



The variation management framework (VMF): A unifying graphical representation of robust design

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The Variation Management Framework (VMF) for Robust Design

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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 steps 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 Variation Management Framework (VMF) shows how variation can be mapped from production right through to quality loss in the market place and identifies areas where action should 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). Seven levers which can be activated to increase product quality are described and positioned on the VMF. Proposals for combining with complexity analysis and a set of linked quality and robustness metrics are proposed.

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 can be viewed as a subset of reliability and quality 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 input 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.

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 Variation Management Framework (VMF) which links variation experienced in production, to how it affects the product, to how it impacts on the perception to the user in

terms of quality loss. 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 (Axiomatic Design, Transfer Function and Quality Loss Function, described in the follow subsections) that compose the Variation Management Framework (VMF). These three models, are quite dominant in literature related to robust design, however, how these models are as yet not explicitly integrated and exist as part of their own methodologies.

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) makes the provocative claim that underpinning engineering design there are just two fundamental axioms (self-evident truths). Derived from these axioms are a series of corollaries and theorems to help to recognise and remedy problematic design situations. In this model based theory, there are four key domains proposed: CA – Customer Attribute, FR – Functional Requirement, DP – Design Parameter and PV Process variable. The axioms apply to the mappings between each domain. An important thing to note is that variation can be experienced in all of the domains.

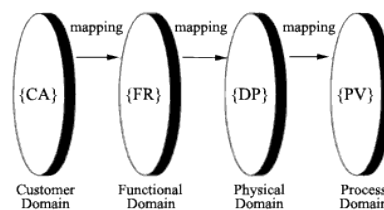


Figure 1. The domains of Axiomatic Design

Figure 1 show the relation between the four domains where each domain only has a relationship with the domain next to it. In its simplest form it is one dimensional, showing how one CA maps to one FR to one DP and one PV. This simplification is also made in the VMF proposed in section 3 which maps variation in all four domains as part of the framework. However, products usually do not have such a one dimensional relation and we experience more of a hierarchical structure in reality, as shown in figure 2.

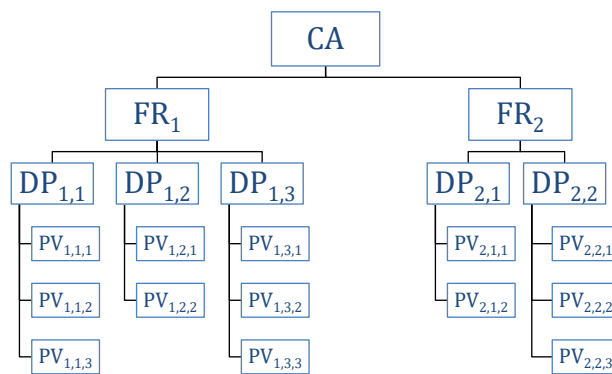


Figure 2. The hierarchy of domains in Axiomatic Design

It is also very likely that there will be multiple levels within each domain, for example, in order to achieve a certain geometry or value for a design parameter, this may require several process steps each step containing Process Variables that may influence the next process step. However, for clarity this will not be considered further in this paper.

2.2. Transfer Function

The transfer function provides the best model to graphically describe Robust Design and its affects. On the X axis of Figure 3, is placed an input variable (or the Design Parameters in Suh's terminology) 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 shallower the gradient the more robust and less sensitive a function requirement is to change in design parameter. 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 can come from any of the six sources of variation listed in the introduction, but is often the production tolerance or process capability (Okholm et al 2014). The transfer function is centrally placed in the VMF.

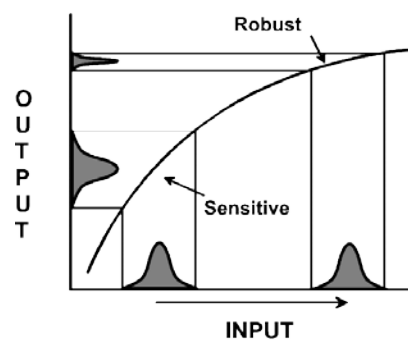


Figure 3. A Model of Variation Transfer (Transfer function)

For non-linear transfer functions it is possible to change the value of the design parameter (e.g. a part's dimension) to create a more robust design. Figure 3 shows that when choosing the lower value for the design parameter the same amount of ingoing variation results in a great deal more outgoing variation than for the upper value due to the gradient of the transfer function at that point. This is a very widely used diagram, but for mechanical design this can be somewhat misleading as it is often the case that changing dimensions change the way the product behaves

and therefore this approach indicates a trade-off between nominal performance and robustness (consistency of performance).

