Six Sigma

50. Six Sigma

The first part of this chapter describes what Six Sigma is, why we need Six Sigma, and how to implement Six Sigma in practice. A typical business structure for Six Sigma implementation is introduced, and potential failure modes of Six Sigma are also discussed. The second part describes the core methodology of Six Sigma, which consists of five phases, i. e., define, measure, analyze, improve, and control (DMAIC). Specific operational steps in each phase are described in sequence. Key tools to support the DMAIC process including both statistical tools and management tools are also presented. The third part highlights a specific Six Sigma technique for product development and service design, design for Six Sigma (DFSS), which is different from DMAIC. DFSS also has five phases: define, measure, analyze, design and verify (DMADV), spread over product development. Each phase is described and the corresponding key tools to support each phase are presented.

In the forth part, a real case study on printed circuit board (PCB) improvement is used to demonstrate the application of Six Sigma. The company and process background is provided. The DMAIC approach is specifically followed and key supporting tools are illustrated accordingly. At the end, the financial benefit of this case is realized through the reduction of cost of poor quality (COPQ).

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Finally, last part is given over to a discussion of future prospects and conclusions.

Since the early 1990s, Six Sigma swept the business world, driving an unprecedented emphasis on greater manufacturing and service quality. Six Sigma is one of the few quality initiatives that actually originated from industrial practice. Six Sigma was originally devised as a measure of quality that strives for near perfection. It has developed into a disciplined, data-driven, customer-focused approach to reduce defects and bring about substantial financial growth. Although most Six Sigma efforts were focused on manufacturing operations in the early years, the Six Sigma approach has now been more widely used in non-manufacturing industrial sectors such as finance, insurance, health care, and telecommunications. Users include American Express, American International Group (AIG), Bank of America, Citibank, J.P. Morgan, Chase, Merrill Lynch, Vanguard, etc. These companies have actually seen larger business impacts and cost savings than those in manufacturing.

50.0.1 What is Six Sigma?

Motorola first introduced the Six Sigma program in the late 1980s with the aim of increasing profitability by reducing defects. General Electric (GE) followed the approach at their manufacturing sites and later at their financial service divisions. After that, Six Sigma was thought to be applicable to all processes and transactions within GE. Six Sigma has now evolved from a quality

Table 50.1 Final yield for different sigma levels in multistage processes

Average sigma level	1	2	3	4	5	6
Final yield for 10 stages	0.0%	2.5%	50.1%	94.0%	99.8%	100.0%
Final yield for 100 stages	0.0%	0.0%	0.1%	53.6%	97.7%	100.0%
Final yield for 1000 stages	0.0%	0.0%	0.0%	0.2%	79.2%	99.7%

improvement program to an overall business strategy executive system and business-results-oriented program, which seems more *total* than total quality management (TQM). We will describe the basic definition of Six Sigma in this section and will elaborate its systematic methodology and business structure in later sections.

Six Sigma is both a business improvement strategy and a methodology to measure process performance. It is used to increase profits by eliminating defects, waste, and variability and to find the causes of mistakes in products, processes and services to increase yields. In Six Sigma, focus on the customer is the top priority. Performance standards are based on actual customer input, so that process effectiveness can be measured and customer satisfaction can be predicted.

In terms of business process improvement, variation reduction is the key since variation signals fluctuation in the process output and is often a major source of poor quality. Variation is present in all processes and every aspect of work. Unintended variation reduces process performance and decreases customer satisfaction. Because of the existence of variation, producing high-quality products and services in the modern industrial environment is a tough task.

Therefore, Six Sigma aims particularly at reducing variation. The word *sigma* or the symbol "σ" is used in statistical notation to represent the standard deviation in a population. The standard deviation is also used as a general measure of variation in any kind of product or process. With six standard deviations between the process mean and the customer's specification limit, we arrive at 3.4 defects per million opportunities (DPMO); that is, a 99.9997 percent yield. Before the Six Sigma technique was introduced, a three-sigma level of variation was regarded as being fairly good quality performance. Three sigma may be acceptable for a product or process having only a single or a few stages. It is not good enough for many products that are the result of hundreds of thousands of stages, such as automobiles and computers.

For example, if a production process is made up of ten stages where the yield of each stage is as high as 90%, the probability of producing a satisfactory product in the first run would be $0.9^{10} = 35\%$. This indicates that about 65% of the products are defective. If a production process is made up of 100 stages, the probability of producing a satisfactory product under the three-sigma program could be as low as 0.1%, as shown in Table 50.1. The Six Sigma regime, however, allows only 3.4 defects for every million opportunities, which ensures a quality product even if the process involves a large number of stages (Table 50.1). Part of the reason for using such a strict requirement in quality management is actually to accommodate the common multistage processes in modern industrial practice.

