Key Characteristics

To cut variation and manufacturing costs, focus on key characteristics.

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In the last decade, manufacturing organizations have seen the need to reduce variation in their manufacturing processes because variation generates cost through rework, repair, and customer dissatisfaction. Reduction of cost due to variation is being made in two phases of the product development cycle: design and manufacture.

In the design phase, robust design methods are being used proactively to create products that are insensitive to variation in the manufacturing process. For example, the Ford "Windstar" vehicle development process incorporated the use of assembly variation modeling throughout the product development. Ford estimated that the up-front attention to variation saved between $5 and $10 million in downstream rework costs.

Once a product is in production, variation can be reactively reduced through improvements in the manufacturing processes, such as Motorola's "Six Sigma" drive to reduce defects in its products to no more than 3.4 defects per million by improving process control. Although controlling variation in production is necessary to continually reduce costs, preventing variation from affecting the product (such as robust design) has more cost benefits for a given effort. By reducing the effect of variation early in the design process, expensive monitoring, rework, and quality problems can often be avoided.

Variation reduction has been enabled by tools and aimed at the identification, management, and reduction of the effects of variation. These methods include design of experiments (DOE), Taguchi methods, statistical process control (SPC), variation analysis (VA), robust design, and tolerancing methods. These tools have been used successfully in a variety of organizations to model and reduce variation in product. Despite the success of these methods, there are still limited methods to identify what product features and part dimensions to apply the methods to. Until recently, identification of features that need control has been casual and unsystematic.

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To solve the question of what characteristics must be controlled, the method of "Key Characteristics" (KC) is gaining popularity in a variety of manufacturing organizations. KCs are those features that have significant impact on the product quality. The methods associated with KCs define the process by which the KCs are identified, analyzed, and tracked. Organizations using some form of KC implementation include Boeing, GM, Ford, Chrysler, Xerox, and Kodak.

Variation Reduction

There are several methods used in industry to control variation. In general, both the existing methods and KCs are used to manage variation on several product levels: product, assembly, sub-assembly, and part. At the highest level, the tools manage variation of the product characteristics a customer encounters (such as gaps in a car body, part interchangeability in aircraft, or paper feed jams in copiers). At the detail level, the tools are used to reduce the variation in part feature (diameters of rollers or distances between fixture points in sheet metal). Some tools manage the interactions between the detail level variation and the product level variation.

Variation Analysis

VA simulates how variation in part features will affect the dimensions of a product. VA uses the geometric definition of the part, assembly constraints, and the potential part variations to build a model of the assembly process. Utilizing a Monte Carlo simulation, a large number of products are built "virtually" and the effects of part feature variation on the product features are calculated. Using statistics, the significance of each feature on the product can be measured.

Products function or assembly VA has been found invaluable by a variety of organizations (such as Ford Windstar). However, the modeling process is time consuming and the computations become exponentially more complex with each additional variable. If VA is performed without a focus on the critical feature set, it can often generate too much data.

VA methods are very useful for predicting dimensional variation in assembly but cannot calculate other product characteristics (such as performance). Other modeling methods must be used to predict the effect of the product dimension variation on product performance variation. For example, the variation in the direction an engine points on an aircraft can have a significant impact on fuel efficiency. VA can help predict the variation in the engine placement but other models are needed to calculate the cost impact due to the reduced fuel efficiency.

Cost-Loss Function

The Taguchi quality loss functions or cost-loss functions of product features are used to correlate cost to variation. The loss function is based on perceived cost/loss incurred from problems with a specific product feature. The curves are used to identify where cost is significant and variation should be reduced. When the cost/loss curve is compared to the capability curve, the probability distribution of the feature's value, and the cost of variation can be determined.

Cost/Loss Functions

Figure 1a shows that the manufacturing variation does not significantly affect cost. Even when a feature's value is at one of the tails of the capability curve, the cost of that variation is relatively low. Figure 1b shows that the variation in this manufacturing process will significantly affect cost. Figure 1c shows that the process is precise but the mean shift to the right of nominal results in cost.

These curves can be used to identify where changes in either design or manufacture need to occur. For example in Figure 1b, the design can be made more robust to flatten the cost or the process can be made more capable to make the capability curve narrower.