In mechanical design we are therefore seldom at liberty to select the value of a single parameter purely to increase robustness. Multiple parameter optimisation for robustness can sometime overcome this issue where the values of several parameters can be adjusted to give the same nominal performance but with greater overall robustness. However, in mechanical design there is often still the complication that larger dimensions are usually more robust in mechanisms, but at the same time larger dimensions often have the greatest input variation from manufacturing - the larger the dimension the more variation expected (in absolute terms but not as a percentage of the dimension) (DIN ISO 286).

It is for these reasons that increasing robustness in mechanical design often required a change of solution principle creating an entirely new transfer function. Often a simple way to do this is through the design clarity approach (Ebro et al 2012) aiming for parameter reduction and decoupling, carving away the dimensions of the hypercube describing the 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 seen as equally acceptable (as shown by the left chart in Figure 4). In its pure and original form, Taguchi describes the quality loss function to describe how variation in functional performance leads to a loss to society (in units of USD). However, the approach can be somewhat simplified to

estimate the perceived loss to customer/user/operator instead. Here it is suggested that any deviation from a correctly defined nominal value will result in some quality loss experienced by the user, as can be seen by in the chart on the right of Figure 4. 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 section 3.

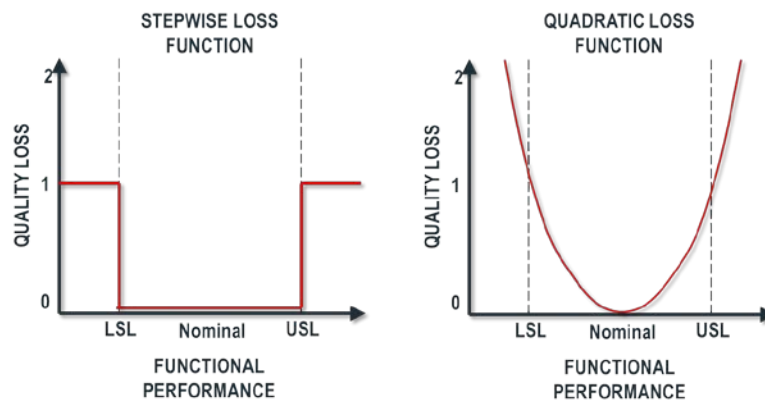


Figure 4. The quality loss function seen as a stepwise function (left) and a quadratic loss function (right).

Quality Loss curve have several specific challenges which will be briefly discussed in turn:

What is the unit of quality loss? The first decision to be made is whether we are referring to the quality loss of the product as a whole or of the single function – this makes a big difference as you could perceive a dramatic quality loss of a single function but if the function is relatively minor with respect to the product’s main functions, the quality loss to the product will be less significant. In Taguchi’s terms quality loss should always be represented in terms of financial impact. If we consider the financial impact to the customer or end user – how much has brand value been damaged, how many product complaints and returns, how many future products will we not sell as a result etc. Another more simple alternative, is to consider the percentage

perceived quality loss of a functional requirement, assuming that no quality loss is performing to the expected levels.

How to quantify quality loss? Even with an established unit for quality loss, there is no clear, simple and reliable approach for quantification. Often this will require asking users to turn a subjective, qualitative judgement into a quantified value. This can be done by asking questions such as how much is this worth? Or how much do you feel the quality has reduced by? Other approaches concern the acceptable range of variation for multiple participants representing the user population. It is possible to quantify the quality loss in terms of how many of the user population either notice a loss or find the loss unacceptable. Figure 5 shows the results of a survey to find the acceptable activation force of a product which can be used to create the upper and lower limits and to model the loss within and beyond the limits by plotting a cumulative curve.

