature.

McPherson, J., and E. Ogawa. 2008. "Reliability Physics and Engineering." In *Handbook of Semiconductor Manufacturing Technology*, edited by Y. Nishi, and R. Doering, 30–31. Boca Raton, FL: CRC Press.

Meyer, Jan. 2002. *A Risk-Based Approach to Optimal Margins in Ship Design*. Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/91373.

Meyer, Jan, and Clifford A Whitcomb. 2004. "Numerical Method for Design Margin Selection." *Journal of Ship Production* 20 (01): 24–42. https://doi.org/10.5957/jsp.2004.20.1.24.

Mohammed, E. A., S. D. Benson, S. E. Hirdaris, and R. S. Dow. 2016. "Design Safety Margin of a 10,000 TEU Container Ship Through Ultimate Hull Girder Load Combination Analysis." *Marine Structures* 46 (1): 78–101. https://doi.org/10.1016/j.marstruc.2015.12.003.

Molina, Marco, and Amalia Ercoli Finzi. 2006. "SAE Technical Paper Series." *SAE Transactions* 1 (1): 304–311. https://doi.org/10.4271/2006-01-2113.

Möller, Niklas, and Sven Ove Hansson. 2008. "Principles of Engineering Safety: Risk and Uncertainty Reduction." *Reliability Engineering & System Safety* 93 (6): 798–805. https://doi.org/10.1016/j.ress.2007.03.031.

Morse, Edward, Jean-Yves Dantan, Nabil Anwer, Rikard Söderberg, Giovanni Moroni, Ahmed Qureshi, Xiangqian Jiang, and Luc Mathieu. 2018. "Tolerancing: Managing Uncertainty from Conceptual Design to Final Product." *CIRP Annals* 67 (2): 695–717. https://doi.org/10.1016/j.cirp.2018.05.009.

Muller, George E., and Clement J. Schmid. 1977. "Factor of Safety – USAF Design Practice." 1-104. Air Force Flight Dynamics Lab Wright-Patterson AFB OH.

Musto, Joseph C. 2010. "The Safety Factor: Case Studies in Engineering Judgment." *International Journal of Mechanical Engineering Education* 38 (4): 286–296. https://doi.org/10.7227/IJMEE.38.4.2.

Neufville, Richard de, Stefan Scholtes, and Tao Wang. 2006. "Real Options by Spreadsheet: Parking Garage Case Example." *Journal of Infrastructure Systems* 12 (2): 107–111. https://doi.org/10.1061/(ASCE)1076-0342(2006)12:2(107).

Newcomer, J. T., and R. L. Bierbaum. 2017. "A Framework and Taxonomy for the Design and Analysis of Margins." *Paper Presented at the 2017), Annual Reliability and Maintainability Symposium (RAMS), Orlando, FL, USA, 23–26 Jan. 2017*.

Pagani, Lorenzo P. 2004. *On the Quantification of Safety Margins*. Massachusetts Institute of Technology. http://hdl.handle.net/1721.1/33642.

Pahl, Gerhard, Wolfgang Beitz, Jörg Feldhusen, and Karl-Heinrich Grote. 2007. *Engineering Design: A Systematic Approach*. London: Springer London.

Peng, Wensheng, and Yonghong Li. 2021. "Reliability Engineering Design Method Based on Generalized Margin Design Theory." *Paper Presented at the IOP Conference Series: Materials Science and Engineering, Shaanxi, China*.

Pepin, Jason, Amanda Rutherford, and Francois Hemez. 2008. "Defining a Practical QMU Metric." *Paper Presented at the, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference; 16th AIAA/ASME/AHS Adaptive Structures Conference; 10t, Schaumburg, IL, 07–10 April 2008*.

Peters, Daniel T., and Man Pham. 2018. "Discussion of the Background of the Design Margins in API 17TR8 HPHT Design Referencing ASME VIII Division 3." *Paper Presented at the ASME 2018 Pressure Vessels and Piping Conference, Prague, Czech Republic, July 15–20, 2018*.

Pilch, M., T. G. Trucano, and J. C. Helton. 2011. "Ideas Underlying the Quantification of Margins and Uncertainties." *Reliability Engineering & System Safety* 96 (9): 965–975. https://doi.org/10.1016/j.ress.2011.03.016.

Rajan, Palani, P. K, M. Van Wie, M. Campbell, K. Otto, and K. Wood. 2003. "Design for Flexibility-Measures and Guidelines." *Paper presented at the DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm*.

Rangan, Ravi M, Kenneth Maddux, and William Duwe. 1994. "A Practical Methodology to Automate Routine and Data Intensive Design Activities." *Paper Presented at the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Minneapolis, Minnesota, USA. September, 11–14, 1994*.

Rankine, William John Macquorn. 1872. *A Manual of Applied Mechanics*. London: Charles Griffin and Co.

Rasky, Daniel, Paul Kolodziej, Mark Newfield, Bernie Laub, and Yih Chen. 2003. "Assessing Factors of Safety, Margins of Safety, and Reliability of Thermal Protection Systems." *36th AIAA Thermophysics Conference*.

