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A Gap Model for Understanding the Variation of the Real Product from the Ideal

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ABSTRACT

Clients have an idealised view of the appearance and functionality of the products they are sourcing. Their product requirements vary according to their specific circumstances and experiences. When designers try to meet or surpass client expectations, variation results and the product will deviate from the client's idealised view. This often results in frustration, disappointment and rework for everyone concerned. Consequently designers must understand the sources of variation affecting their products and the techniques and tools that they can employ to reduce the negative effects of this variation.

This paper examines the factors influencing clients as they formulate their expectations. It investigates why product variation causes the final product delivered to the client to vary from that expected. A gap model is proposed that visually describes the variation and assists in its understanding. This model introduces the concept of gaps and it is these gaps that need to be closed so that the actual product tends towards the ideal product envisaged by the client. The paper also describes some existing approaches that are important for reducing the effects of variation and that help suppliers deliver what customers really expect.

KEYWORDS
Product variation, Gap model, Variation reduction methods.

1. BACKGROUND

Traditionally it was relatively easy to confirm if manufactured parts were meeting quality requirements through simple dimensional and/or functional checks. It is more difficult to rate the quality of a service organisation since the customer's expectations and perceptions play a pivotal role. The main source of this difficulty is that expectations and perceptions differ for everyone depending upon their specific circumstances and experiences. Clients now take for granted that a component part will meet the dimensional requirements; they expect more. To quote Ann Livermore, who heads the services organization at HP: "These days, building the best server isn't enough. That's the price of entry" [1].

Clients have an idealized view of how products that are contracted out for development will look and function. To be successful suppliers must strive to deliver the ideal products imagined by their clients. However, despite the best intentions of the contractor the client seldom gets the ideal product initially imagined; there is a gap between the ideal and delivered products. Suppliers need to understand the causes of the gap between the actual products that they can deliver and the ideal products imagined by their clients so that they can fine tune their process to more closely meet customer expectations. Models used to describe this gap between the ideal and delivered products should incorporate characteristics of how service quality is evaluated in addition to the form/fit/function of engineering components.

In this paper the author proposes a model to help suppliers understand how a client develops an "ideal" product expectation and the gaps preventing a supplier from delivering this. This model is based on the concept of gaps and indicates those gaps that need to be closed so that the actual product and the ideal product envisaged by the customer converge. The proposed model is defined in section 2. Methods that can be used to reduce the effects of this variation, thus closing the gaps, are summarised in section 3. The paper concludes with section 4 stating the paper's conclusions.

2. MODEL DEFINITION

The proposed model consists of 2 separate and distinct parts:

1) The "Idealised product definition" shows the various factors that influence a client when developing an ideal product expectation.
2) The "Actual product variation" shows the sources of variation causing the gap between the ideal and actual product received by the client.

2.1 "Idealised product" definition

Zeithmal et al. [2] described a customer service model listing criteria by which a customer will evaluate goods or services and also confirmed that the only criteria in evaluating service quality are defined by customers. Customers define their expected/idealised product based upon similar criteria. Hence Zeithmal et al.'s model is useful in understanding how a client's idealised product will vary depending upon factors, including their past experiences and personal needs, as shown in Figure 1.