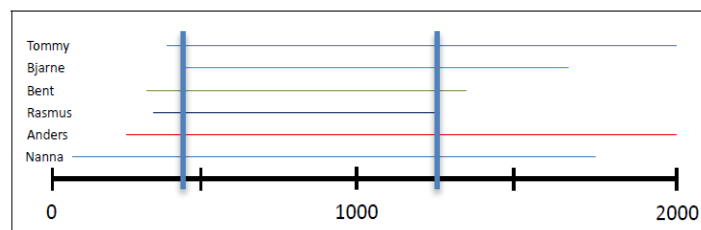


Figure 5. Acceptable activation force survey

It may also not be necessary to quantify the quality loss, and instead use a qualitative scale of Excellent, good acceptable, noticeably bad, bad.

How to gather the data? So even if theoretically quantifiable, gathering the data to fit a quality loss curve is no easy task. For software solutions it is more plausible, where parameters such as size, colour etc. can be varied and user responses gained in a survey or interview setting. For hardware/physical products it is often extremely hard to isolate the influence of single parameters. When it comes to results related to visual appearance the product can be simulated

and electronically, often done for split lines in mobile phones and cars, for example (Wagersten et al 2007, Huittinen 2015, Forslund, et al 2006). However, when concerning audio (Boegedal et al 2015) or tactile issues, physical experiments may be required, such a rig used to vary the activation force for participants (used to generate the data in Figure 5).

In recent work (Pedersen et al 2015), attempts have been made to incorporate quality loss functions into requirements specifications, so that The effect of variation is clear to the engineering designer. This would allow the engineering to assess where the nominal value should be placed and to decide if necessary which side of the nominal variation would have less impact.

3. The Variation Management Framework (VMF)

The VMF takes the concept of the quality loss function and the transfer function to represent variation across the four domains proposed in axiomatic design. The objective of the framework is to explain and visualize how variation transfers from one domain to then next and what strategic levels are available to project managers with regards to improving product quality. The VMF proposed in this paper consists of three main quadrants linking the four domains of axiomatic design (labeled on the axes), as shown in Figure 6. The fourth quadrant can be seen to represent tradeoff between production process investment and quality loss in the mark, however, this quadrant will ne be detailed further as this is just one of several quality trade-offs areas depicted by the VMF. The figure shown uses estimated data and relationships to populate a VMF modelling the pull off force required to remove a pen cap. Marked onto the model are 7 blue circles indicating the lever positions where the project manager has the opportunity to invest in quality improvements. Each quadrant will now be discussed in turn.

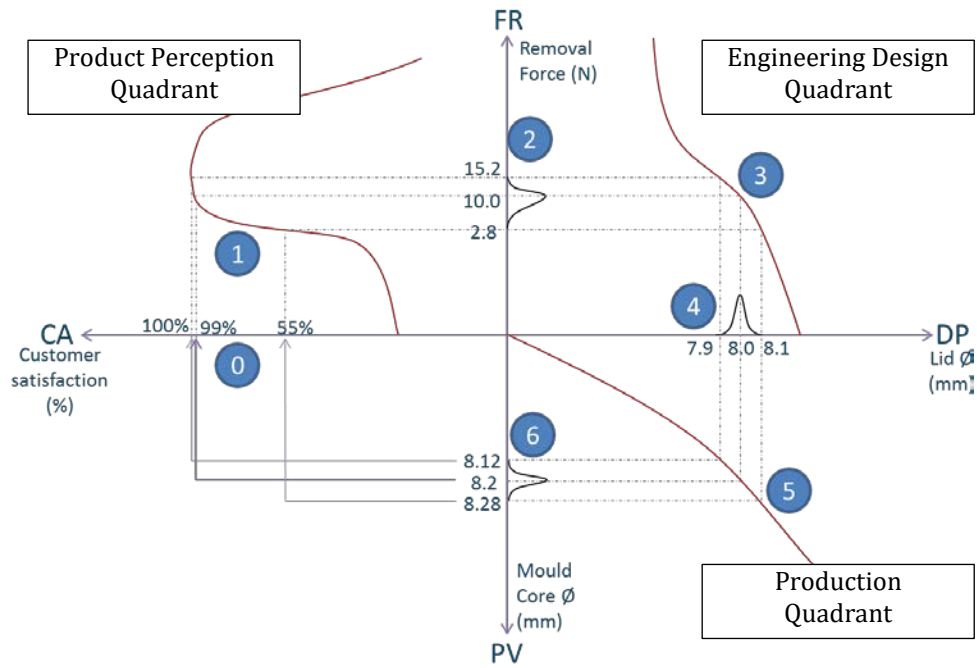


Figure 6. Variation Management Framework (VMF) modelling an example of a pen cap removal force

The Variation Management Framework can be used to describe the journey to quality. During the design phase the product development team will run through the VMF sequentially in order CA-FR-DP-PV with some feedback loops. However, on the design and quality verification side it will be the reverse process PV-DP-FR-CA. Each direction requires different activities, however the dependences identified during the design phase can be used to predict product quality based on real measurement data.

