DEALING WITH EXTREME REQUIREMENT VALUES: WHAT METHODS TO DESIGN SCHOOL CHAIRS AND OFFSHORE WIND TURBINES HAVE IN COMMON

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ABSTRACT

Many designs are “driven” by requirements that describe maximum or minimum values of high-variability variables that must be considered. In ergonomics, minima and maxima of anthropometric variables like body height shape the design of a product. Similarly, in structural design, the highest environmental loads that can be expected during the lifetime of a product drive the design. Consequently, a wide range of methods that help designers deal with extreme requirement values has been developed. In this paper, we review these methods and propose a model for the process of dealing with extreme requirement values. The model comprises two broad stages. In the first stage, requirement values are statistically defined and in the second stage, a design is synthesized and evaluated against the requirement values. Throughout the paper, we use two examples: the design of an ergonomic chair and of an offshore wind turbine. We focus on how requirement values are defined for these two products and how they are used throughout the design process. Although these products are vastly different, both are designed by statistically deriving requirement values and then systematically designing against these values.

Keywords: Requirements, Design process, Design methods, Ergonomics, Structural Design

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1 INTRODUCTION

The natural world is full of variation. Individuals of any species – potato plant or oak tree, cat or dog, chimpanzee or homo sapiens – come in different sizes, shapes, colors, and other phenotypes. The weather – and its associated parameters like wind speed, precipitation, and wave height – constantly changes. If we want to design something that interacts with this wild variety, we need to properly deal with it.

While for some products the interaction with natural variation is only a minor design aspect, for other products dealing with variability is the main aspect. When designing a school chair, a major aspect of the design process is making sure that the chair comfortably fits a high percentage of the pupils of the respective age group (see, for example, Molenbroek et al. 2003). When designing an offshore wind turbine, a major design aspect is making sure that the wind turbine can withstand all weather conditions that can reasonably be expected to occur during its design life (International Electrotechnical Commission, 2019; Haselsteiner et al., 2022).

Expected body heights and wind speeds can act as "requirement values" in the design process meaning that a design solution has to perform satisfactorily for those body heights or wind speeds. Usually, feasibility and viability will impose limits to the requirements values, as it is more difficult to fulfill the requirement for very low or very high values than for typical values (Figure 1). In the school chair example, if a chair comfortably fits two children with body heights of 120 and 160 cm, the chair can be expected to also comfortably fit a child with 140 cm body height. Similarly, if a wind turbine withstands wave heights of 10 m it should withstand a typical 2 m wave too. Thus, designing for satisfactory performance when the requirement variable is extreme, can be a shortcut to creating a design that is satisfactory for a wide range of requirement values and avoid the necessity of testing whether the design performs satisfactorily throughout the interval. As a design strategy for such cases, one can design for the maximum required value, the minimum required value, or for both, a maximum and minimum value.

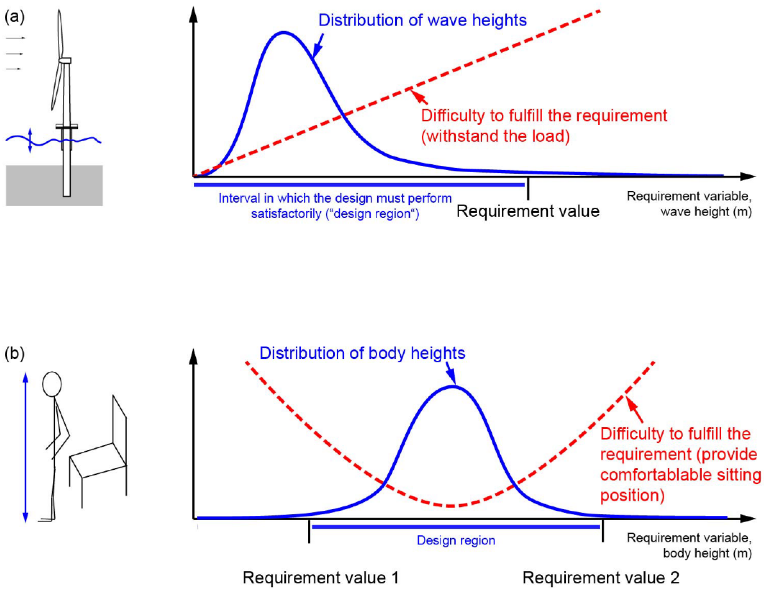

Figure 1. Extreme requirement values represent the boundary of the interval in which a design must perform satisfactorily. They are derived from a probability distribution. (a) Structural design of an offshore wind turbine and the requirement that it must withstand loads caused by waves. With increasing wave height it becomes increasingly difficult to fulfill this requirement. (b) Ergonomic design of a school chair and the requirement that a high percentage of pupils should feel comfortable sitting on the chair. Body heights follow a statistical distribution and it becomes increasingly difficult to design a comfortable chair for increasingly short and tall pupils.