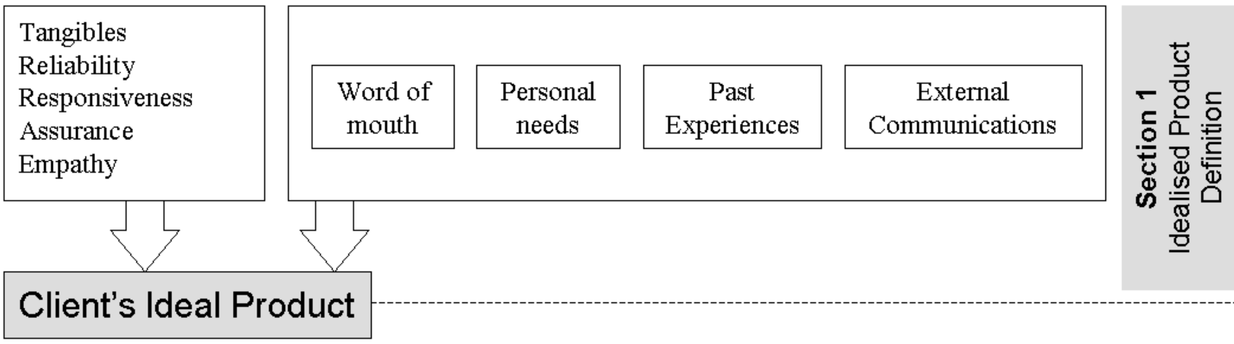

Figure1: showing influences on clients when developing an ideal product expectation

2.2 Actual product variation

Product life cycles include the categories of product definition, design/tooling and mass production. Activities such as concept design, recycleability/disposal at end of life should be addressed during design and can be incorporated within these categories. Activities in each of these categories cause a discontinuity, or gap, resulting in the actual product delivered deviating from that imagined by the client.

2.2.1 Variation Gap (Product definition phase)

Product definition prior to design is vital to ensure that the contractor is actually designing the product that the client wants. Sometimes a customer might not fully explain their **requirements** and a design engineer might forget to ask the appropriate questions to probe this in more detail. Kamm, who designed an assembly machine, quotes an apt example of what went wrong when he designed an assembly machine [3]. When the completed machine was undergoing final qualification the client expressed horror at the assembly cycle time and discovered that the real cycle time was substantially different than originally expected and used to cost the project, but the expected assembly cycle time was never explained to him. (See ΔR in Figure2)

Sometimes a customer might explain their requirements but might not be clear enough resulting in **misinterpretation** by the client. Simple examples might be colours (for example "Grey" instead of "*pantone* grey") or size ("must fit comfortably in your hand" might give totally different results depending upon the average hand size in the region where the customer and client are located). (See ΔI in Figure2)

2.2.2 Variation Gap (Design and tooling phase)

Weak design can often cause issues for a product. Design is interrelated to product cost and reliability so it is vital to develop a strong design according to client priorities. In sectors such as healthcare or defence, this might be reliability whereas in others, such as consumer electronics, it might be cost or size. Trends are for increased reliability at minimum cost. (See ΔD in Figure2)

Material variation should be addressed by designers during the design phase. For example if a sheet steel supplier cannot supply material within specific temper/hardness bands then problems (for example cracking) may be seen between batches during stamping/forming operations. (See ΔM in Figure2)

During product design a nominal dimension and tolerance band is specified. If the tooling (mould/die) being used varies from nominal the process window available during mass production is reduced. Designers should specify the most important dimensions so that tooling vendors can get the relevant tooling dimensions as close to nominal as possible and/or have adjusters in the tool. The optimum situation (when a bilateral tolerance has been specified) occurs when **nominal tooling dimensions** are centred about the required nominal component dimensions. (See ΔT in Figure2)

2.2.3 Variation Gap (Mass production phase)

During process qualification and mass production it is important that the product being made is dimensionally checked to ensure that it is within the specified design tolerance. The observed value is the sum of the actual value and the **measurement error**. Companies must ensure that dimensions made by different operators using the same gauge/measurement system are comparable. If more than one gauge is needed (for reasons of capacity or multiple manufacturing locations) duplicate gauges must be referenced relative to each other. (See ΔMe in Figure2)

During mass production inherent **process variation** can cause the dimensions of the parts produced to vary. Factors such as machine rigidity and positional repeatability contribute to this variation. In addition special-cause variation due to identifiable sources can also cause the actual dimensions to vary from nominal. Special-cause variation has identifiable sources and these can be traced and eliminated. An example would be damage to or breakage of mould inserts which could cause flash or malformed parts until the insert is repaired/replaced. (See ΔP in Figure2)