50.0.2 Why Six Sigma?

The successful implementation of Six Sigma can result in benefits in the areas of cost reduction, increased profit, increased market share and enhanced business competitiveness, mainly by the reduction of the cost of poor quality (COPQ).

COPQ usually includes appraisal costs, internal failure costs, and external failure costs. Appraisal and inspection costs are often incurred, for example, in checking finished goods before they leave the factory, inspecting purchased equipment/supplies, proofreading financial and legal documents, reviewing charges prior to billing, etc. Internal failure costs are those for repairing, replacing, or discarding work in progress or completed work before the delivery of the product to the customer. External failure costs are those that directly affect the customer and are the most expensive to correct, including tangible remedial costs and the intangible costs associated with losing dissatisfied customers.

COPQ cannot be underestimated. In manufacturing industries, COPQ sometimes reaches 15% of total sales (source: Six Sigma Academy). In service industries, the situation is even more serious. COPQ may account for as much as 50% of total costs.

However, these COPQ could be saved with the use of Six Sigma. General Electric has estimated savings of 2 billion US dollars during the first five years of Six Sigma implementation, and Allied Signal has estimated savings of 1.1 billion US dollars in two years. Indeed, thousands of companies around the world have enjoyed the breakthrough benefits of Six Sigma.

For example, Legend Computers in China reported in 2002 savings of $20 million dollars during the first year of implementation. In the same year, the International Bank of Asia in Hong Kong reported savings of 1.4% of total costs during the first year of Six Sigma implementation.

50.0.3 Six Sigma Implementation

Six Sigma implementation is usually a top-down approach, i. e., from the strong commitment of top management. As most Six Sigma projects span several departments, organizational barriers could not be removed without leadership commitment to Six Sigma. Strong commitment, leadership and strategic involvement have proven to be key factors for Six Sigma's success. Secondly, as Six Sigma requires a long-term mentality, it needs to be positioned first as a strategic initiative and then be linked to operational goal. It is important to tie the Six Sigma implementation to corporate goals, such as increased profits through lower costs and higher loyalty, for example. Also, effective internal communication is another key issue for the success of Six Sigma implementation.

In the following, a typical business structure for Six Sigma implementation is introduced. Several potential failure modes and practical considerations of Six Sigma implementation are also discussed.

Training and Belt Structure

The deployment of Six Sigma in a company usually starts with education. Without the necessary training, people are not able to bring about Six Sigma breakthrough improvements. Six Sigma establishes well-defined and structural roles and responsibilities for a project team, and team members are given formal training according to their roles to help the team work effectively. A Six Sigma team is usually organized in a belt structure (as in martial arts) as follows.

At the top of the belt structure is the Six Sigma executive. The Six Sigma executive could be a council that consists of top managers who have the vision and make strategic decisions for a company. They are responsible for establishing the roles and structures of Six Sigma projects. They also need to make decisions on project selection and resources allocations. A progress review is conducted periodically to monitor projects.

Champions are the senior managers who supervise Six Sigma projects. They report directly to the Six Sigma executive and represent the team to the executive. They also need to seek resources and to learn the focus of the business from the Executive. In addition, champions meet black belts and green belts periodically to review the progress and coach the team.

Master black belts work with the champions to ensure that Six Sigma objectives and targets are set. Meanwhile, they are the statistical problem-solving experts in a company. Their responsibilities include determining plans, providing technical expertise, training and coaching black and green belts.

Black belts, as on-site Six Sigma experts, usually possess the technical background needed to help green belts and the other team members to understand the project and apply appropriate statistical techniques. Their roles are to provide formal training to local personnel in new strategies and tools, provide one-on-one support to local personnel, pass on new strategies and tools in the form of training, workshops, case studies, local symposia, etc., and find application opportunities for breakthrough strategies and tools, both internal and external (i. e., to the suppliers and customers).

Green belts, on the other hand, execute Six Sigma in their specific area as a part of their overall job. They may assist black belts in completing sections of their projects and apply their learning to their daily performance of their jobs.

According to the Six Sigma Academy, black belts are able to save companies approximately US$230 000 per project and can complete four to six projects per year. The American Society for Quality (ASQ) has been certifying Six Sigma black belts (SSBB) internationally in recent years. Up to the middle of 2002 there were around 200 ASQ-certified black belts in the US and only 11 ASQ-certified black belts outside the US. Among them, there was only one in the greater China area (Table 50.2).