We have looked into two very different fields in which researchers and practitioners have developed methods that help deal with extreme requirement values: in ergonomics, methods to deal with the variability of human body sizes, and in structural design, methods to deal with the variability of environmental loads. In this paper, we review these methods from a broad engineering design and statistics

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perspective. We will show that methods to design school chairs and offshore wind turbines have more in common than might be expected and that they can be represented in a common process model that describes how designers can deal with extreme requirement values.
This paper is organized as follows. First, we will briefly summarize research into the engineering design process and the role of extreme requirement values (section 2). Then, we will review the methods in ergonomics and structural design that deal with extreme requirements (section 3). Based on similarities among the methods in the two fields, we will propose a common process for dealing with extreme requirements (section 4). Finally, we will discuss the outlined process and draw conclusions (section 5).

2 EXTREME REQUIREMENT VALUES IN THE DESIGN PROCESS

The design process deals with the creation of artifacts. Researchers have developed models of the process, either based on empirical studies or on a prescriptive approach with the goal of supporting or improving the process. A recent review on models of the design process is provided by Wynn and Clarkson (2018).
Usually, a design project starts with the clarification of the task, a part of which is the elaboration of a set of requirements (see, for example, Pahl and Beitz 1996). Requirements describe desired properties of a product and deal with such diverse aspects as function, aesthetics, law conformance, manufacturing, and economics. The goal of the design process is to find a design solution that satisfies the formulated set of requirements (see, for example, Simon 1996; Visser 2009).
Requirements can change during the design process and new ones may have to be added, as shown, for example, by Almefelt et al. (2006) and Fernandes et al. (2015). According to Hubka and Eder (1988) "every technical system accepts inputs (a) from humans, (b) from other technical systems, and (c) from the active environment" (Figure 2 a). These classes of external influences match the two fields we consider in this paper: Ergonomics deals with humans as external influences while offshore structural design deals with the environment – winds and waves – as external influences.

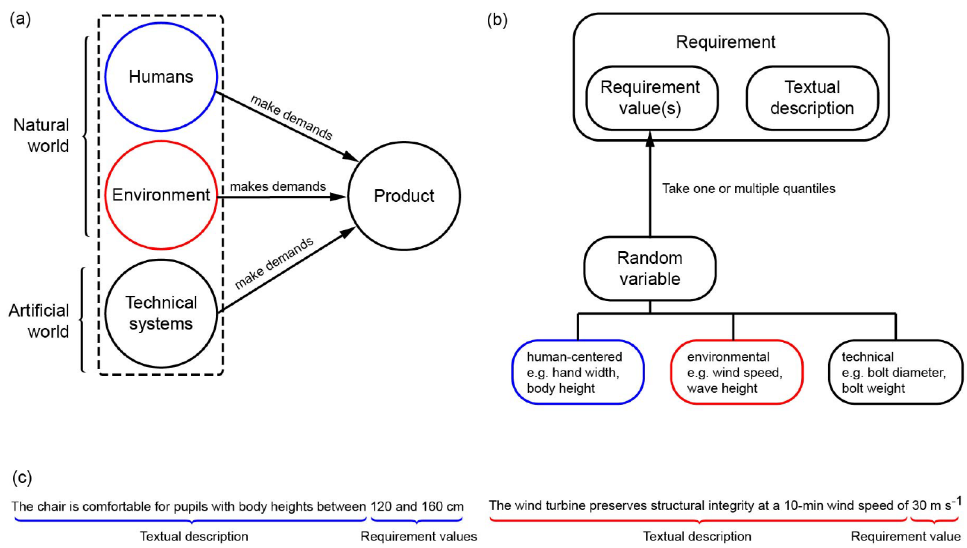

Figure 2. Representation of a requirement used in this work. (a) Requirements are based on external influences that make demands on the product. (b) A requirement comprises a textual description and a "requirement value," which is a quantity, based on a random variable that might describe a property of one of the external influences which we group as human-centered, environmental, and technical. (c) Examples of requirements.

