Robust Design Principles for Reducing Variation in Functional Performance

Abstract:

This paper identifies, describes and classifies a comprehensive collection of Variation Reduction Principles (VRP) that can be used to increase the robustness of a product and reduce its variation in functional performance. Performance variation has a negative effect on the reliability and perceived quality of a product and efforts should be made to minimise it. The design principles are identified by a systematic decomposition of the Taguchi Transfer Function in combination with the use of existing literature and the authors’ experience. The paper presents 15 principles and describes their advantages and disadvantages along with example cases. Subsequently, the principles are classified based on their applicability in the various development and production stages. The Variation Reduction Principles are to be added to existing Robust Design methodologies, helping the designer to think beyond Robust Design tool and method application, towards forming product variation management strategies.

# Introduction

The quality of a product lies in its ability to consistently meet user expectations in terms of its functional features and its behaviour. Examples of functional behaviour could be the force required to open a car door or the noise generated by a motorised TV wall bracket. The inevitable presence of variation in the properties of the product’s components, caused by e.g. conditions of use and variation in manufacturing and assembly, result in variation in the functional behaviour of the product. The variation can occur either over time within the same sample or as variation from sample to sample. The variation conflicts with the intention of consistent behaviour and can lead to product failures, dissatisfied customers, the need for increased quality control, and added development and service costs – all of which impact the overall profit of the organisation (Ebro et al 2015). Therefore, it should be the aim of the design engineer to design the product and define relevant subsequent activities such that the variation in functional behaviour is minimised. A product typically has multiple functions and subfunctions, which can be *identified* and *mapped* using e.g. Functions-Means Trees that decompose the product’s main functions into sub-functions, or Quality Function Deployment (QFD) that creates links from qualitative customer statements (Voice of the Customer) to functional requirements and design parameters. Multiple methods and tools are available for *analysing* the level and the effects of variation in functional behaviour of a design, e.g. Design of Experiments (DOE), Variation Mode and Effects Analysis (VMEA), Failure Modes and Effects Analysis (FMEA). Although these methods identify potential failure modes and sensitive design parameters, they only provide limited guidance as to how the variation in performance can be *reduced*. This paper seeks to present a comprehensive collection of design principles that can support the design engineer in selecting the most appropriate principles for reducing variation in functional behaviour, thereby answering the question:

Which principles are available for reducing variation in the functional behaviour of a product?

The focus of the Variation Reduction Principles (VRP) is *not* delimited to the design of the product, but also includes principles related to e.g. how the product is produced and assembled, thereby resulting in a wider range of principles.

The remainder of the paper consists of five sections: 2) Theoretical background, 3) Methodology, describing how the principles have been identified, 4) A presentation of the Variation Reduction Principles, 5) A categorisation of the principles, 6) Discussion of the value, limitations, and intended use of the VRP, and 7) Conclusion, which summarises the paper.

# Theoretical Background

This section first describes the theoretical background of why it is beneficial to obtain products with a low variation in functional performance and then describes current frameworks of principles, practices and tools for obtaining consistent performance.

## The need for consistent behaviour

A product is defined by its structure, which describes the characteristics of the product and by its behaviour, which describes how the product performs (Andreasen et al 2014). The intended behaviour of a product is described by the product specifications, typically using a target value and an upper and/or lower acceptance limit, e.g. ‘*Force to trigger dose button = 7±1N’.* Initially, only high-level specifications are defined, but during the course of the development project, a substantial number of additional functional requirements may be added as sub-functions and design details are included in the design, e.g. the required holding force of a screw connection. The design engineer is faced with many requirements in terms of cost, risk, quality, reliability, robustness, etc. Amongst these requirements, is the task of obtaining a design where all functional specifications are fulfilled. This involves two different types of activities: 1) Nominal dimensioning, where the product’s design parameters are defined (dimensions, material properties, surfaces (Tjalve 1976)), striving to obtain a nominal performance equal to the target specification. 2) Minimising the variation in functional performance. Because the world is stochastic by nature, variation will occur in the product’s design parameters and this will lead to variation in the functional performance, both within the same sample over time e.g. due to temperature changes and wear and from sample to sample due to e.g. wear of the production tools or float during assembly. A large variation in functional performance can have a negative influence on the design in several ways:

1. **Failures due to exceeding specification tolerance limits**

If the functional variation is high, it will increase the probability of products performing outside the defined specification limits, meaning that the failure rate will increase, as shown in Figure 1a, where the variation must be reduced to fulfil the functional requirements. In other words, a large variation in functional performance can result in poor reliability.

1. **Excessive cost due to increased safety margins**

For one-sided specifications (lower/higher-the-better) the objective is to minimise the expected failure rate by defining a sufficient safety margin between the nominal performance and the specification limit (Figure 1b). A design with large performance variation must have a larger safety margin to obtain the same probability of failure, which can lead to material waste, added cost, increase in the size of the product etc.