Six Sigma Failures (Sick Sigma)

Although Six Sigma is a powerful approach, it can lead to failure when some critical issues are neglected. How-

Table 50.2 Number of Six Sigma black belts certified by the American Society for Quality (ASQ) internationally (ASQ record up to April, 2002)

Indonesia	1	United Kingdom	1
India	5	Hong Kong	1
Japan	1	Mainland China	0
Australia	1	Taiwan	0
Brazil	1	Singapore	0

ever, as more companies have implemented Six Sigma since the 1990s, the factors that have led to failure have been identified and summarized. According to *Snee* and *Hoerl* [50.1], project selection and management support are usually the two main sources of failure.

The failure modes in project selection usually include projects not tied to financial results, poorly defined project scopes, metrics, and goals, projects lasting more than six months, the wrong people assigned to projects, project teams that are too large, and infrequent team meetings. On the other hand, the failure modes in management support may include black belts with little time to work on projects, poor or infrequent management reviews, poor support from finance, information technology (IT), human resource (HR), etc., and poor communication of initiatives and progress [50.1].

Especially, for a Six Sigma program to sustain without failure, recognition and reward systems are the key. If recognition and reward systems are lacking or remain unchanged, the program cannot last. Necessary practices include establishing and using selection and promotion criteria and developing corresponding performance management and reward systems. GE's approach, which links 40% of management bonus to Six Sigma, may be too aggressive, but a company must adequately compensate those high-performing members.

Note that the use of statistical methods is not on the list of major failure modes. With recent advances in information technology, computing and sensing technology, the use of advanced statistical methods has become handy via commercial software packages (such as MINITAB, JMP, etc.). Therefore, the use of statistical tools is no longer a bottleneck in Six Sigma implementation.

Moreover, various industry types and company natures are also not an excuse for Six Sigma failure. Six Sigma has been successfully applied to many processes outside of manufacturing, regardless of the company size or nature of the industry. In particular, transactional processes, such as software coding, billing, customer support, etc., often contain variation or excessive cycle time and can be optimized by applying Six Sigma. For example, HR managers may apply it to reduce the cycle time for hiring employees, and regional sales may apply it to improve forecast reliability, pricing strategies or variations.

50.1 The DMAIC Methodology

50.1.1 Introduction

The development of Six Sigma is evolutionary, not revolutionary, and it integrates many useful quality management tools. Thus, it is not surprising to find overlaps between the Six Sigma, TQM, lean, and ISO approaches. The core methodology of Six Sigma is driven by close understanding of customers' needs and the disciplined use of facts, data and statistical analysis, which consists of five phases, i. e., define, measure, analyze, improve, and control (DMAIC).

In the define phase, the specific problem is identified, and the project goals and deliverables are defined. In the measure phase, the critical-to-quality (CTQ) characteristics are identified and the measurement system is reviewed. The nature and properties of the data collection have to be understood thoroughly to ensure the quality of the data. In the analyze phase, both quantitative (i. e., statistical) methods and qualitative (i. e., management) tools are used to isolate the key information that is important to explaining defects. In the improve phase, the key factors that cause the problem should be discovered. In the control phase, the key factors and processes are controlled and monitored continuously to ensure that the improvement is sustainable and the problem will not occur again. A detailed case study on the implementation of the DMAIC methodology in printed circuit board manufacturing can be found in *Tong* et al. [50.2]. The paper "Six Sigma approach to reducing fall hazards among cargo handlers working on top of cargo containers: a case study" by *Ng* et al. [50.3, 4] is another case study using DMAIC that focuses on a non-manufacturing case.

50.1.2 The DMAIC Process

More specifically, we implement the DMAIC methodology in detailed steps in sequence to shift our focus from the output performance (i. e., y) to the root causes (i. e., the x). Based on these steps, we transfer a practical problem into a statistical problem (e.g., mapping x and y), find out a statistical solution for that [e.g., solving $y = f(x)$] and then transform the statistical solution into a practical solution. Each step is described in the following, and the corresponding key tools will be further explained in a later section.

Phase 1: Define (D)

This phase defines the Six Sigma project, which includes a problem statement, the objectives of the project, the expected benefits, the team structure and the project time line. At the end of this phase, we should have a clear operational definition of the project metrics for the final evaluation. In this phase, the main tasks are to identify who the customer is, select the project area, define the goal, scope and resources of the project, form a Six Sigma project team, define the team members' responsibilities, and estimate the profit and cost for this project to ensure the value of the project. Key tools in this phase include the project charter; business process mapping; suppliers, inputs, process, outputs and customer (SIPOC); etc.

Phase 2: Measure (M)

By taking steps in the measure phase, we have a clear understanding of the performance of the current process and, only after knowing where we are now, can we determine where we should be in the future. Three implementation steps in this phase are to select the critical-to-quality (CTQ) measures, determine deliverables, and quantify the measurability of y.