In this work, we are interested in a particular type of requirement: a requirement with a requirement value that is "extreme" in the sense that it is the highest – or lowest – value of a high-variability variable that is considered in the design process. We choose to represent such extreme-value-based requirements – for brevity just "requirement" – in a simple form: A requirement is a condition that a design must fulfill to be satisfactory. Each requirement comprises a textual description and one or multiple requirement values, which are quantities (Figure 2 b; a similar representation has been used in the first author's dissertation, Haselsteiner 2022). A requirement value is based on a random variable that might describe a property of a human, the environment, or a technical system, that is a human-centered, environmental, or technical requirement variable. For example, the body height of pupils or the hourly mean wind speed can be described as random variables. To obtain the requirement value, first, the probability distribution of the random variable has to be established. Then the requirement value can be defined by taking a quantile of interest, for example, the 99th percentile.

Consider the requirement "The chair is comfortable for pupils with body heights between 120 and 160 cm." This requirement contains two requirement values, 120 cm and 160 cm, which were derived by taking quantiles of the probability distribution of pupil body heights. The rest of the requirement, "The chair is comfortable for pupils with body heights between," is a textual description to provide context.

While there are various types of requirements, we are interested in requirements that are considered "extreme". These are requirements related to external high-variability variables of which very low or very high values are of special concern. Dealing with this type of requirement can be important from an ergonomic point of view - the design should be usable for as many users as possible, and in offshore structural design, where extreme environmental phenomena are of concern. In the next section, we will review the methods that have been developed to define ergonomic requirements for human-centered design and environmental requirements for structural design.

3 METHODS TO DEFINE EXTREME REQUIREMENT VALUES

A wide range of methods has been developed to support designers with the definition of requirements that describe extreme values. The identified methods vary in the number of requirement variables that they take into account: There are univariate, bivariate, and multivariate methods. Some of the methods deal with low values, some with high values, and some with both high and low values.

When describing the methods, we will use the following terminology: The interval of the requirement variable that designers explicitly design for is called "design region." The design region's boundary is called "exceedance boundary." It is a threshold that is exceeded with a prescribed probability α. When only one requirement variable is considered, a univariate probability distribution is used and the exceedance boundary is a scalar, an upper or lower threshold (Figure 3). However, when multiple requirement variables are considered in a joint distribution, the exceedance boundary becomes a curve (for a bivariate distribution) or a (hyper)surface (for multivariate distributions with at least three requirement variables).

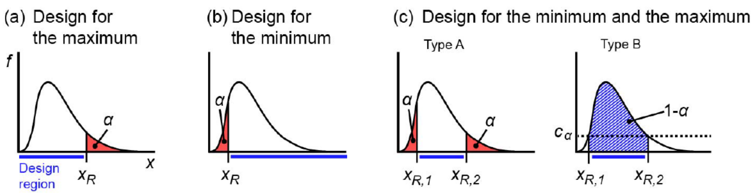

Figure 3. Depending on the requirement variable x and the particular design problem, one might design for the maximum, for the minimum or for both. In the "design for the minimum and for the maximum" approach different ways to define the design region are possible. α = probability of exceedance, c_α = minimum probability density of the design region, f = probability density, $x_R, x_{R,1}, x_{R,2}$ = requirement values.

When designers are concerned with high values of the requirement variable, they will define the exceedance boundary to separate a region of very high values from the design region ("design for the maximum"; (Figure 3 a). Similarly, when low values are of concern, the exceedance boundary separates a region of very low values from the design region ("design for the minimum"; Figure 3 b). Finally, when both, very low and very high values, are of concern the design region is defined to be between a lower and an upper threshold (Figure 3 c). Based on these concepts – type of requirement variable, number of variables, and design for the minimum, maximum, or both – we will now review the methods.

3.1 Ergonomics: Human-centered requirement variables

The field of ergonomics investigates and proposes theories, methods, and guidelines to ensure that products are designed to fit their users by taking into account human factors, including physical, mental, and perceptual capabilities. The recent review by Dianat et al. (2018) describes how anthropometric variables are used in ergonomics. Here, we will present the field's methods that focus on defining extreme requirement values.