Riaz, A., M. D. Guenov, and A. Molina-Cristobal. 2017. "Set-Based Approach to Passenger Aircraft Family Design." *Journal of Aircraft* 54 (1): 310–326. https://doi.org/10.2514/1.C033747.

Robertson, Bradford, Dimitri Mavris, and Jeffrey Zweber. 2012. "Initial Formulation of a Hybrid Probabilistic Method for Design Margin Estimation for a Novel Concept." *Paper Presented at the AIAA SPACE 2012 Conference & Exposition*.

Sahin, Onur, and Ayse K. Coskun. 2015. "On the Impacts of Greedy Thermal Management in Mobile Devices." *IEEE Embedded Systems Letters* 7 (2): 55–58. https://doi.org/10.1109/LES.2015.2420664.

Saleh, Joseph H., Elisabeth S. Lamassoure, Daniel E. Hastings, and Dava J. Newman. 2003. "Flexibility and the Value of On-Orbit Servicing: New Customer-Centric Perspective." *Journal of Spacecraft and Rockets* 40 (2): 279–291. https://doi.org/10.2514/2.3944.

Schulz, T. L. 2006. "Westinghouse AP1000 Advanced Passive Plant." *Nuclear Engineering and Design* 236 (14-16): 1547–1557. https://doi.org/10.1016/j.nucengdes.2006.03.049.

Schulz, H., and P. Gruner. 1990. "Questions on Safety Margins of Components at Loads Beyond Design – Failure Modes of the Primary System of PWRs." *Nuclear Engineering and Design* 124 (1-2): 143–152. https://doi.org/10.1016/0029-5493(90)90360-A.

Shah, H., S. Hosder, and T. Winter. 2015. "Quantification of Margins and Mixed Uncertainties Using Evidence Theory and Stochastic Expansions." *Reliability Engineering & System Safety* 138: 59–72. https://doi.org/10.1016/j.ress.2015.01.012.

Shanley, F. R. 1962. "Historical Note on the 1.5 Factor of Safety for Aircraft Structures." *Journal of the Aerospace Sciences* 29 (2): 243–244. https://doi.org/10.2514/8.9385.

Snape, S., S. Whittle, P. Sen, and E. Rajabally. 2005. "Margins of Performance in Engineering: The Requirement for a Systematic Approach." *Paper Presented at the DS 35: proceedings ICED 05, the 15th International Conference on Engineering Design, Melbourne, Australia, 2005*.

Sobek, I. I., K. Durward, Allen C. Ward, and Jeffrey K Liker. 1999. "Toyota's Principles of set-Based Concurrent Engineering." *MIT Sloan Management Review* 40 (2): 67. https://sloanreview.mit.edu/article/toyotas-principles-of-setbased-concurrent-engineering/.

Sobieszczanski-Sobieski, Jaroslaw. 1995. "Multidisciplinary Design Optimization: An Emerging New Engineering Discipline." In *Advances in Structural Optimization*, edited by José Herskovits, 483–496. Dordrecht: Springer Netherlands.

Söderberg, Rikard, Lars Lindkvist, and Stefan Dahlström. 2006. "Computer-aided Robustness Analysis for Compliant Assemblies." *Journal of Engineering Design* 17 (5): 411–428. https://doi.org/10.1080/09544820500275800.

Söderberg, Rikard, Kristina Wärmefjord, Johan S. Carlson, and Lars Lindkvist. 2017. "Toward a Digital Twin for Real-Time Geometry Assurance in Individualized Production." *CIRP Annals* 66 (1): 137–140. https://doi.org/10.1016/j.cirp.2017.04.038.

Suh, N. P. 1999. "A Theory of Complexity, Periodicity and the Design Axioms." *Research in Engineering Design* 11 (2): 116–131. https://doi.org/10.1007/PL00003883.

Swanson, Andrew R, and Kevin Galvin. 1984. "The Quantification of an Overdesign Factor for Coal Preparation Plants." *Coal Preparation* 1 (1): 93–110. https://doi.org/10.1080/07349348408945541.

Tackett, M. W. P., C. A. Mattson, and S. M. Ferguson. 2014. "A Model for Quantifying System Evolvability Based on Excess and Capacity." *Journal of Mechanical Design* 136 (5): 051002. https://doi.org/10.1115/1.4026648.

Taguchi, Genichi, and Madhav S Phadke. 1989. *Quality Control, Robust Design, and the Taguchi Method*. New York: Springer.

Takamatsu, Takeighiro, Iori Hashimoto, and Suteaki Shioya. 1974. "On Design Margin for Process System with Parameter Uncertainty." *Journal of Chemical Engineering of Japan* 6 (5): 453–457. https://doi.org/10.1252/jcej.6.453.

Tan, Jun Yuan James. 2017. *Design Margins as a Strategy for Early State Design: A Complex Systems Approach*. Singapore University of Technology and Design. https://sutd.primo.exlibrisgroup.com/permalink/65SUTD_INST/1uiev4u/alma999472558802406.