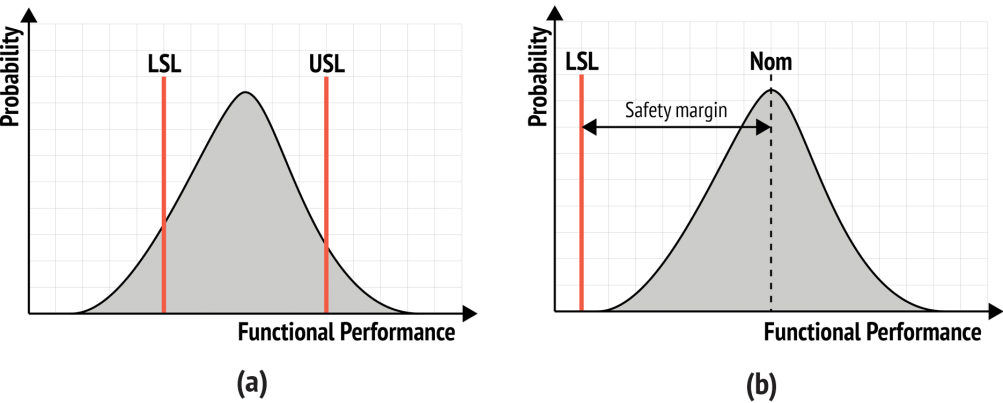


Figure 1. (a) Large variation in functional performance increases the probability of performing outside the upper and lower specification limits (USL & LSL). (b) Large functional variation results in the need for a larger safety margin.

1. **Dissatisfied customers due to Quality Loss**

In the traditional understanding of quality, any performance within the performance specifications is perceived as being equally acceptable. However, the Quality Loss Function (QLF) developed by Taguchi (Taguchi et al 2004) states that any deviation from the intended value incurs a loss to the user and the society, an example of which is given in a popular case study by Phadke (1995), where two TV-production sites adhering to the two different quality paradigms experienced large variations in customer satisfaction. As shown in **Error! Reference source not found.**, when the variation in functional performance is reduced, the number of users experiencing a given (high) quality loss is also reduced. Quality loss can also occur internally in an organisation, e.g. as problems with the assembly of a product, requiring it to be reworked, scrapped, or taking extra time to assemble.

Summing up, reducing the variation in functional performance is an essential part of the design engineer’s tasks as it has obvious links to the perceived quality, failure rate, reliability and profitability of the product.

## Existing frameworks and compilations

The task of reducing variation in functional performance can be seen as an ongoing and iterative process consisting of three steps (), each with a designated set of tools and methods.

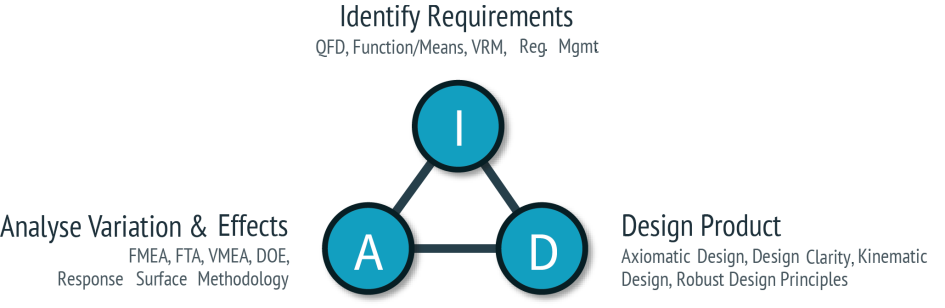


Figure . The iterative workflow related to variation in functional performance. The design engineer shifts between identifying requirements, analysing and documenting sensitivity and performance and designing the product.

1. **Identifying** functional requirements involves a continuous decomposition and mapping of functions and subfunctions along with the relevant performance requirements using methods such as QFD (Akao, King 1990) and Functions/Means Trees as well as frameworks like Variation Risk Management (Thornton 2004) and the more general field of Requirements Management. The output of this step is a list of functional requirements, ideally with allowable variation limits.
2. **Analysing** the design to identify the nominal as well as the variation in the functional performance. This is done using general tools such as tolerance calculations and structural analysis as well as more specialised tools such as FMEA (Teng & Ho 1996), VMEA (Chakhunashvili et al 2004), Design of Experiements (DOE) (Phadke 1989) and Fault Tree Analysis (FTA) (Lee et al 1985) that describe the occurrence and effects of performance variation.
3. **Designing** the product involves the definition of the product’s structure (i.e. form, dimensions, material, surface), but the designer also plays a role in defining subsequent activities in manufacturing and assembly (Booker et al 2001), e.g. through tolerance requirements on the production drawings and testing procedures.

The Design-step, i.e. identifying ways of reducing functional variation, is described in existing literature, which comprises a number of compilations and frameworks, some of which are listed below.

Matthiassen (1997) - provides a set of specific design principles for obtaining robust and reliable designs, such as redundancy and the separation and integration of functions. The principles focus on the product itself and do not include principles applicable in production and assembly.