A commonly used approach in ergonomics is using univariate percentiles in the formulation of requirements (Dianat et al., 2018), also called "min design" and "max design" (Kroemer, 2006), or "design for the tall" and "design for the small" (Molenbroek, 2000; Molenbroek and de Bruin, 2005). Often products are designed to fit 90% of the population by making sure a 5th percentile and a 95th percentile person can still use the product properly (Jürgens et al., 1998; Kroemer, 2006). Depending on the variable, though, only the upper or only the lower tail may be of interest

This approach, however, becomes problematic if multiple anthropometric variables are of importance. For example, if the stature of a person is in a certain population percentile this does not mean that his or her other body dimensions are in that same percentile. This misconception introduces errors (Vasu and Mital, 2000). Moroney and Smith (1972) found that when they combined the 5th and 95th percentiles of 13 anthropometric variables, only 47% of the population fell into the described design region. Similarly, when Gordon et al. (1997) combined five anthropometric variables, the region contained 67% of the population instead of the desired 90%.

Consequently, methods that are based on bivariate or multivariate statistics have been developed. The method that is implemented in the tool "Ellipse" (Molenbroek, 2000; Molenbroek and de Bruin, 2005) uses univariate percentiles, but provides users an estimate of the percentage of the population that is excluded if certain percentiles of two variables are used. Thus, users can choose the percentiles such that their target inclusion probability, for example, 90%, is reached. Ellipse assumes that the anthropometric variables follow a bivariate normal distribution.

Gordon et al. (1997) developed a multivariate method for ergonomic design. The authors used principal component analysis to reduce a 12-dimensional dataset to two dimensions. Then, they fitted an ellipse to the reduced dataset to define joint extreme values. Eight points that could serve as requirement values were selected along the ellipse. In addition, the multivariate average was calculated as a ninth requirement value. Finally, these two-dimensional extremes were transformed back to 12 dimensions. Similar approaches have been applied with higher-dimensional joint distributions such that values along an ellipsoid (Hsiao, 2013) or a hyper-ellipsoid (Bittner, 2000) were selected.

The requirements contour method we developed (Haselsteiner et al., 2019) is a multivariate method that does not make assumptions about the type of joint distribution nor requires a variable transformation. The method comprises estimating the joint distribution of the anthropometric variables, computing an exceedance boundary, and selecting individual points along the exceedance boundary to define requirement values. Because many variables are not normally distributed, in the requirement contour method, the exceedance boundary is typically not an ellipse.

In summary, in ergonomics univariate, bivariate, and multivariate methods to define requirements exist. These methods use global probability distribution models to describe datasets. Typical values for the probability of exceedance range from 10^{-1} to 10^{-2}.

3.2 Structural design: Environmental requirement variables

Various engineering disciplines deal with extreme values of environmental variables and how to use them to design structures: Aerospace, civil, coastal, marine, and mechanical engineers deal with extreme wave heights, tides, currents, and wind speeds when designing, for example, wind turbines, dykes, or dams. In contrast to anthropometric variables, environmental variable datasets are usually time series. Further, many environmental variables are time-integrated over a reference time, or "state duration." For example, significant wave height is based on a time series of the sea surface elevation, often with a reference time of 1 or 3 hours, and wind speed, often with a reference time of 1, 10, or 60 minutes.

As a consequence, an environmental variable's exceedance probability is linked to time. This link is often expressed in terms of the return period. Gumbel (1941) defined a univariate return period to be the arithmetic mean of the intervals between two events that exceed the threshold.

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In structural design, it is common practice to use an extreme environmental condition associated with a particular return period to perform structural integrity calculations. In many cases, the structure's response is highest at this extreme such that it is sufficient to perform a single structural integrity analysis at the extreme instead of considering all values of the design region. Univariate return periods are applied to define, among others, extreme wind speeds (International Electrotechnical Commission, 2019), extreme wave heights (Battjes, 1970), and extreme earthquakes (Cornell, 1968).
The bivariate and multivariate equivalent to the univariate return period method is the environmental contour method. It was introduced by Haver (1985) and Winterstein et al. (1993) to define extreme sea states and received considerable interest from other researchers in the last decade. The environmental contour method is recommended in standards and guidelines (for example, International Electrotechnical Commission, 2019; DNV GL, 2017) and is therefore widely used in engineering practice. For a recent benchmarking study on the environmental contour method, see Haselsteiner et al. (2021).
In summary, methods that support the definition of requirements based on environmental variables are linked to time such that an exceedance probability α is linked to a return period. Univariate and multivariate methods exist and typical α-values range from 10^{-3} to 10^{-6} (if the state duration is in the order of hours and these states are considered to be independent events), which are several orders of magnitude lower than typical α-values in ergonomic design. Besides the time-dependency and the lower α-values, however, these methods share a similar objective and similar steps as the methods from ergonomics. Thus, in the next section, we will describe a general process for dealing with extreme requirement values. It applies to both human-centered and environmental variables and shall serve as a model that integrates the various ergonomics and structural design methods.

