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**Howard, Thomas J.; Ebro, Martin ; Eifler, Tobias; Pedersen, S.; Göhler, Simon Moritz; Christiansen, A.; Rafn, A.**

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# The Variation Management Framework (VMF) for Robust Design

T. J. Howard, M. Ebro, T. Eifler, S. Pedersen, S. M. Göhler, A. Christiansen & A. Rafn  
Technical University of Denmark

*Keywords: Robust Design, Quality Loss, Variation Management, Reliability Engineering*

## Abstract

Robust Design is an approach to reduce the effects of variation. There are numerous tools, methods and models associated with robust design, however, there is both a lack of a process model formalising the step of a robust design process and a framework tying the models together. In this paper we propose a framework for robust design and variation management by combining central models to Robust Design, namely, the Quality Loss Function, the Transfer Function and the Domains of Axiomatic Design. The framework shows how variation can be mapped from production right through to quality loss in the market place and identifies areas where action can be taken against variation. An additional benefit of the framework is that it makes the link between visual/sensory/perceptual robustness, product robustness, and production variation (Six Sigma).

## 1. Introduction

Despite the known benefits of Robust Design, studies have shown that the uptake in industry has been limited (Krogstie et al 2014) and that a lack of process or framework may be the reason for the inability to utilise the many tools available (Eifler et al 2013).

Robust design is a subset or reliability engineering. Where reliability engineering focuses on approaches to prevent the product from failing (or causing related systems to fail), robust design only concerns reliability related to variation. Robust Design is therefore defined as a methodology for designing products and mechanisms that are insensitive to variation. Here, 'insensitive' means that the product's performance, reliability and quality are consistent despite the ingoing variation. The types of input variation considered are related to (Christensen et al. 2012):

1. Manufacturing – part level deviations from the specified/nominal geometry
2. Assembly – misalignment of parts during assembly
3. Time – changes as a result of time such as creep, fatigue or wear.
4. Ambient conditions – changes due to environment, such as heat expansion
5. Load – variation caused by changing loading conditions
6. Material – batch to batch variations in material properties

*Material variations were not mentioned in the original list but have since been added.*

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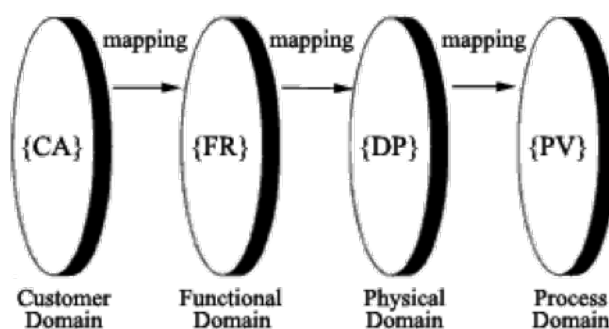
As robust design is defined by the term variation (as well as sensitivity), it is important to also consider where variation is introduced into product development and where it takes effect. This article proposes a framework to which attempts to describe robust design, sensitivity as well as variation throughout product development through the Variation Management Framework (VMF). In doing so the model brings together three central model based theories of robust design, namely, the transfer function, the quality loss function and axiomatic design.

## 2. Related Robustness Models

In this section we introduce the three model based theories related to robust design that compose the Variation Management Framework (VMF).

### 2.1. Axiomatic Design

Suh's Axiomatic Design, first proposed as the Principles of Design (Suh 1990) followed by Axiomatic Design, the Advanced Formulation (Suh 2001). In this model based theory, there are four key domains proposed, but each domain only has a relationship with (or through) the domain next to it in figure 1. An important thing to note is that variation can occur in all of the domains. Figure 1 describes the simplest form that the four domains occur and that actually there may be multiple levels to the process domain as well as multiple levels of Design parameters and function requirements linking to a single customer attribute. This simplification is also made in the VMF proposed in section 3 which uses all four domains to describe the framework.



*Figure 1. The domains of Axiomatic Design*

### 2.2. Transfer Function

The transfer function is almost synonymous to the definition of Robust Design. On the X axis is placed an input variable (or the design parameters) which relates to the output variable (the functional requirement) through a transfer function. The gradient of this function represents the sensitivity of a function to a change in a parameter, in other words its robustness. The transfer function is an excellent way to represent the conversion of input to output variation, where the output variation is the performance variation and the input variation is the process capability (Okholm et al 2014). The transfer function is centrally placed in the VMF.