Thornton (2004) provides a framework for identifying a product’s key characteristics, measuring the performance of the product, and mitigation strategies for improving the performance. The mitigation strategies can be further extended and added to the ten design principles for reducing variation proposed by Andersson (1996), and to the principles of robust design proposed by Arvidsson and Gremyr (2008) , although their main focus is on experimental and analytical tools and less on design principles.

Taguchi (1986) provides a three-step process (System, Parameter, and Tolerance Design) for eliminating variation. The main focus of this work lies on the parameter and tolerance design and the statistical optimisation of parameter values. As such, the focus is relatively narrow and does not include e.g. changing the design concept.

Design for Six Sigma (Yang & El-Haik 2003) is a framework which has gained popularity in recent years. The main driver is obtaining ‘six sigma-performance’ by design (rather than by production only). The main focus is on the overall design process (DMAIC) and less on the specific solutions and principles.

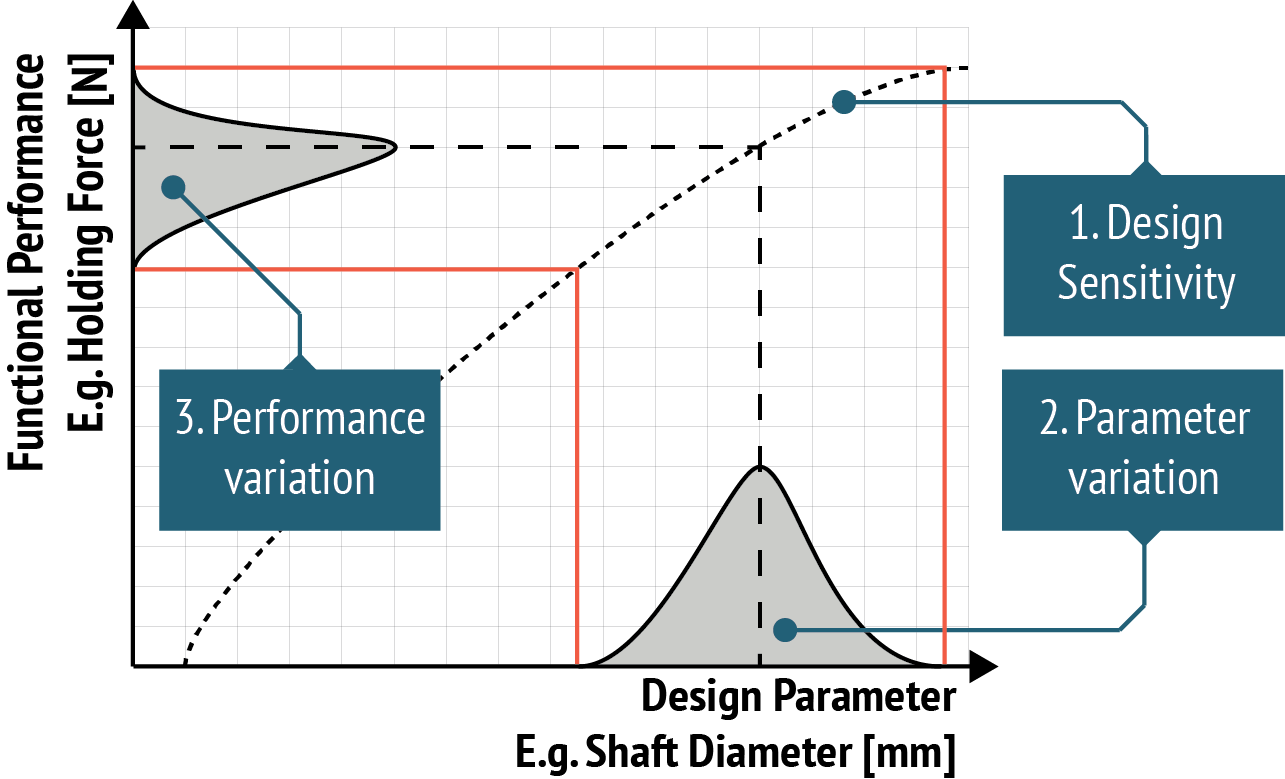
Finally, generic development processes, such as Pahl, Beitz et al (2007) typically provide various Design-for-X guidelines, such as design techniques for obtaining easy manufacturing, easy assembly and low-cost. However a process that focuses specifically on eliminating performance variation has not been found.

The existing compilations and frameworks provide different types of overviews of tools, principles and methods related to quality engineering, and the reliability and robustness of a product. It is therefore argued, that there is a potential for augmenting the existing compilations, by specifically targeting the variation in functional performance and by also including principles outside of the design domain. Especially principles that provide specific support for the design engineer and are applicable at the point-of-design are needed. Such an overview will complement the large suite of methods available for identifying functional requirements and analysing the performance of designs (as shown in Figure 3) and will compile and extend available design strategies by also covering strategies not directly related to the design of the product, but rather how the product is manufactured and assembled.