3.1. The Product Perception Quadrant (CA-FR)

The upper left quadrant of the VMF represents the Quality Loss Function related to the removal force of the pen cap. In order to fit to the VMF the inverse of the Quality Loss Function is sketched. On the vertical axis is the functional requirement with the variation in functional performances sketched. On the x axis is degree of customer satisfaction (%), where the red

curve shows how there is a significant loss in satisfaction (a quality loss) as the value of the functional performance varies greatly from the nominal. In Figure 6 the mean of the functional performance distribution is actually not optimally positioned and the upper end of the distribution at around 15N leads to a greater customer satisfaction. This is sometimes overlooked in companies where there will be large robustness and quality control programmes which may be optimizing around a sub-optimal goal from a customer satisfaction point of view.

It may also be observed from Figure 6, that the quality loss function has an optimal or target point around 15N. This is not always the case as many loss functions will have either a smaller-is-better characteristic (e.g. Weight - this often has an upper limit but otherwise, the lighter the better), or a larger-is-better characteristic (e.g. Stiffness – often will have a lower tolerable limit but otherwise, the stiffer the better).

In this quadrant there are three main levers:

Lever 0 – where it is possible to simply accept the current levels of quality loss. This is a non-action and therefore not really a lever, thus the label of 0. Obviously this is not a desirable strategy, however, it may be the best option when the loss is low or the cost/time of implementing change at any of the other lever points is too great. It may be possible to market and price the product at a low price point to compensate.

Lever 1 – here we have a possibility to try to limit how the variation in functional performance negatively impacts the perception of the user/customer. There are few established design approaches to achieve this, however, one approach that has been considered with some success is the visual robustness approach. A nice example can be taken from (Forslund et al 2013) shown in Figure 7. The figure shows two vacuum cleaners A and B where the panels on the

vacuum cleaners a very slightly misaligned from where they should be. Vacuum clean A is visually sensitive and it is very easy to see that the panels are not ‘flush’ as they should be. Vacuum clean B is relatively much more visually robust, as the user will not be able to sense the variation in the positioning of the dark and light panels. In other words B can have looser tolerances, more variation and still be perceived as better quality by the consumer.

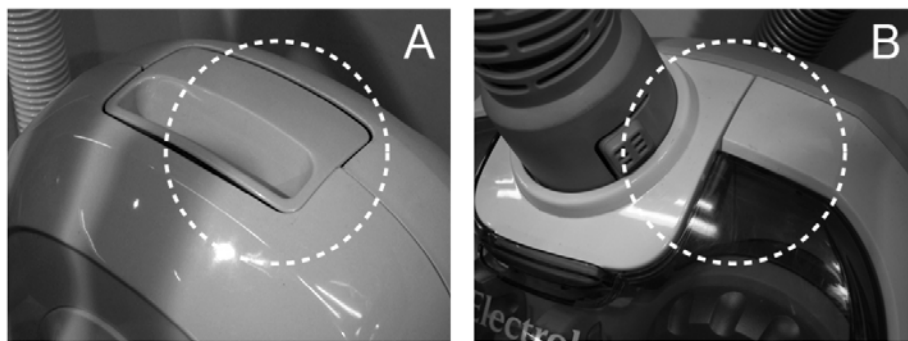


Figure 7. Example of Visual Robustness

Schvaneveldt and Enkawa (1992) term this type of lever as a “compensatory approach” to reducing quality loss. They provide some simple examples from the service sector to illustrate the concept, such as reducing the customers sensitivity to flight delays by providing complementary refreshments and entertainment during the waiting period. In the example case of the pen cap, providing a user with an opening tool or feature to enable the user to apply more force/grip would prevent the user from being overly dissatisfied when the cap becomes too tight.