The above relates to component manufacture. Further variation can result if the part is **processed into a final product**. This can cause the final product to vary from the ideal. For example, it may vary visually (discoloration during reflow) or geometrically (deformation during reflow). (See ΔA in Figure2)

The variation resulting in the actual product deviating from the idealised one can be expressed by:

Total Variation	=	Variation gap during product definition phase	+	Variation gap during design & tooling phase	+	Variation gap during Mass production

Combining the two sections of the model, as shown in Figure2, allows suppliers to understand the factors that cause a client to have an idealised view of the product to be developed and also illustrates the gaps that help to explain why the actual product delivered does not always match this idealised view. The vertical steps represent the gaps caused by each contributing factor. Anecdotal evidence and the direct industrial experience of the authors suggest that the largest contributors are variation of tooling dimensions from nominal and process variation. To be successful suppliers must close (or reduce) these gaps and in so doing offer clients the ideal product, not just a functioning one.

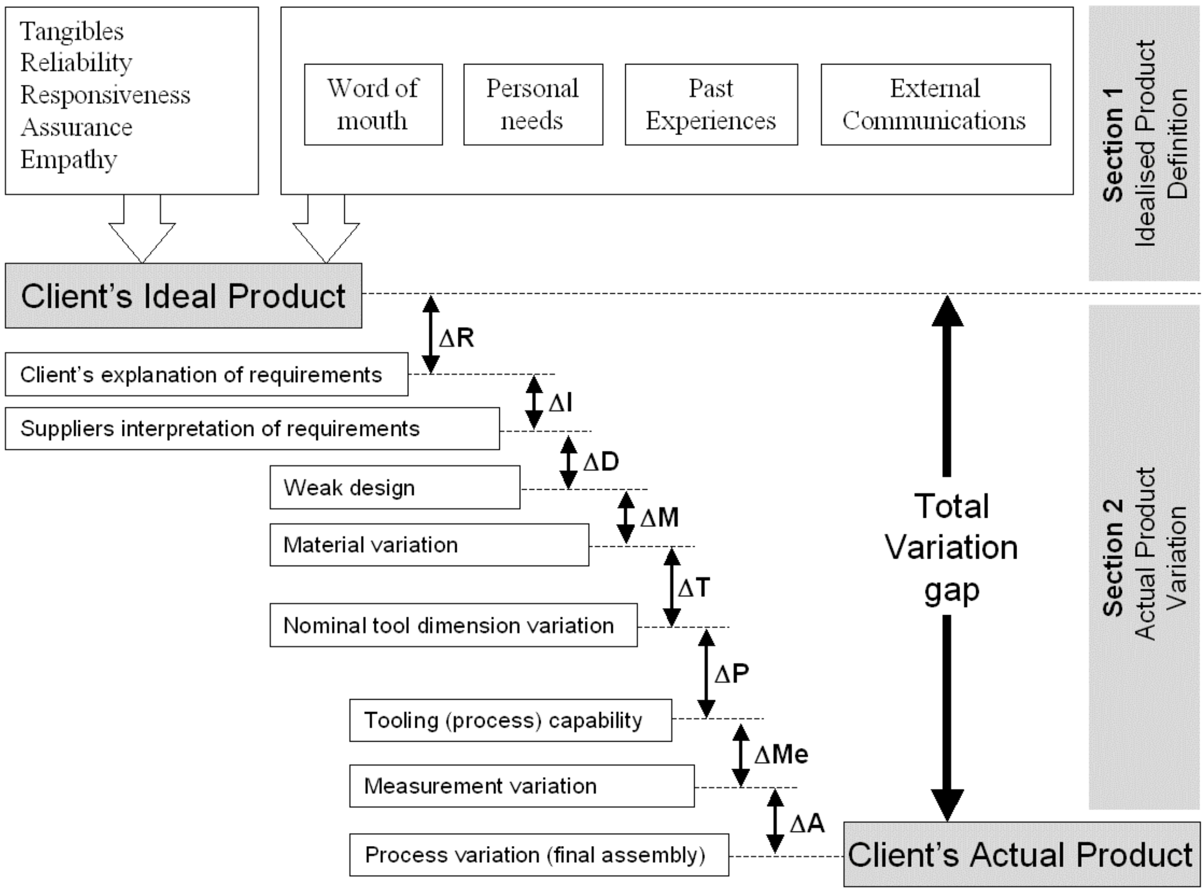

Figure2 showing the full model. The factors influencing the client when considering the ideal product and the factors causing the gap between this ideal and the actual product that the client receives can be clearly seen.

3. CLOSING THE GAP BY REDUCING THIS VARIATION

Product definition Phase:

Design for Six Sigma (DFSS) is a systematic methodology using tools, training, and measurements to enable the design of products, services, and processes that meet customer expectations at Six Sigma quality levels [4]. Tools included in the DFSS toolbox are Voice of the Customer (VOC), Quality Function Deployment (QFD), DFSS scorecards, Pugh Concept Selection Technique. VOC attempts to accurately hear what the customer really wants, to literally listen to the voice of the customer. QFD consists of two major processes; product quality deployment which translates customer language into technical specifications and deployment of the quality function, the definition of the overall manufacturing process. Some companies use co-location, where an employee from the contractor works alongside the client (or vice-versa), encouraging better communication and understanding between both parties.