# Research Methodology

This section describes the methodology used to identify and structure the design strategies. The strategies have been identified using the Transfer Function as a structured framework. The Transfer Function (Figure 4) is a visual and mathematical representation of the relationship between the functional performance and the design parameters that affect the performance (Taguchi 1986). It consists of three main elements; 1) the design parameter(s) on the horizontal axis, 2) the sensitivity of the design shown by the graph, and 3) the functional performance on the vertical axis. Improving any of the three main elements of the Transfer Function will result in a reduction of the performance variation. For each of the three elements, strategies were identified by analysing relevant literature supplemented with the authors’ experiences. Since the authors have a background as consultants and researchers within the fields of reliability, quality, and robustness in engineering design and therefore have been working with a wide array of design strategies.

Figure 4. The Transfer Function’s three main elements were used as a framework for identifying the Variation Reduction Strategies.



For each of the identified strategies, the advantages and disadvantages were described and a relevant case was provided to illustrate the use of the strategy. Certain strategies are directly related to the design of the product, whereas others relate to the way the product is manufactured or assembled. To illustrate this, the strategies were mapped onto a generic product development process, thereby indicating at which phases the given strategies are applicable.

# Design Principles

This section presents the 15 Variation Reduction Principles (VRP) that have been identified. They are structured into three groups, based on which element of the Transfer Function they address. References are provided for the principles where further information is available in literature.

## Principles related to Design Sensitivity (changing or shifting the Transfer Function)

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| **1 – Parameter Optimisation** | |
| **Description:**  If the Transfer Function is non-linear, the performance variation can be reduced by adjusting the values of the design parameters to fit with the ‘flat’ (non-sensitive) areas of the transfer curve. | |
| **Example: Press fit**  The holding force of a press fit is very sensitive to variation of the overlap between the two parts. The design is changed from a long interference fit (a) with a small radial overlap, to two short fits with a larger overlap (b). The nominal holding force is the same but the variation in holding force is reduced significantly. | |
| **Pros:**  Parameter optimisations typically will not require any conceptual changes, which allows for this strategy to be applied relatively late in the design process. | **Cons:**   * Not all sensitivities can be found analytically, but require tests, simulations, DOE). * Requires a non-linear Transfer Function * Limited improvement potential |
| **References:** (Taguchi 1986) |  |

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| **2 – Change of Design Principle** | |
| **Description:**  If the conceptual solution is changed, the Transfer Function and the design parameters will also change. As part of the concept selection process, the expected performance variation of each solution can be calculated and used as input. | |
| **Example: Wind Turbine Coupling**  A coupling and bearing system for the main shaft of a wind turbine was designed to have a nominal lifetime of 20 years, but was very sensitive to misalignment of the bearings, with large variation in expected lifetime as a result. A conceptually different system was designed introducing several more degrees of freedom to the gearbox coupling. This made the design insensitive to misalignment, which extended the nominal lifetime and improved the predictability of the performance, which made predictive maintenance easier. | |
| **Pros:**  Potential for larger improvements compared to e.g. parameter optimisation. | **Cons:**  By default, this strategy requires a complete change of concept. |
| **References:** (Thornton 2004) | |

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| **3 – Uncoupling and Decoupling** | |
| **Description:** If multiple functions depend on the same design parameter, the range of available values for a design parameter is reduced, because two functional requirements have to be met simultaneously. As a consequence, the design engineer may have to make a compromise and select design parameters resulting in a mean functional performance that is different from the target value, which in turn increases the performance variation. | |
| **Example (adapted from (Söderberg et al 2006)): Positioning of parts**  The positions of components A-D have functional requirements. In a coupled design (a), the position of e.g. D will depend upon the positions of A-C, which reduces the probability of finding an optimal solution for all 4 components. In the decoupled design (b), the parts can be designed in a specific order, and thereby compensate for design parameters, that have been ‘locked’ by previous requirements. In the uncoupled design (c), the designer is free to specify the optimum design parameters. | |
| **Pros:**  Reduces number of trade-offs, as functional requirements can be optimised individually. | **Cons:**  Challenging to identify the coupled design parameters early in the design process, and challenging to decouple them late in the design process, especially for highly integrated products. |
| **References:** (Suh 2001), (Söderberg et al 2006) | |

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| **4 – Minimise number of design parameters (Design Clarity & Kinematics)** | |
| **Description:**  Intuitively, the variation of a functional performance is proportional to the number of influencing design parameters, because the variation of each design parameter will contribute further to the variation of the functional performance. This strategy focuses on reducing the number of influential design parameters by using the principles of kinematics and design clarity. Avoiding long tolerance stack-ups is an inherent part of applying this strategy. | |
| **Example: Large flatbed scanner**  A shaft for a large flatbed scanner has to run with constant frictional torque to produce high-quality scanning images. In the original design (a), the torque was a function of 13 design parameters, due to over-constraints and interface ambiguities. In the new design (b), the number of influencing parameters is reduced to three, resulting in reduced variation in frictional torque. | |
| **Pros:**   * Reduces the number of specifications, resulting in a reduced need for verification and quality control * Often, changes to the detailed interface design are sufficient. | **Cons:**  Conceptual changes may be necessary in certain situations. |
| **References:** (Christensen et al 2012), (Blanding 1992) | |