4 A PROCESS FOR DEALING WITH EXTREME REQUIREMENT VALUES

The proposed model of the process of dealing with extreme requirements values is shown in Figure 4. For simplicity, a case with a single requirement value is illustrated here.

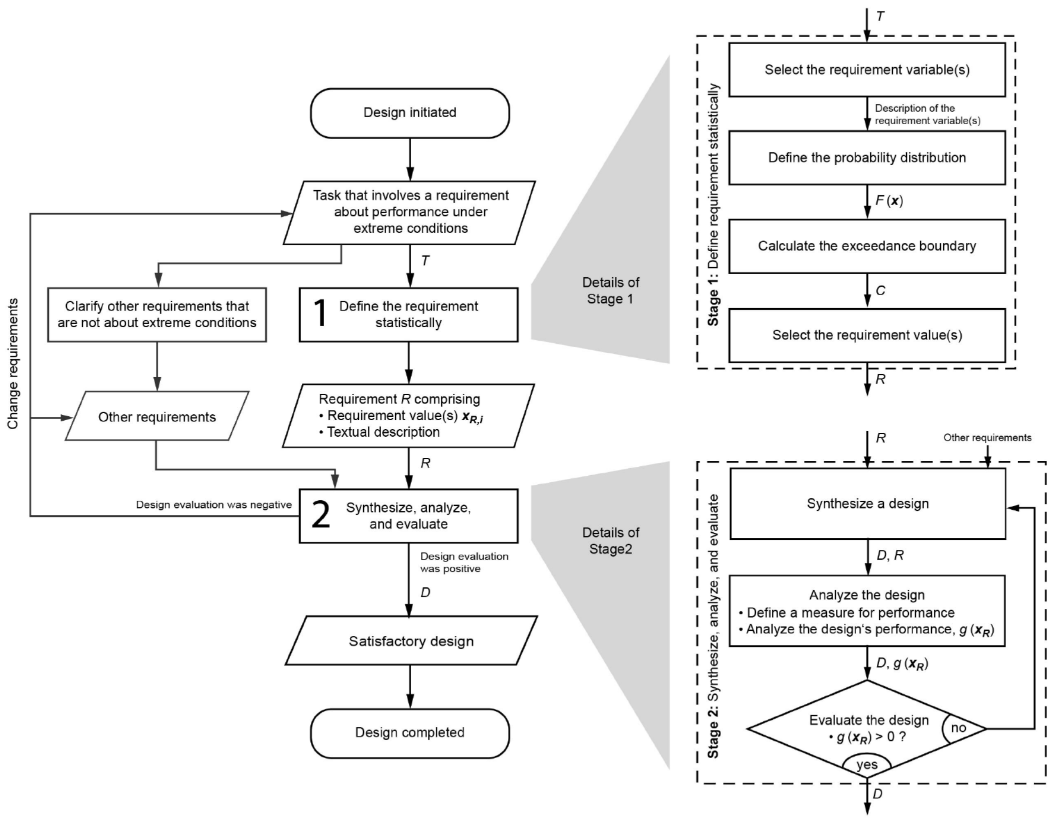

Figure 4. Proposed model of the process of dealing with extreme requirement values. The left side shows the overall process while the right side shows the details of Stage 1 and Stage 2 (these details are substeps of the left side's "stage 1 box" and "stage 2 box").

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The process comprises two main stages: Stage 1 addresses requirement definition, Stage 2 addresses synthesis, analysis, and evaluation. In Stage 1, the ergonomic and structural design methods reviewed in section 3 help to define requirements statistically. They are the means to generate - based on a task T - a formal requirement R about the performance of a product under some extreme conditions. As mentioned, such a requirement comprises one or many requirement values and a textual description for context.