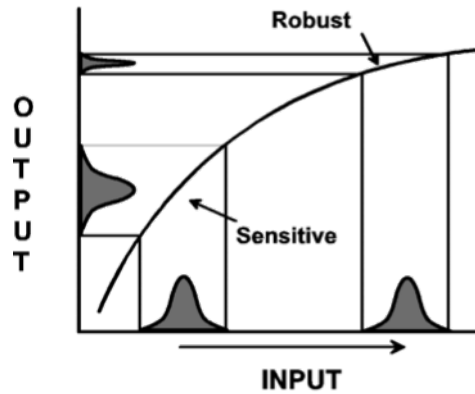


Figure 2. A Model of Variation Transfer (Transfer function)

### 2.3. Quality Loss Function

Taguchi in various works, e.g. (Taguchi et al 2005) discusses the concept of quality loss. Until this, the notion of upper and lower specification limits represented the cut off point for the allowable variation in a part/product and between these limits all variations are equally as acceptable (as shown by the red line in figure 3). The quality loss function describes a more accurate way to describe how acceptable a part/product is to the customer/user/operator. It suggests that any deviation from a correctly defined nominal value, will result in some quality loss experienced by the user. Minimising quality loss (or expenditure to achieve it) is ultimately the goal of robust design and is well represented by the quality loss function which is also integrated into the VMF in the following section.

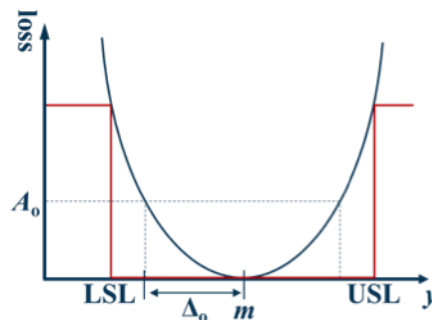


Figure 3. Quality Loss Function

### 3. The Variation Management Framework (VMF)

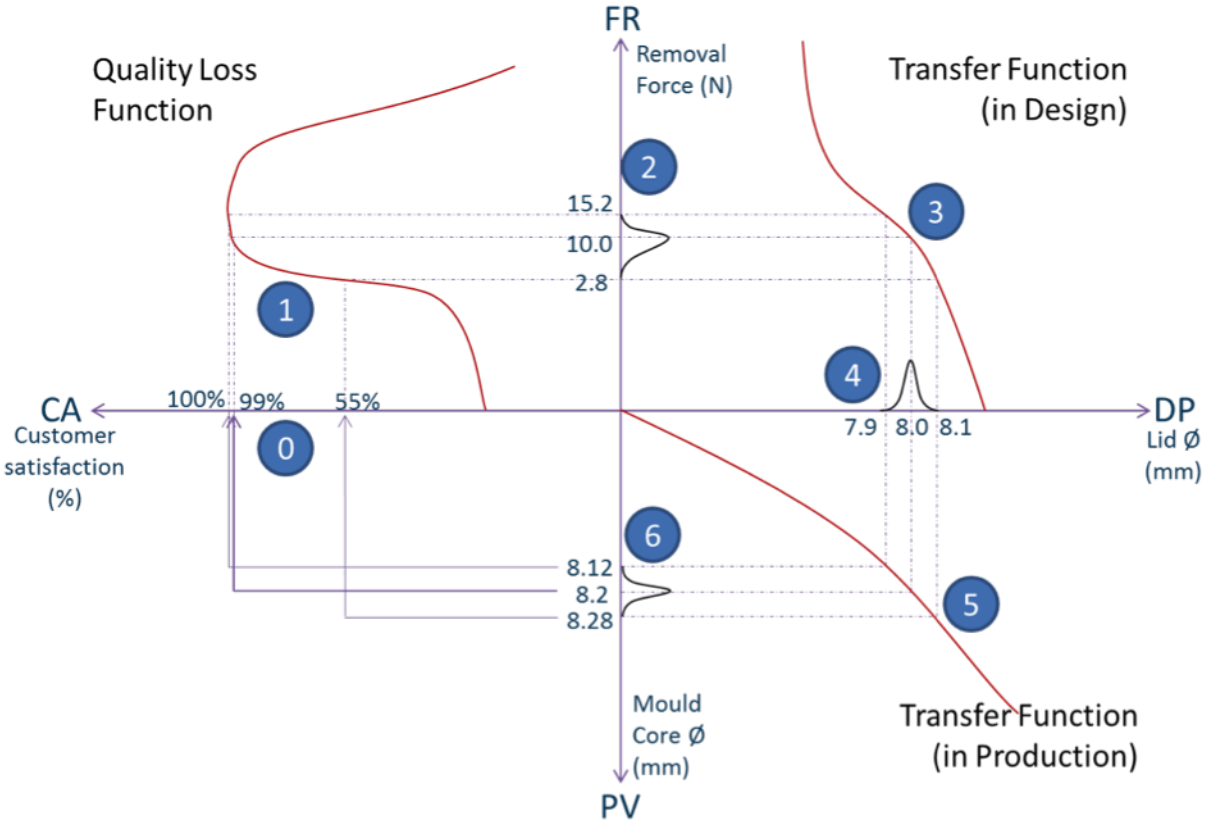
The VMF proposed in this paper consists of three main quadrants and a fourth representing tradeoff as shown in figure 4. The example data within figure 4 represents the variation of the pull off force required to remove a pen lid. The four axes of the VMF represent each of the four domains described by axiomatic design.