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| **5 – Self-reinforcement** | |
| **Description:**  This principle is an extreme case of sensitivity reduction, where the functional performance improves as certain design parameters deviate from nominal conditions. | |
| **Example: Rubber Seals**  One functional requirement of a sealing is that it must not leak. If the pressure difference becomes too high, a solution with an o-ring will leak. A lip-ring, however, becomes tighter as the pressure increases. Hence, the functional performance is independent of the pressure. | |
| **Pros:**  Functional variation is eliminated even for extreme parameter variation. | **Cons:**   * Not generally applicable. * Typically, the reinforcement only works in one direction. |
| **References:** (Matthiassen 1997) |  |

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| **6 – Flexibility** | |
| **Description:**  Flexible parts can absorb parameter variation and therefore reduce the performance variation. It is worth noting, that flexibility is a function of both material properties and geometry, and changing either of these will change the functional performance. This strategy is especially applicable for functional requirements involving load bearing parts. | |
| **Examples: Chair and LEGO®-brick**  One functional requirement for a LEGO®-brick (a) is the ‘clutch power’ (the force to assemble and disassemble the bricks) which should be within a narrow range for billions of combinations of bricks. By combing a flexible material (ABS) with a geometry where only limited volumes of material have to be deflected in the press-fits between the bricks, the variation in the clutch power is reduced. Figure (b) shows how the interface featuresconsist of tiny protrusions and small ribs that act as deformation zones. Figure(c) shows the geometry (red circle) of the interfacing LEGO®-brick | |
| **Pros:**  Can be executed as a material selection and/or a design change | **Cons:**   * Permanent stress in parts, which could lead to creep. * Position accuracy and predictability of parts is reduced * Flexible parts can experience large deflections, which may not be desirable. |
| **References:** (Christensen 2012), (Andersson 1997) | |

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| **7 – Play** | |
| **Description:**  Introducing play essentially ‘delays’ how variation of a design parameter influences the functional performance. If play exists between two functional surfaces, variation of one surface can occur to some extent without affecting the interfacing surface (depending on the specific design) and therefore will not change the functional performance. | |
| **Example: Electromechanical Switch**  One functional requirement for a push-button switch is the allowable stress on its terminals, when it is mounted on a PCB. Variation in the distance between the holes of the PCB will result in stress in the terminals of the switch when it is mounted. By introducing play (larger holes), the design becomes less sensitive to variation in the hole distance, which in turn results in the stress in the terminals being eliminated within a certain variation window. | |
| **Pros:**  Applicable at detailed design stage. | **Cons:**   * The positioning accuracy in the interface is reduced, because the float or assembly variation will be increased. * Play can lead to noise/rattle due to vibrations and feel sluggish to the user. |
| **References:** N/A |  |

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| **8 – Redundancy** | |
| **Description:**  Redundancy is typically used where the functional variation can become so extensive that it turns into a failure with serious consequences. The redundant functionality can be inactive during normal use, e.g. a back-up power supply for a nuclear power plant, or be an active part of normal use, e.g. multiple engines on an airplane. | |
| **Example: Coaxial Piping**  One functional requirement of a pipe for transporting e.g. liquids is to prevent leakage. Due to e.g. corrosion, a pipe can lose containment (leak). However, if a coaxial system of pipes is used, the outer pipe is initially redundant, but becomes active when the walls of the inner pipe become become corroded.  Inner (main) pipe  Outer (redundant) pipe | |
| **Pros:**   * Avoidance of serious effects of failure * Allows for safe detection of need for maintenance | **Cons:**   * Conceptual decision - difficult to implement at the detailed design stage. * Added cost of a redundant system |
| **References:** (Matthiassen 1997) | |

## Principles related to Parameter Variation

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| **9 – Tight Tolerances** | |
| **Description:**  Tightening the allowable parameter variation, will inherently reduce the performance variation, especially if this is targeted at the design parameters that have the largest influence on the functional performance. These parameters can be identified using sensitivity studies. | |
| **Example: An overconstrained mechanism**  A mechanism should ideally have a mobility equal to the number of motion inputs to the system (a), otherwise it may jam. However, theoretically overconstrained mechanisms (b) can still work, if the variation of the design parameters is low, e.g. if the lengths of the links and positions of the joints are precise. | |
| **Pros:**  Only requires changes on the production drawing, and therefore very simple to apply at late design stages. | **Cons:**   * Tightening tolerances increases cost (higher scrap rates, extra machining processes, added quality control, etc. * Risk of tightening tolerances beyond the process capability. * Variation from loads, ambient conditions and wear cannot be controlled by this strategy. |
| **References:** (Taguchi 2004) |  |