In Stage 2, the formal requirement R serves as input for design synthesis, analysis, and evaluation. Any design candidate that is synthesized must fulfill R, meaning that it must perform satisfactorily under all requirement values. The evaluation process in structural design that uses a performance or "failure" function $g()$ inspired this stage (for more details, see Haselsteiner et al. 2019). In this stage, based on a requirement R, a design D is created. We use D to denote a synthesized design and $\mathbf{x}$ to denote a realization of the requirement-specific random variable, for example, $\mathbf{x} = (2\,\text{m wave height})$ in a univariate case or $\mathbf{x} = (2\,\text{m wave height}, 8\,\text{m/s wind speed})$ in a bivariate case. Further, $g()$ denotes a performance function such that $g(D, \mathbf{x})$ or simply $g(\mathbf{x})$ describes a design's requirement-specific performance.

If $g(\mathbf{x} = \mathbf{x_R})$, the function describes how well a design performs at a particular requirement value $\mathbf{x_R}$. The performance function $g()$ is defined such that it evaluates to > 0 if the design fulfills the requirement and such that it evaluates to ≤ 0 if the design does not fulfill the requirement. We call a design that fulfills the condition $g(D, \mathbf{x_R}) > 0$ "satisfactory" and a design that does not fulfill the condition "unsatisfactory." If the design candidate does not perform satisfactorily, the design candidate can be discarded and a new design candidate is synthesized. Alternatively, the requirements might have to be changed to accept a candidate design and its performance. Note that if a requirement contains more than one requirement value, the performance function must evaluate to > 0 for all requirement values to be satisfactory (more details on using a performance function for design evaluation are available in Haselsteiner et al. 2019).

Based on the shape of the performance function (Figure 5), two design types to achieve satisfactory performance can be differentiated:

- A "static design" does not dynamically change with the requirement value, it behaves similarly for low and high requirement values, while
- an "adaptive design" changes with the requirement value to achieve improved performance at high (or low) values.

Note that this definition does not imply that a static design's performance stays constant over the design region: It changes because performance usually decreases as the requirement value increases (or decreases; Figure 5). A static design, however, does not actively adapt to the requirement value nor uses different "modes" at different requirement values.

In contrast, an adaptive design typically has different modes that allow it to adapt to the current value of the variable of interest. Often, it continuously adapts when the requirement value is within a particular interval – there, the design is in a continuous adaptation mode – but stops the continuous adaption when the requirement variable exceeds a threshold. At this threshold, the design switches into a second mode, a configuration that is well-suited for high values of the requirement variable.

Consider a typical offshore wind turbine: It is a static design with respect to wave height (the wind turbine does not change its geometry or configuration with increasing wave heights) but it is an adaptive design with respect to wind speed (the wind turbine constantly pitches its blades during power production mode and fully pitches them to reduce loads if the cut-out wind speed, typically 25 m/s, is exceeded; Haselsteiner et al. 2022). For school chairs, both static and adaptive designs with respect to pupil body height are common: Some school chairs have a fixed geometry (static design) while other school chairs provide a mechanism to control the chair height to better fit different heights (adaptive design).

5 DISCUSSION AND CONCLUSIONS

A distinct aspect of designing for extreme values is its way of evaluation. Evaluating performance only at the design region's extreme, as we propose, is based on the assumption that the design's performance is worst at this extreme. Sometimes this is not the case. For example, if a structure resonates at a specific wind speed value relying solely on designing for minimum or maximum values would potentially lead to failure. In such cases, additional requirement values within the design region should be used. Designers could either add selected values or use an approach that takes the full design region into account.