Taguchi methods are useful where the cost of variation can be calculated or estimated. During the design stage the cost of variation can be often estimated for the product characteristics (such as performance). Although the capability of achieving the product performance characteristics is often not available, the cost/loss curves

Three Cost/Loss Functions

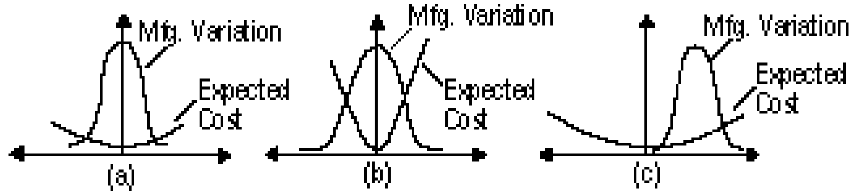

Figure 1.

can be used to set the acceptable variation. In the case of part features, the variation information may be available but the cost/loss curve for that variation can be difficult to calculate.

Design of Experiments

Often it is necessary to understand the relationship between product characteristics and their contributing features. One way to develop this understanding is to model the interaction (such as injection molding simulation).

But in the case of complex products, this may not be possible. Therefore, a more empirical model is needed to understand the relationships through experimentation. DOE is used to structure a testing program to obtain information about the contribution of single factors to a performance/product characteristic. DOE is used in the area of reactive and proactive robust design. It is used reactively to discover the source of problems and used proactively to set both the values of design parameters and process parameters for a robust product and processes.

Statistical Process Control

SPC is used in the manufacturing environment to measure and monitor the variation of critical parameters. It is used to present the current process capability in a visual format to quickly identify where manufacturing processes are out of control and/or incapable.

The success of SPC depends on being able to identify the correct features to monitor. The identification and control of features that don't contribute significantly to the product features is not useful and can be expensive. In addition, a minimal set needs to be identified to effectively monitor the features.

The features to monitor using SPC are identified in two ways. The first method identifies the features before production starts. The second identifies the features after production starts and problems with variation occur. The identification of features in both cases is done using a

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variety of methods including integrated product teams (IPTs), DOE, VA, and Taguchi loss functions.

Summary

The methods described above are used to develop the cost of variation (Taguchi), manage variation (SPC), and predict the effect of variation (DOE and VA). But all these methods depend on the identification of the correct features to monitor and analyze. Ideally, these features should be identified early in the design process. By identifying them early, decisions can be made to either improve the design to make it more robust to the existing variation or improve the manufacturing process cabability.

The identification of the important features at the part level is rarely straightforward for complex products. The variation that affects the customer's perception of the product and/or the performance of the product is often not assignable to the variation of a single manufactured feature. For example, in the automotive industry, the steps and gaps between the body panel strongly influence a customer's perception of a product. However, it is not useful for only the gap to be monitored using SPC because there can be hundreds of product features contributing to the creation of that gap including part shape dimensions, fixturing features, and assembly and manufacturing processes.

If SPC is applied to the gap alone, it is possible to track when the gaps become unacceptable but not why they become unacceptable as the failure cause can result from any number of sources. It is also not economically feasible to monitor each possible contributing characteristic. In addition, unless the relationship between the feature variation and the gap is understood, it may not be possible to track which features are causing the problems.

Key Characteristics

Manufacturing organizations use KCs to address the problem of what features are critical to the customer's perception of the product and may need monitoring to ensure quality. KC or equivalent systems are being implemented in a large number of organization including: GM, Vought Aircraft Company (a subsidiary of Northrop Grumman Corporation), Boeing Commercial Aircraft Group, Xerox, Ford, Chrysler, McDonnell Douglas, and Kodak.

KCs are product features, manufacturing process parameters, and assembly features that significantly affect a product's performance, function, and form. KC implementation started in the 1980s at some major U.S. companies to help focus on the important product features for producing quality products. Although the KC terminology and implementation schemes vary between corporations, the organization-specific methods have common goals: to identify a small set of critical features for an organization to focus on during design and manufacturing.

This section provides overviews of current KC implementations at several U.S. companies. The author observed a variety of organization KC processes — both what they state as their method and what their actual practice is. Discussions with implementation teams, product developers, and review of product development handbooks formed the basis of the following sections.

KCs have been defined in several different ways. In general, the organizations break the KC definitions into two classes: those associated with the product and those associated with manufacturing. This article deals only with those associated with the product. The definition of a product KC is usually given as those characteristics, which, when there is significant variation, affect the performance of the product significantly. The following sections describe the observations by the author of four different companies' product KC methods.

Company A

Company A developed a KC system to identify product features that "need extra control," to promote teamwork, and to improve communication. KCs are supposed to help the engineers at company A maintain focus on the problem areas of the product that require extra manufacturing process control to keep them in specification. The methods take a reactive focus to the identification of KCs for products already in production. The method is based on the notion that KCs depend on current manufacturing capabilities and customer concerns.