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| **10 – Sorting and Matching during assembly** | |
| **Description:**  During assembly components can be sorted and matched to fulfil the functional requirement, e.g. an intended fit or stack-up height of components. Essentially, parts are categorised based on the values of given design parameters and then paired with the appropriate category of the interfacing part. | |
| **Example: iPhone 5**  One functional requirement on the iPhone 5 is the size of the split line on the backside (left). To fulfil the requirement, the frame is scanned and paired with the best match amongst 725 possible plates (right) that have also been scanned. This is done automatically using assembly robots and vision technology. | |
| **Pros:** Extremely tight fits and split lines made possible with looser tolerances. | **Cons:**   * Extra process step 🡪 Longer assembly time * Replacement/service of parts can be difficult, since spare parts may not fit. * Quality is operator dependent (if done manually) * Risk of scrap if the distributions of the different components do not match each other (many small ‘holes’, but only a few small ‘pins’) |
| **References:** (Thornton 2004) |  |

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| **11 – Shielding** | |
| **Description:**  This strategy reduces parameter variation by shielding the product from the cause of the variation. Thermal expansion can e.g. be avoided by insulating critical components and deflections from loads can be avoided by designing the load path so sensitive parts do not experience any loads. | |
| **Example: Space Shuttle Thermal Protection Tiles**  The tiles used for thermal protection of the NASA space shuttles during re-entry in the Earth’s atmosphere are very brittle and cannot withstand the structural deflections and expansions of the shuttle itself. Therefore, they are shielded from deflection by being glued to a separate Strain Isolation Pad, which in turn is glued to the shuttle. | |
| **Pros:**  Noise factors such as temperature and loads are difficult to predict and specify. Shielding can reduce the need for use specifications. | **Cons:**  Primarily relevant for cases involving thermal variation and loads. |
| **References:** N/A |  |

## Principles related to Performance Variation

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| **12 – Adjustment during assembly and in use** | |
| **Description:**  A product can be designed to allow for adjustment during assembly and in use. In practice, a given functional performance is measured and specific adjustments are made, until the functional performance is as intended. This can be done by using grub screws, clamping, shimming, spacing, etc. The adjustment can be carried out during manufacturing, during assembly, prior to use, and during use. | |
| **Example: Motorised wall bracket for TV**  One functional requirement of a TV Wall Bracket is the angular deviation of the TV from a perfect horizontal line. Since the designers have no control of how close to horizontal the bracket is mounted on the wall, an adjustment screw (red circle) is added to the bracket to enable the user to adjust the TV after it has been mounted. When noise factors (uncontrollable to the designer) enter during the user installation or use phases, enabling user adjustment is often neccesary. | |
| **Pros:**   * Compensates for noise factors and parameter variation over time and during use. * Allows for more parameter variation (looser tolerances) during production, because these are eliminated by the adjustment. | **Cons:**   * Assembly time is longer, due to time spent on adjustment. * Quality can depend on the competencies of the operator/user |
| **References:** (Thornton 2004) |  |

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| **13 – Post-assembly Processing** | |
| **Description:**  This strategy is based on processing certain features *after* assembly of the relevant parts, thereby reducing the parameter variation. | |
| **Example: Chair**  Large complex carbon fibre shells with high levels of variation make drilling holes prior to and aligning during assembly unfeasible. Instead, mounting holes are drilled in-situ after the shells have been assembled. This ensures that the holes are correctly aligned. However, it does not ensure that they are positioned the same for each product and exchanging parts (e.g. in case of service replacements) is not possible. | |
| **Pros:**  Reduced need for precision and control of design parameters. | **Cons:**   * Extra process step. * Risk of compromising the subassembly during processing. |
| **References:** N/A |  |

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| **14 – Quality Control** | |
| **Description:**  Parts and products can be subjected to in-line quality control during and after assembly. This strategy will keep sub-assemblies and products with a performance deviating too far from the intended value from reaching the market. The products that are taken aside can either be scrapped or re-worked. The earlier in the assembly process the quality control takes place, the lower the cost of scrap will be. | |
| **Example: Medical Device**  Quality control is used heavily in the medical device industry. During the automated assembly of an injection device, each assembly station is succeeded by a control station, which controls the performance of the sub-assembly. Examples include vision control equipment that controls the position of the print on the housing and depth gauges that control the position of an assembled part. Sub-assemblies not fulfilling specifications are scrapped – therefore the drug cartridge – which is by far the most expensive component – is assembled last. | |
| **Pros:**   * High level of control of what reaches the market * Costs of in-line control equipment using e.g. vision technology is steadily decreasing. | **Cons:**   * Requires control of all products which can be costly. * Scrap rates can become excessive, leading to high costs. * Not actually *reducing* variation, but merely removing products not performing as intended. |
| **References:** (Booker et al 2001) | |