Lever 2 – Here, the most simple intervention is to set the target value of the functional performance to achieve a more optimal position on the quality loss curve. This is a simple matter of definition in the requirements specification but requires good data from the QLF in

order to set the correct values. Schvaneveldt and Enkawa (1992) term this type of lever a “facilitating approach” to reducing quality loss, where the idea is to reduce the functional performance variation. In the flight delay example, this activating this lever would mean cutting delays by using advanced boarding techniques or seating and baggage arrangements etc. In the pen cap example, this lever would take the form of a quality control filter preventing pens will too high or low pull off force from entering the marketplace.

In a recent article Ebro and Howard (2015) list a number of additional robust design strategies for variation reduction. The strategies that apply for this lever are post assembly adjustment – were the product can be adjusted or calibrated to reduce the variation in its functional performance, and also post assembly processing, where for example an assembled product can be ground down to the correct overall length. Not that lever 2 options also apply at the output of the production quadrant.

3.2. The Engineering Design Quadrant (FR-DP)

The upper right quadrant is a typical transfer function linking design parameter variation to variation in functional performance. The example shows how the pull off force of a cap varies with variation of a single design parameter - the cap diameter (assuming the cap fits to a nominal pen and all other cap parameters are constant, such as its thickness). In order to undertake the engineering design work in this quadrant, a quantified functional requirement must be transferred from the Product perception quadrant setting the nominal target for the functional requirement. In an ideal situation the quality loss function would have already been sketched out at this point, the target value set along with the upper and lower specification limits to coincide with tolerable quality loss to the user.

The job of the engineering designer is then to create a design that meets the requirements and is as robust as possible. A robust design will reduce the gradient of the transfer function and therefore allow a greater amount of input variation in the design parameter for the same functional performance on the output. This is directly linked to cost saving since the more robust the design is the looser the production tolerances can be.

The functional requirements can take many forms describing the performance of the product that matters to the user, the Design parameters are those that are specified on engineering drawings and part selections, such as coefficient of friction, stiffness, but more often than not it will be single dimensions or a tolerance chain.

In this quadrant there are two main levers to reduce quality loss:

Lever 3 – reducing the gradient of the transfer function is the essence of robust design. There are numerous ways in which this can be done, to name a few (Ebro & Howard 2015):

- *Parameter optimisation* – When we have multiple parameters interacting to achieve the functional requirement, the engineer can specify a legal range of values for each parameter. The optimisation algorithm will then find combinations of the values for each design parameter to achieve the functional requirement with minimum affect from parameter variation. However, a full mathematical description of the transfer function is required.
- *Change of Design Principle* – This has the most potential for large improvements in robustness and should be considered thoroughly during the early stages of design. However, it is often the case the robustness needs to be trades off against other factors

such as cost, usability, manufacturability etc. which can somewhat limit the options available.

- *Uncoupling & Reducing Design Parameters* – It is not well described by this one dimensional version of the VMF, by reducing the number of design parameters and the coupling between them and the different functional requirements is an extremely effective way to increase robustness (Göhler & Howard 2015; Suh 2001)
- *Play and flexibility* – These are often undesirable options as they often have negative and unpredictable consequences, such a noise vibration and lack of control of positioning of mechanisms. However, both can be an effective way to fix quality issues at late stages of the development process.
- *Self-Reinforcement and Shielding* – By applying this strategy, one of the specification limits of the device or product is effectively removed. For example a tong clamp need not be adjusted as its grip mechanism is designed to compensated for variation in the weight of the object being lifted. Shielding works in a similar way, where the product is made to be insulated from external disturbances and noise factors.
- *Redundancy* – *Redundancy is often considered as either passive, where the product is performing with excess capacity so that if one element fails the product continues to perform (e.g. Airplane engines), or active, which is when one element of a product fails a new element is activated to take its place (e.g. the use of circuit breakers). A four legged chair of often used incorrectly as an example of passive redundant design. While it is correct that the chair need only three legs, if one of the four legs was to give way, the redundant leg would not be activated or of any use. This is often cited as a violation of design clarity of Suh's information axiom.*
- *Over Engineering* – *on typical approach to dealing with variation is to over engineer the product to make sure that even at the extremes of variation, there will not be a*

failure. Of course this is undesirable of often a consequence of the design not fully understanding the behaviour of the design of the limits of the use conditions.