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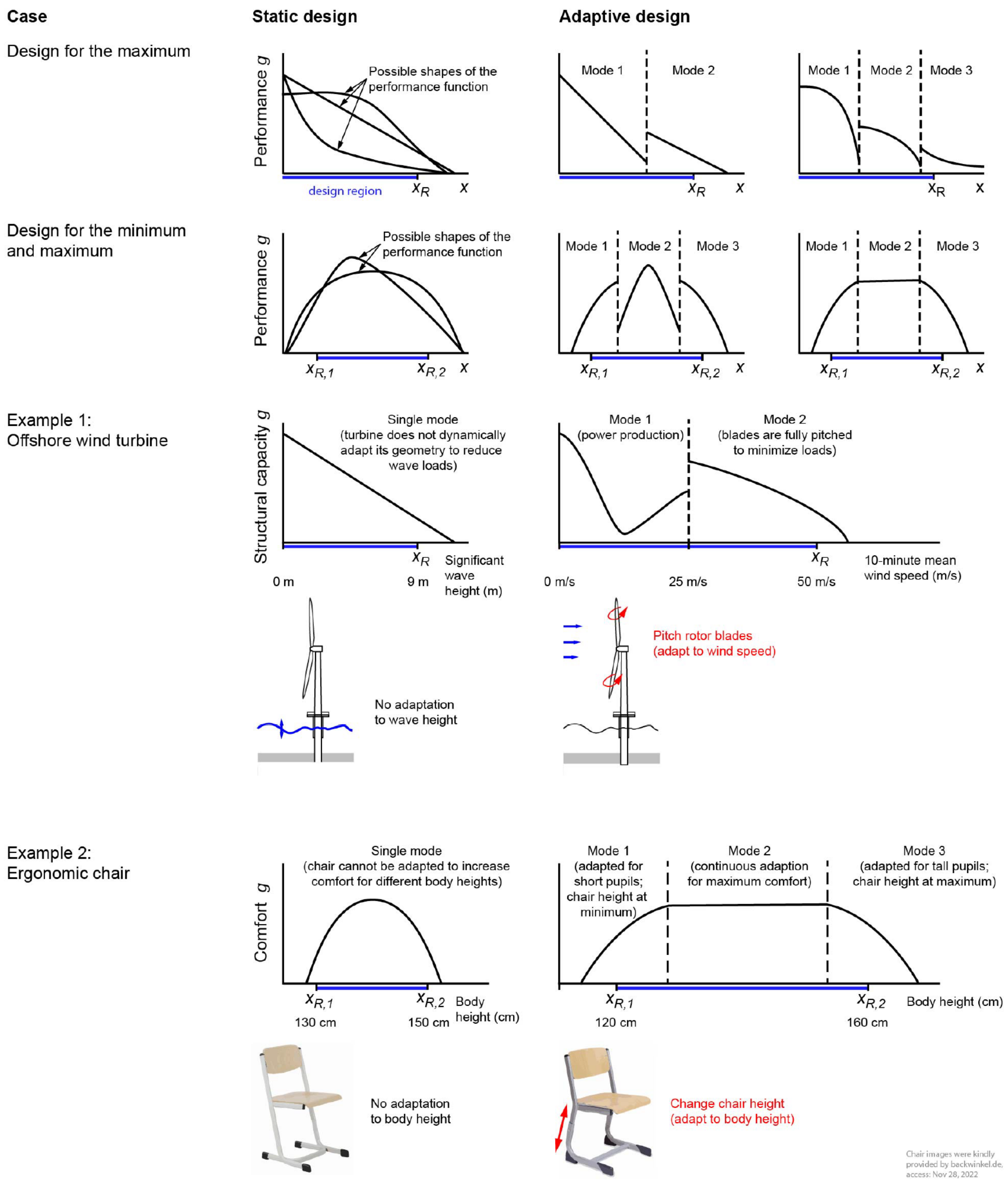

Figure 5. Two types of design to fulfill extreme requirement values x_R can be differentiated: static design and adaptive design. Static designs do not dynamically change with the requirement value while adaptive designs do. Adaptive designs usually have different modes for different intervals of the requirement variable. Often they continuously adapt within one mode but do not change within other modes.

Such approaches are, for example, the "full long-term analysis" (Muliawan et al., 2013; Haselsteiner et al., 2022) in structural design and the "grid method" (Jung et al., 2010) in ergonomic design. These approaches avoid the risk that a value within the design region leads to unsatisfactory performance, however, at the cost of a high number of different design evaluations.

In this work, we laid out a general process for dealing with extreme requirement values. The process comprises two main stages: First, requirement values are statistically defined based on a probability distribution and a probability of exceedance. Then a design candidate is evaluated against these requirement values. If the product's performance is worse at very high or very low requirement values than at typical values, the procedure ensures that the design performs satisfactorily for a defined probability of outcomes of the requirement variable.

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We also differentiated two design types to achieve satisfactory performance when dealing with extreme requirement values: A "static design" uses a single mode to deal with both low and high requirement values while an "adaptive design" changes its behavior based on the value of the requirement value. The examples we used, offshore wind turbines and school chairs, are vastly different products with different requirements. Nevertheless, we could show that both can be designed by statistically deriving requirement values and then systematically designing against these values.

The proposed process model can serve as a "wrapper" of various methods that are used in ergonomics and structural design. Its goal is not to push a new way of designing but to enhance the understanding of the role of established, specific methods in the general design process.

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