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| **15 – Change Functional Requirements** | |
| **Description:**  In certain cases, the reliability of the functional requirements can be challenged. If the gradient of the quality loss function is low, the quality loss associated with deviating from the nominal value is limited and therefore it may be a more viable strategy to change the specifications than to change the design of the product. | |
| **Example: Motorised TV-wall bracket**  The initial requirement for the horizontal misalignment of a TV-wall bracket was 0.5°, which was challenging to fulfil. A mock-up test documented that the users did not notice a misalignment until it exceeded 1.5°. Therefore, the functional requirement was changed. | |
| **Pros:**  Does not require any changes to the product. | **Cons:**  From the user’s point-of-view the quality of the product has not improved. |
| **References:** N/A |  |

# Categorisation

In this section, the identified principles are categorised. It is our impression that the cost and benefit of applying a given principle will depend so much on the specific context that it is not possible to quantify or rank the principles in terms of the cost of applying them. In general terms however, principles involving extra operations (e.g. sorting, matching, controlling) are expected to be less favourable than the principles based on a design change, because a design change is a one-off operation, whereas extra operations must be withheld for the remainder of the product life-time, which is more costly.

An initial categorisation already exists, as the principles were identified using the three elements of the Transfer Function. Therefore, the principles have been grouped into the categories of 1) Design Sensitivity, 2) Parameter Variation and 3) Performance Variation. Furthermore, it is of interest to categorise the principles in terms of when in the design process they can be applied. This is important because the number of potentially applicable principles is expected to decrease as the development project progresses. In Table 1, the Variation Reduction Principles are mapped on a generic product development process model adapted from Pahl and Beitz et al (2007). Not surprisingly, the table shows that as a project progresses, the number of applicable principles is reduced and that once the manufacturing phase is started, only a limited and seemingly more costly selection of principles is applicable.

Table . Applicability of Variation Reduction Principles

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| **Category** | **Principles** | **Conceptual Design** | **Embodiment Design** | **Detailed Design** | **Manufacturing** | **Assembly** |
| Design Sensitivity | 1 – Parameter Optimisation |  | x | x |  |  |
| 2 – Change of Design Principle | x | x |  |  |  |
| 3 – Uncoupling & Decoupling | x |  |  |  |  |
| 4 – Minimise number of design parameters |  | x | x |  |  |
| 5 – Self-reinforcement | x | x |  |  |  |
| 6 - Flexibility | x | x | x |  |  |
| 7 - Play |  | x | x |  |  |
| 8 - Redundancy | x | x |  |  |  |
| Parameter Variation | 9 – Tight tolerances |  | x | x | x |  |
| 10 – Sorting and Matching during Assembly | x | x | x | x |  |
| 11 – Shielding | x | x |  |  |  |
| Perfor-mance Variation | 12 – Adjustment during assembly and use | x | x | x | x | x |
| 13 – Post-assembly processing | x | x | x | x |  |
| 14 – Quality Control | x | x | x | x |  |
| 15 – Change functional requirements | x | x | x | x | x |

It is important to note that even principles related to later phases of manufacture and assembly should be decided upon during the early design phases when forming the product’s variation management strategy.

# Discussion

In this section, the intended use scenario, value, limitations and further research possibilities are discussed.

The VRP are intended to serve as a catalogue of inspiration for the design engineer and project management. It is the task of the design engineer to estimate, simulate or test the product’s functional performance – not only in terms of the expected nominal performance, but also in terms of the variation in performance. There will always be a potential for further reducing the variation and ultimately the design engineer will have to make a trade-off between the costs of further variation reduction efforts, versus the loss incurred by the expected variation. Furthermore, the alternative to a design with high performance variation could be a design with less variation but with a nominal performance which is worse. This would also demand a trade-off by the design engineer. It is worth noting, that the principles are not mutually exclusive, meaning that it is possible to combine multiple principles to obtain the desired results. Finally, it should be mentioned that the principles are not applicable in all design phases. As shown in , the design principles have a given ‘window’ where they are applicable. As an example, the principle ‘Minimise number of design parameters’ cannot be applied in the concept stage, as the design parameters have not been designed yet, but also cannot be applied during Manufacturing (or later) as the design is then locked. These restrictions therefore dictate which principles should be considered in a given development phase.

The **value** of the VRP lies in their simplicity and early-stage applicability. The field of robust design and reliability has a tendency to primarily focus on late-stage analysis and verification and less on simple principles and strategies which are applicable at the *point-of-design*, i.e. while the sketches and 3D-CAD are being produced. Furthermore, the value lies in the structure and comprehensiveness of the principles; they provide an overview of a wide array of alternative principles, which may support the design engineer in making the right decisions and pursuing all competitive principles for reducing variation in functional performance.

Although the advantages and disadvantages for each principle are presented, one of the **limitations** of the VRP is that it does not provide specific values for the costs and effects of applying a given principle. As a consequence, assumptions or further analyses must be made in order to evaluate whether there is a positive return of investment for applying a given principle.