When problems with customer satisfaction are identified in production, a team investigates and develops a list of KCs to monitor and improve. When a manufacturing process improves and the problem disappears, the feature's KC status is removed. When there is a new problem with a different performance or functional issue, a new KC is realized. The specifications for new manufacturing equipment are set to achieve the KCs of the product.

The method used to identify the KCs include identifying or eliminating KCs by analyzing Taguchi quality loss functions (also known as cost/loss functions) of product features and correlating them with their manufacturing capabilities. This loss function along with manufacturing SPC data are used to help identify key product characteristics and key control characteristics.

The loss function is developed based on perceived cost/loss incurred from customer dissatisfaction caused by variation from nominal of a specific product feature. However, the analysis is based on a qualitative "feel" for how the product feature variation will affect the customer requirement, not quantitative measures.

Company B

A supplier of sub-assembly parts and designs for a prime contractor implemented KCs approximately five years ago. They have methods to identify KCs in products in production as well as products in development.

Company B defines KCs as features that have the potential for strongly influencing product performance, assembly, and cost. In both new and existing programs, process management teams (PMTs), composed of mechanics headed by a floor supervisor, and IPTs, composed of engineers and headed by a program end-item manager, are brought together to help identify key characteristics using internal risk analysis techniques similar to failure mode and effects analysis (FMEA).

On existing products, features that are believed to create assembly fit problems are selected to be KCs and are given extra care and control. Similar to company A's approach, KC identification on existing programs is reactive. KCs are identified as problems arise — and they continue to monitor those features they consider high risk after the problems disappear. The selection is based on qualitative methods and discussions between the IPT members.

KCs are identified on new products in design using a proactive process. System-level KCs are identified during the design stage and these are translated to the feature level KCs. Some of the KCs are used to coordinate locating and reference points on fixtures. Other KCs are identified as being critical to satisfying other customer requirements.

The proactive process generates a long list of KCs and there are no quantitative measures used to prioritize them. They are all marked for measurement and, as a result, conducting appropriate measurement plans within reasonable time and cost limits becomes difficult.

Both the reactive and proactive KC identification are qualitative and do not use quantitative data such as manufacturing capability and costs to identify the KCs. The reactive mode of KC identification is similar to company A's method but is better because they maintain consistent measurements.

Although they are using a proactive approach in identifying KCs in the design process, their methods are ineffective, as demonstrated by KC proliferation. Because of the unreasonable set of KCs identified for measurement, the measurement plans are often not followed. The sets are unreasonable because there are too many identified and in many cases the features identified are not measurable. As a result, in some cases, the organization has reverted to the reactive mode of discovering problems in production.

Company C

Company C began using KCs as part of a larger initiative to improve quality through the control of variation. The KCs are defined by Company C as those product features for which controlling variation is a major factor in improving assembleability, performance, and repair requirements. The implementation was originally focused on improving the variability of parts from suppliers but it is now being used in house as well. The KC methods are aimed at improving products before production begins — a proactive approach.

During design, KCs and the part features are identified at the top level. The flowdown is tracked through the assembly drawings. When performing the flowdown, they do not identify the mid-level KCs. As a result, it is very difficult to quantify the effect of variation in a part feature on a product KC.

KCs are identified using the cost/loss function, described in the previous section. Similar to the other companies described, Company C uses a qualitative "feel" for what is critical. The KCs are used to design the datum structure for the parts and tooling. In addition, measurement plans have been implemented to track the performance of KCs.

Like company B, company C has had problems with the implementation of a proactive KC methodology. One major issue is that too many KCs are identified by the product development teams and it is impossible for all of them to be monitored during production. Proliferation was a result of the assumption that every KC identified needed monitoring. Features that were considered to be critical by the designer were not at risk given the current manufacturing capability but were still identified for measurement. This was the result of the inability to qualitatively measure what KCs were at risk. As a result, the measurement plans became very cumbersome. The disproportionately large number of features identified for measurement defeats the purpose of a measurement plan that relies on focusing an organization on a small set of features.

Company D

Company D produces high-volume product where the exact performance of the mechanism is critical to the quality of the final product. The mechanism is complex and the function is created by a moving assembly of many parts, each of which has potential for variation. To ensure that their products have consistent quality, company D expends significant effort to analyze the effects of variation to identify the KCs of the part.

The robustness of the product is achieved by a three-part process. First, the variation in the mechanisms is modeled using variational analysis. The relationship between dimensional variation and the product performance is also modeled. Using these tools, the required tolerances of the part features are determined. Second, the tolerances are compared to the current capability for the manufacture of the parts. Those that don't match are considered KCs. Third, if there are conflicts, either designs are changed or a more expensive manufacturing process is employed.