A Key Characteristic (KC) is a feature of a material, part, assembly, or system in which variation from nominal has the most adverse impact on fit, performance, reliability, or cost of the part [5]. KC methods are used by designers to identify and communicate to manufacturing groups where excess variation will most significantly affect product quality[6]. The use of KC to prioritise features having most impact on the final product performance is well established in industry. Each KC costs money and the identification of too many KCs can reduce the positive effects of using KCs. Manufacturing groups must be able to economically measure and chart such features. If not then statistical control and process capability cannot be demonstrated [7]. KCs can also be used to optimise variation reduction plans by estimating both the cost of variation in product-KCs and the cost of variation reduction [8].

Design and tooling Phase:

Companies deal with weak design by ensuring that their engineers are well trained, experienced, and can use design tools to ensure that their designs are analysed to reduce potential risks. One standard tool is Design Failure Modes and Effects Analysis (DFMEA). This allows a design team to quantify the possible failure modes and the likelihood of problem detection. The resultant Risk Priority Number (RPN) allows engineers to focus on the most important design risks.

For some manufacturing processes, such as moulding, the raw material is normally quite consistent and variation of material properties is normally not a major problem. For processes such as stamping variation in strip thickness, hardness and temper can cause big problems. As components become smaller these issues increase in importance since natural variation in raw materials and processes does not scale. Raw material strip suppliers can improve their tolerances and perform various processes, such as annealing, to produce a more dimensionally consistent strip and remove some of the internal stresses remaining after final rolling/slitting. This can be time consuming and costly. A better approach is to modify the design and/or assign tolerances so that a product can accommodate these natural variations in material, operational environment, ambient conditions and assembly process. Robustness is an attribute of design that integrates the interactions between uncontrollable variables (noise variables) and controllable variables (signal variables) requiring no human intervention for acceptable performance [9]. The objective during design is to predict design sensitivity and link it to process variability. Efforts can focus on redesigning the product, refining or changing the manufacturing process to minimise process variability or both depending upon the level of variability between the process and the product [10].