As for **further research**, it would be interesting to analyse current industrial use of the presented principles and identify if and why certain principles are used more often than others, e.g. due to certain principles being inherently better than others or due to when in the design process the principles are applied. Furthermore, a more detailed and more quantified description of the pros and cons for each principle would provide the design engineer with a better foundation for making the right decisions and trade-offs. Finally, a framework to capture where variation enters the product and where strategies can be targeted would help to define a more formal and rigorous approach to a product variation management strategy.

# Conclusion

The aim of this paper was to identify principles for reducing variation in the functional behaviour of a product. Reducing the variation in functional performance is important because it reduces the product’s failure rate, it prevents unnecessary over-dimensioning of parts, and it reduces the quality loss experienced by the user. A catalogue of 15 design principles – called Variation Reduction Principles (VRP) – has been presented, along with case examples and a description of the advantages and disadvantages for each. Finally, the principles have been structured based on their applicability in the various product development stages. The VRP catalogue is intended to be a detailed support for the design engineer and a reminder to continuously strive for minimal variation in functional performance. Also, the VRP are seen as a counterweight to the many analysis and documentation tools often seen in the field of robustness and reliability engineering, as they are intended to be applied – or at least decided upon – at the point-of-design, rather than later in the design process.

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# References

Akao, Y., & King, B. (1990). Quality function deployment: integrating customer requirements into product design (Vol. 21). Cambridge, MA: Productivity Press.

Andersson, P. (1996). A process approach to robust design in early engineering design phases. Lund University.

Andersson, P. (1997). On robust design in the conceptual design phase: a qualitative approach. Journal of Engeering Design, 8(1), 75-89.

Andreasen, M. M., Howard, T. J., & Bruun, H. P. L. (2014). Domain Theory, its models and concepts. In An Anthology of Theories and Models of Design (pp. 173-195). Springer London.

Arvidsson, M., & Gremyr, I. (2008). Principles of robust design methodology.Quality and Reliability Engineering International, 24(1), 23-35.

Blanding, D.L. (1992), Principles of Exact Constraint Mechanical Design, Eastman Kodak Company, Rochester, NY.

Booker, J. D., Raines, M., & Swift, K. G. (2001). Designing capable and reliable products. Butterworth-Heinemann.

Chakhunashvili, A., Johansson, P. M., & Bergman, B. L. (2004, January). Variation mode and effect analysis. In Reliability and Maintainability, 2004 Annual Symposium-RAMS (pp. 364-369). IEEE.

Chen, K. S., Huang, M. L., & Li, R. K. (2001). Process capability analysis for an entire product. International Journal of Production Research, 39(17), 4077-4087.

Christensen, M. E., Howard, T. J., & Rasmussen, J. J. (2012). The foundation for robust design: enabling robustness through kinematic design and design clarity. In Design 2012-12th International Conference on Design (pp. 817-826).

Ebro, M., Krogstie, L, & Howard, T. J. (2015). A Robust Design Applicability Model. Submitted to 20th International Conference on Engineering Design (Under review).

Eifler, T., Christensen, M. E., & Howard, T. J. (2013). A classification of the industrial relevance of robust design methods. In 19th International Conference on Engineering Design (pp. 427-436).

Hasenkamp, T., Arvidsson, M., & Gremyr, I. (2009). A review of practices for robust design methodology. Journal of Engineering Design, 20(6), 645-657.

Lee, W. S., Grosh, D. L., Tillman, F. A., & Lie, C. H. (1985). Fault Tree Analysis, Methods, and Applications ߝ A Review. Reliability, IEEE Transactions on,34(3), 194-203.

Matthiassen, B. (1997). Design for Robustness and Reliability: Improving the Quality Consciousness in Engineering Design. PhD-thesis, Technical University of Denmark

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). Engineering design: a systematic approach (Vol. 157). Springer Science & Business Media.

Phadke, M. S. (1989). Quality engineering using design of experiments. InQuality Control, Robust Design, and the Taguchi Method (pp. 31-50). Springer US.

Phadke, M. S. (1995). Quality engineering using robust design. Prentice Hall PTR.

Söderberg, R., Lindkvist, L., & Dahlström, S. (2006). Computer-aided robustness analysis for compliant assemblies. Journal of Engineering Design,17(5), 411-428.

Suh, N. P. (2001). Axiomatic Design: Advances and Applications (The Oxford Series on Advanced Manufacturing).

Taguchi, G. (1986). Introduction to quality engineering: designing quality into products and processes.

Taguchi, G., Chowdhury, S. and Wu, Y. (2004) Introduction to the Quality Loss Function, in Taguchi's Quality Engineering Handbook, John Wiley & Sons, Inc., Hoboken, NJ, USA.

Thornton, A. C. (2004). Variation risk management: focusing quality improvements in product development and production. John Wiley & Sons.

Tjalve, E. (1976). Systematic Design of Industrial Products—Tools for the Design Engineer. DTU, Copenhagen: Akademisk Forlag.

Yang, K., & El-Haik, B. S. (2003). Design for six sigma (pp. 184-186). New York: McGraw-Hill.