This method is very effective in identifying the KCs of the product: those that are at risk of preventing satisfaction of customer requirements. Critical to the success of this method is the application of quantitative methods to predict potential variation in the manufacturing process. In addition, there is a systematic understanding of what characteristics are important and how to map current capability to the functionality of the part.

Summary

There are two major problems in the current methodologies. The first is that many organizations are using KCs in a reactive mode. In this case, organizations are identifying problems with the product in production, forming teams to identify the features that need to be measured. The reactive method incurs cost on two levels, first, the cost of producing low-quality parts and second, the cost of solving the problem. In this process, it is often necessary to "reverse engineer" the product to understand what is happening. In addition, time is lost in reacting to problems rather than preventing them. It would be more efficient to identify the high risk areas early, implement SPC on those features, and begin the manufacturing process with a set of goals directly related to improving the quality of the product.

However, in cases where organizations are proactively identifying KCs, they are not implementing them effectively. First, there are too many KCs identified by design for monitoring during the manufacturing process. This both generates cost (monitoring features generates cost) and also defeats the propose of measurement plans.

Where there are too many KCs, data being taken aren't used. In other cases, the measurement plans are never implemented because they are not feasible. In both cases, the organizations observed tend revert to a reactive process of identifying the KCS when problems arise.

The identification of too many KCs is caused by two problems. First, organizations often don't flow the KCs down through the assembly and sub-assembly features. In many cases, the high-level KCs are identified and then the feature-level KCs are identified and linked back to the high-level KCs. As a result, it is very difficult to trace what characteristics are significant and how the variation in the features will affect the performance. Secondly, the KC flowdown is not trimmed using quantitative methods to assess risk.

Conclusions

The following is a proposed proactive KC process. This five-step process is a combination that is currently being implemented at a variety of organizations.

1. *Identify the high-level/product-level KCs and acceptable variation.* These are often set in the early design phases. For example, in automotive and aircraft industries, quality, reliability, and fit requirements are set to place the new product competitively in the market place. In addition to identifying the KCs at the product level, it is necessary to identify the acceptable variation in those characteristics. Information about the latitude a KC has is necessary to identify those KCs that are at risk of being unacceptable. The bounds of acceptable variation can be identified using methods such as Taguchi's cost/loss functions.
2. *Flow the KCs down to the feature level.* Each customer-level KC is created by features in the subassemblies that make up the final product. In turn, each

feature in the sub-assembly is created by features in its sub-assemblies. This “flowdown” occurs until the part features created by the manufacturing processes are reached. The hierarchy of a feature is termed the “KC tree.” Methods such as House of Quality and IPTs have been used to identify the KC tree. It is naive to build a measurement plan for SPC and process improvement based solely on the KC flowdown. The tree will have too many features to monitor each effectively and not all are necessarily at risk.

3. *Identify the capability of achieving the feature-level KCs.* A list of those KCs that need to be monitored should be identified from the complex set identified in step 2 based on capability and latitude, given the expected variation of the feature level dimensions. Ideally, an organization would be able to predict the capability of achieving the high-level KCs based on existing capability of creating the part features. This is not always possible where designs have changed significantly between generations. Most understanding of capability exists on the feature level. Given the feature capability, that information should be propagated up the KC tree. This can be done using a variety of methods including VA or DOE.

4. *Identify what customer requirements are at risk.* Given the understanding of the capability, the customer requirements at risk of not being achieved can be identified. In addition, those KCs that are the significant contributors to the high-risk KCs can also be identified. These KCs that are at risk are termed StatKCs. This process is critical to the effective implementation of KCs. As shown above, it is not feasible to monitor a large set of KCs. It has also been observed that when IPTs come together to assess the relative importance of the KCs, without a quantitative backup to support one KC over another, decisions are often made based on who shouts the loudest.

5. *Implement either design changes to achieve a robust design or use methods such as SPC to monitor and track the high-risk features.* If the product cannot be changed, the process needs to be improved. In this case, key process characteristics can be identified using DOE to highlight where the process can be improved.

KCs have been identified as a useful process to focus organizations on the critical features that drive the success of a product. They have, if implemented properly, potential to help organizations reduce and manage variation in the product. But critical to the success of this method is: 1) flowing down the KC through the product levels; 2) systematically understanding the capability and its effect on the customer requirements; and 3) the ability to identify the StatKCs.

Anna Thornton joined the faculty at MIT in 1994. In addition to her work on Key Characteristics, she has researched and written on design automation, computational tools for product design, and product benchmarking. She has worked with a variety of companies including Boeing, GM, Chrysler, Ford, Intel, Kodak, Polaroid, and Concentra.

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