In order to model the sensitivity to the design parameters with respect to the functional requirement, there are basically three options available:

1. Analysis – the underlying formula (first order principle) can be derived and basic input – output variation calculations can be made.
2. Simulation – simulation packages are able to create a surrogate model that can be used to determine the sensitivities of the design parameters. Not all simulation tools have robustness optimisation, so the variation may need to be introduced manually and used in conjunction with Design of Experiments (DoE).
3. Experimentation – When no simulation is available, a physical model or test rig can be created to test the sensitivities. This requires that the parameters can be accurately controlled and adjusted and the resulting output on the functional performance measured. DOE can also be utilised here as well.

In design terms, the above three options are in order of preference as it is quick, easier and less expensive to work using analytical models or even simulations wherever possible. The experimentation route does have the added benefit that it will better consider noise factors and unanticipated disturbances. Nevertheless, it is often seen as a good approach to experiment in order to verify analytical models or simulations, not in order to build them.

Lever 4 – involves reducing the input variation into the design. In manufacturing terms this can mean utilising inline quality control to prevent parts or subassemblies which are out of spec

from progressing further. Tightening the quality control filter will improved product quality and consistency to the customer, but it is costly and involves more scrapped material.

If the component is out of spec, there are other options available as opposed to scrapping the part. It may be possible to re-work, trim, sim or adjust the component so that it is in spec. Of course this is not very viable for mass produced parts, but in the aerospace industry, it is often economically viable to try to save expensive turbine blades through re-work.

For mass production there is another option available. In the bearing industry the different sizes of ball bearings can be matched to the different size races. For example, ball bearings at the upper limit of size can be match with inner races at the lower limit and outer races at the upper limit so to fit more tightly. Apple also used this approach for the iPhone 5 where the edge of each aluminium bodies is matched to the closest profile of 725 glass inlays to ensure a better quality fit.

3.3. The Production Quadrant (DP-PV)

The lower right quadrant is also represented with a transfer function but for production. In order to achieve the 8mm nominal diameter of the cap, a mould with the correct diameter core must be created to achieve it (assuming all other Process Variables are kept constant). However, in multiple cavity injection-moulding machines, each mould tool will be different which is why we may see some stochastic variation on the y axis of the process variable. The process variable will then influence the resulting design parameter through the process transfer function (the red line in the third quadrant). In the example case linking the mould tool diameter to the cap diameter the transfer function is likely to be very linear, however, it would look different for different process variables such as injection pressure and temperature. This is the

area that the quadrant in which six sigma methodologies have traditionally focused on with respect to quality engineering.

The levers applicable in this quadrant are:

Lever 5 – is about reducing the impact of changes in the process variables on the design parameter. These levers would utilise approaches such as mould flow simulation and optimisation techniques which can also be optimised for robustness. The process design team also have some decisions related to design, such as the inlet position and the position of the mould parting lines. Mould construction can also have an impact on the robustness of the process, especially in terms of the number of pieces and the construction of the mould.

Further process steps also have influence, such as whether to over-mould components, see (Muteau & Fahrner 2009) for example. By over-moulding the outer component is by the nature of the process dimensioned to the inner components. Where if it were to be separately moulded and then assembled there would be tolerances from both inner and outer components to factor in.

A very important decision at this stage is if the process design team want the components or the fixture to be responsible for the overall tolerance of the geometry. In the former case it is important that all of the individual components and interfaces between are tightly controlled in order to reduce the variation of the overall tolerances chain. However, when the tolerance chain becomes too large it may be more beneficial to adjust or set the geometry of the assembly based on a fixture which can be precisely controlled. This is a method known as variation absorption.

When processes are running over long periods of time they will typically drift (mean shift). When calculating the Cpk and sigma values of a production system, 1.5 sigma is often deducted to estimate the long term process capability (Okholm et al 2014). However, this is simply an estimate and more robust process will degrade by less where sensitive processes will degrade by more. At this stage it is valuable to consider the monitoring/inspection approach to identify mean shift and to strategically design in flexible and adjustable elements into the process so that the mean performance of the device can be realigned to the nominal more easily.

It is often possible to predict the direction that the mean will drift towards, furthermore, it may even be possible to design the process to drift in the less sensitive direction relative to the product performance. When the direction of drift can be predicted in advance, the design of the adjustable or flexible elements can be done more effectively.