Tan, James, Kevin Otto, and Kristin Wood. 2016. "Concept Design Trade-Offs Considering Performance Margins." *DS 85-1: Proceedings of NordDesign 2016, Volume 1, Trondheim, Norway, 10th-12th August* 2016:421-9.

Thomsen, Benjamin, Michael Kokkolaras, Tomas Månsson, and Ola Isaksson. 2017. "Quantitative Assessment of the Impact of Alternative Manufacturing Methods on Aeroengine Component Lifing Decisions." *Journal of Mechanical Design* 139: 2. https://doi.org/10.1115/1.4034883.

Thunnissen, D. P. 2004. "Method for Determining Margins in Conceptual Design." *Journal of Spacecraft and Rockets* 41 (1): 85–92. https://doi.org/10.2514/1.9211.

Thunnissen, Daniel P., and Glenn T. Tsuyuki. 2004. "SAE Technical Paper Series." *SAE Technical Paper*, 1–20. https://doi.org/10.4271/2004-01-2416.

Tilstra, Andrew H., Peter B. Backlund, Carolyn Conner Seepersad, and Kristin L. Wood. 2015. "Principles for Designing Products with Flexibility for Future Evolution." *International Journal of Mass Customisation* 5 (1): 22–54. https://doi.org/10.1504/IJMASSC.2015.069597.

Touboul, Adrien. 2021. *Model of margin, margin sensitivity analysis and uncertainty quantification in graphs of functions in complex industrial systems*. École des Ponts ParisTech. https://pastel.archives-ouvertes.fr/tel-03435011

Ulrich, Karl T., Steven D. Eppinger, and Maria C. Yang. 2020. *Product Design and Development*. New York: McGraw-Hill Education.

Urbina, A., S. Mahadevan, and T. L. Paez. 2011. "Quantification of Margins and Uncertainties of Complex Systems in the Presence of Aleatoric and Epistemic Uncertainty." *Reliability Engineering & System Safety* 96 (9): 1114–1125. https://doi.org/10.1016/j.ress.2010.08.010.

van Grootel, Alexander, Jiyoun Chang, Brian L. Wardle, and Elsa Olivetti. 2020. "Manufacturing Variability Drives Significant Environmental and Economic Impact: The Case of Carbon Fiber Reinforced Polymer Composites in the Aerospace Industry." *Journal of Cleaner Production* 261 (1): 121087. https://doi.org/10.1016/j.jclepro.2020.121087.

Wallstrom, T. C. 2011. "Quantification of Margins and Uncertainties: A Probabilistic Framework." *Reliability Engineering & System Safety* 96 (9): 1053–1062. https://doi.org/10.1016/j.ress.2011.01.001.

Ward, Allen C, Jeffrey K Liker, Durward K Sobek, and John J Cristiano. 1994. "Set-Based Concurrent Engineering and Toyota." *Paper Presented at the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Minneapolis, Minnesota, USA. September, 11–14. 1994*.

Watson, J. D., J. D. Allen, C. A. Mattson, and S. M. Ferguson. 2016. "Optimization of Excess System Capability for Increased Evolvability." *Structural and Multidisciplinary Optimization* 53 (6): 1277–1294. https://doi.org/10.1007/s00158-015-1378-x.

Wilbur and Orville Wright Papers, Manuscript Division, Library of Congress, Washington, D.C. "Family Papers: Correspondence." http://hdl.loc.gov/loc.mss/mwright.02055.

Wilks, S. S. 1941. "Determination of Sample Sizes for Setting Tolerance Limits." *The Annals of Mathematical Statistics* 12 (1): 91–96. https://doi.org/10.1214/aoms/1177731788.

Wilson, Robert. 1874. *A Treatise on Steam Boilers: Their Strength, Construction, and Economical Working*. London: Lockwood.

Wisch, D. J. 2006. "Offshore Structures: Adequate Margins." *Paper Presented at the Offshore Technology Conference, Houston, Texas, USA, 1-4 May, 2006*.

Wynn, D. C., and C. M. Eckert. 2017. "Perspectives on Iteration in Design and Development." *Research in Engineering Design* 28 (2): 153–184. https://doi.org/10.1007/s00163-016-0226-3.

Wynn, David C, Claudia M Eckert, and P. John Clarkson. 2007. "Modelling Iteration in Engineering Design." *Paper Presented at the DS 42: Proceedings of ICED 2007, the 16th International Conference on Engineering Design, Paris, France, 28.—31.07. 2007, Paris, France*.

Zang, Thomas A, Sankaran Mahadevan, Jimmy C Tai, and Dimitri N Mavris. 2015. "A Strategy for Probabilistic Margin Allocation in Aircraft Conceptual Design." In *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, 3443. Dallax, TX, USA*.

Zhu, Jianmin, and Kwun-Lon Ting. 2000. "Performance Distribution Analysis and Robust Design." *Journal of Mechanical Design* 123 (1): 11–17. https://doi.org/10.1115/1.1333095.

Zio, E. 2009. "Reliability Engineering: Old Problems and new Challenges." *Reliability Engineering & System Safety* 94 (2): 125–141. https://doi.org/10.1016/j.ress.2008.06.002.