The upper left quadrant of the VMF represents the Quality Loss Function related to the removal force of the pen lid. The Quality Loss function is actually inverted to better fit the axiomatic domain of the customer attribute, terming it the degree of customer satisfaction (%). In figure 4, the example is constructed to show that a nominal force of 10N is not correctly set as the customer is most satisfied at 15N and thus over-spec lids will be preferred by customers. The 10N nominal removal force occurs due to the values of certain design parameters. For simplicity, the model in the upper right quadrant shows how this force varies with variation of a single design parameter - the lid diameter (assuming the lid fits to a nominal pen and all other

lid parameters are constant, such as its thickness). This is represented with a Transfer Function (in Design). The lower right quadrant is also represented with a transfer function but for production. In order to achieve the 8mm nominal diameter of the lid, a mould with the correct diameter core must be created to achieve it (assuming all other Process Variables are kept constant). With the example VMF now in place it is easy to see at least 7 areas where the variation can be traded-off (blue circle).

**Table 1. Variation Intervention and Trade-off points**

0	Accept variation in the marketplace
1	Reduce sensory/perceptual robustness (perhaps add more tactile features to lid)
2	Reduce outgoing variation by increasing outgoing quality control (product sampling)
3	Reduce the sensitivity of the design
4	Reduce ingoing variation by increasing ingoing quality control (part measurement)
5	Reduce production sensitivity (design of experiments)
6	Reduce production variation (iteration and re-working of moulds)



**Figure 4. Variation Management Framework (VMF) modelling an example of a pen lid removal force**

**4. Conclusion**

The Variation Management Framework (VMF) has successfully integrated several central theories related to robust design. The framework is perhaps the only one of its kind linking variation in production to the quality loss experienced in the marketplace. The VMF has so far proven to be a useful framework to communicate robust design and variation at both engineering and senior management levels.

In addition to the VMF's descriptive utility, it has also been shown as a potentially useful model on which to base variation-cost tradeoff decisions in product development. It illustrates, that a robust design can be achieved by applying other strategies that merely applying parameter optimization, which is often described as the main focus of robust design. The VMF has also been adopted for use in framing a robust design research programme between Novo Nordisk and the Technical University of Denmark, where the work packages have been positioned in each of the four quadrants to delimitate the project work.

The model does bear a number of limitations due to its simplified nature, the main limitation being its lack of ability to describe complexity. In axiomatic design terms, issues arise when multiple Design Parameters are interacting with Multiple Functional Requirements in a coupled manner. As the VMF only represents a one dimensional view such coupling and complexity issues are not captured. The same is true for the numerous Process Variables and noise factors at play when producing a part.

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Thomas J. Howard  
Head of Robust Design Group  
Department of Mechanical Engineering  
Technical University of Denmark  
Produktionstorvet Building 426, 2800 Kgs. Lyngby, DK  
Tel: +45 45254741  
E-mail: thow@mek.dtu.dk  
URL: www.mek.dtu.dk