Tooling dimensional variation is the difference between the mean component dimension and the nominal dimension specified on the drawing. The optimum situation is when the actual product dimension is centred about the nominal but bias often occurs. This is important when dealing with small components (considered to be <1mm in this case), especially when multi-cavities and multi-up dies are used. Variation between cavities in addition to variation of the mean can cause a lot of problems, particularly for automated assembly as the dimensions of components and relative tolerances decrease. Common solutions to address this form of variation are to:

- improve the accuracy of the tools being used (which increases the cost of the tools);
- reduce the number of cavities/ups (with a resulting drop in output);
- cavity sorting with selective assembly (where the output from each cavity is sorted into separate groups and subsequent assembly operations are optimised for each group).

Mass production Phase:

During mass production a product's dimensions will change over time. This can be the result of effects such as worn tooling, different lubrication, operating temperatures or different operators. It is difficult and expensive to try and tackle all of these and the best way to solve the problem is to ensure that the tolerances specified on the part can accommodate this shift. Traditionally design experts have used their experience and rules of thumb to specify the tolerances. More recently companies allocate tolerances based on real-life Process Capability Data (PCD). Without accurate PCD it is not possible to predict the end quality of designs or to improve product robustness [11]. Since this is historical data, certain discontinuities may occur when a company introduces more up-to-date technology. This might initially result in reduced capability and/or increased scrap levels. Examples include reduced pitch connectors needing tighter tolerances not previously attempted. In such instances trials, perhaps using Design of Experiments (DOE), can be made to efficiently gather the data needed for realistic tolerance allocation. PCD can be of great benefit to designers and can save a lot of rework in the long term despite efforts needed to maintain databases.

Statistical Process Control (SPC) control charts are used during mass production to ensure the manufacturing process is stable. In situations where a manufacturing system is stable but there are still issues causing the parts to deviate from requirements Pareto analysis can be used to study where variation reduction efforts can be best focussed to deliver maximum benefit. The Pareto Rule (also called the 80/20 Rule) asserts that a minority of causes usually lead to a majority of the outputs [12]. This provides a methodology to prioritise the order in which issues are dealt with (it's best to tackle the 20% of possibilities causing 80% of the issues first).

Capability studies are performed to quantify variation within a manufacturing process. The outputs from such studies are dimensionless indices such as Cp and Cpk, the two most-commonly used indices, which gives an indication of how capable a product is. These indices are used for long-term and short-term situations. Other indices exist for other situations.

In addition to the capability regarding manufacturing processes, variation also causes problems for product reliability. There are several examples where increased reliability is experienced with products produced according to tight tolerances. One striking, anecdotal, example is the comparison between gearboxes made in Japan (by Mazda) and the Unites States (by Ford) according to the same design, processes and materials. Drivers of cars using the gearboxes made in Japan claim them to be smoother, quieter and more energy efficient.

4. CONCLUSIONS

A model to help suppliers understand how a client develops an "ideal" product expectation and the gaps preventing a supplier from delivering this has been described. Some techniques commonly used in industry to reduce variation and reduce these gaps were summarised. The model is based on the concept of gaps since it features the discrepancies that must be tackled in order that the end product delivered by the supplier and the ideal product envisaged by the customer converge. As described by Taguchi [13] the optimum situation would be zero deviation from nominal. However achieving this situation requires the expenditure of resources and the benefit achieved may not justify the cost involved.

The model described here is a qualitative one; quantifying the gaps in the proposed model and the development of appropriate metrics necessitates a detailed review of reasons for engineering changes and quality notifications. Such a quantitative model would allow customer satisfaction to be measured and also allow suppliers to conduct a cost-benefit analysis.

Although this paper has focussed on mechanical engineering assemblies the same issues are being faced by other engineering disciplines. In the case of civil engineering there is a big move to off-site production and installation/final assembly on-site. Examples of this range from fitted kitchens to prefabricated bathroom units to steel beams fabricated off-site for fitting/welding on-site [14]. If not dimensionally correct the final assembly might be difficult or even impossible to carry out. In any case, it is essential to become aware of the gaps between customer-supplier expectations, understand the causes of these gaps, and investigate methods for reducing them.

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