It is often the case that the sensitivity of each of the process variables with respect to the design parameters will not be known. Sometimes these sensitivities can be gained through simulations; however, Design of Experiments (DoE) is often used to understand the relationships and Pareto diagrams created to show the relative sensitivities.

Lever 6 – involves the tight control and regulation of process variables. This can involve a number of typical production techniques such as:

- climate controlled production,
- monitoring, testing and control of material stock,
- operator training and standardised operating procedures
- regular tool maintenance and changes
- quality control and inspection of tooling

- robust fixtures, jigs and nests
- more regular billets and blanks
- noise and vibration balancing

4. Key Performance Indicators (KPIs) and Metrics

It is a future goal for the VMF to develop KPIs or metrics that can be combined from one domain to the next, so that their influence on the overall product quality can be determined. In Figure 9, seven positions for metrics are laid out where the theta (θ) metrics represent sensitivities, and metrics on the axes represent variation related metrics. Q_{pk} is the final metric of product robustness, which should be maintained and improved during any quality initiative.

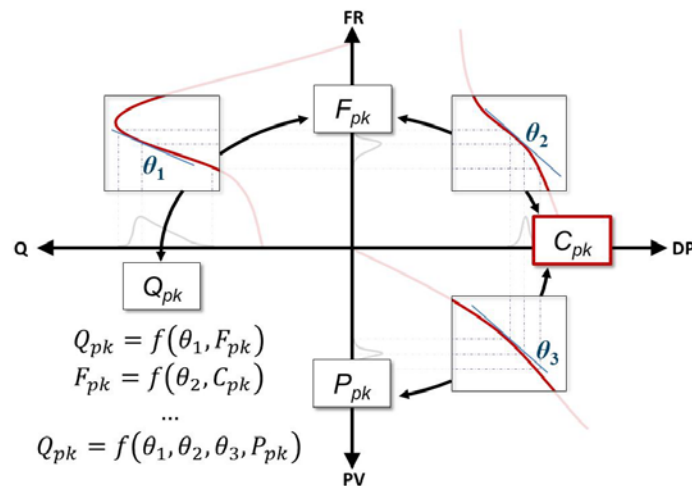


Figure 8. VMF KPIs

These KPIs are based around metrics that production would then typically use, such as C_p (variation only) and C_{pk} (variation and mean shift) values to determine how well their production is meeting the tolerance limits. In production, terms such as tolerance, nominals, C_p , and C_{pk} values can be confusing, not least because it is sometimes ambiguous whether it refers to the part characteristic or the product function. In the VMF the distinction is clear between the F_{pk} (the ability of a process to achieve a function tolerance) and the C_{pk} (the

ability of a process to achieve the feature tolerance).

If we take a single chain of variation PV-DP-FRCA and we assume there are no quality control gates, then the perceived quality of the product would, in theory, be linked directly to the Variation in process parameters through the three sensitivity values: $Q_{pk} = f(\theta_1, \theta_2, \theta_3, P_{pk})$. As can be seen from the third section, this is directly complementary to the calculation of the VRPN.

5. 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, low quality-loss design can be achieved by applying other strategies that merely applying parameter optimization at each of the seven different lever positions. The VMF has also been adopted for framing research initiatives, where it is now possible to more clearly define where the different robust design researchers are working and how their contributions link together.

The case example of the pen cap is a mass produced product. The FR target and limits were set based on user studies. The design was not iterated altering levers 0, 1 afterward. During production, functional testing (in level position 2) was conducted and fault analysis could be undertaken if unexplained variation was identified from the sampling. Variation was mainly

reduced through lever 3 where the interface geometry was optimised for robustness, where rather than using the entire diameter of the lid to secure it, small protrusions were used. These small protrusions can be produced with much looser tolerances and still provide the same variation in removal force (meaning the gradient of the transfer function in quadrant 2 was dramatically reduced). Levers 5 was also well iterated through DOE in order optimising the production to create minimal part variation and input variation controlled in lever 6 accordingly. As the product was mass produced (roughly 1 billion items) lever 4 could not be used extensively as not all caps were measured, however, batches of caps could be discarded based on sampling and statistical process control.

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. However, integration with Multiple Domain Matrices has been proposed and appears promising. Future work on the VMF will seem it expanding into a more operational control panel allowing the quality for the product to be predicted in design and during production.

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