Select the Critical to Quality (CTQ) Measures. In this step, we will identify the external CTQ from the customer's point of view (i. e., the big Y) that will be improved, and then link that with the internal CTQ (i. e., the small y), which is a quantitative measure in the company and will be the focus of the project. Key tools in this step include customer needs mapping (CNM), quality function deployment (QFD), failure modes and effects analysis (FMEA), etc.

Deliverables. We will establish a performance standard and develop a data collection plan for the internal CTQ y in this step. If the measure of y from the previous step is attributal, what is the definition of a defect? If the data are continuous, what are the lower and upper specifications for defectiveness? Key tools used in this step include process mapping and yield calculation.

Quantify Measurability. We validate the measurement system on y to ensure the measurement results are accurate for the following analysis. We may need to improve the measurement system before continuing. Key tools include measurement system analysis (MSA), gage repeatability and reproducibility (R&R) study.

Phase 3: Analyze (A)

After we identify the y in the process, we need to determine the x (root causes), which may impact on the performance of the y. In the analyze phase, we use various management and statistical tools to discover the x for future improvements. Three implementation steps in this phase are to establish the baseline, determine the improvement plan, and identify the sources of variation.

Establish the Baseline. We will establish the process capability for the current process to understand where we are now. We need to collect the current process data, use graphical tools to analyze the data, and calculate the process capability indices, the defect per million opportunities (DPMO), and the sigma level (Z). Key tools include: histograms, process capability indices (PCI), etc.

Determine Improvement Plan. We quantify the goals for the improvement to make the aim of the project clear, and we may determine if the goal is significantly different from today's performance (i. e., the baseline) through hypothesis testing. Key tools include benchmarking, hypothesis testing, t-test, analysis of variations (ANOVA), etc.

Identify Variation Sources. We list all the potential factors (x) that may influence the performance of y. Regression analysis may be conducted, where applicable, to identify potential x. Key tools include brainstorming, cause-and-effect diagram, regression analysis, etc.

Phase 4: Improve (I)

As the root causes for variation are obtained, it becomes possible for us to fix these root causes. In the improve phase, the way that we can achieve a better process needs to be found, where the design of experiments (DOE) is a key technique to help us quantify the relation between the ys and xs, and to improve the process by finding the optimal setting of xs for each y. In this phase, we follow three implementation steps: screen potential sources of variation, discover variable relationships, and formulate the implementation plan.

Screen Potential Sources of Variation. We determine the few vital xs from the many trivial xs in this step. DOE is a key tool for factor screening. Both full factorial and fractional factorial experiments can be used. If necessary, historical data can be used with care, and a similar model or simulation may be used as well.

Discover Variable Relationships. We develop the transfer function [$y = f(x)$] linking the y to the vital xs. Based on this, we then determine and confirm the optimal settings for the vital few xs. DOE is a key tool for characterization and optimization as well. Various DOE techniques, such as the response surface method (RSM), robust design and the Taguchi method, can be applied in this step. Other than that, simulation or surveys can also be used to find the relationship.

Formulate Implementation Plan. In this step, if a new process or process steps have been put in place, show the new process map. For the new process, indicate the new in-process measurements and associated specifications. If there is not a new process, indicate any new measurements put in place. We list how the changes to the xs will be implemented and how much flexibility is available in the settings of each x. Key tools in this step include tolerance design, main effects plots, interaction plots.

Phase 5: Control (C)

After determining how to fix the process, we want the improvement for the process to be sustainable. The control phase is set up to ensure sustainable improvement and to deploy measurement tools to confirm that the process is in control. It is also critical to realize the financial benefits and develop a transfer plan in this phase. Three implementation steps include validating the implementation plan, controlling the inputs and monitoring the outputs, and finally sustaining the change.

Validate the Implementation Plan. To determine how well the xs can be controlled, we will validate the measurement system on the xs, and we may need to improve measurement system before continuing. We will also report new sigma levels and new DPMO levels at this step. Key tools include gage R&R, ANOVA, etc.

Control Inputs and Monitor Outputs. We determine how each vital xs can be controlled (e.g., attribute control chart, variable control chart, mistake-proofing, etc.) and set up a monitoring plan for the y and xs in this step. Key tools include statistical process control (SPC), attribute control charts, variable control charts, Poka–Yoke (mistake-proofing), etc.

Sustain the Change. The objective of this step is to ensure that changes last after the improvement strategy has been implemented. Process control plans need to be developed and implemented for each x. We will also verify the financial gains that can be achieved and if this project is translatable to any other regions, lines, sites, processes, etc. Key tools in the final step include out-of-control plans, mistake-proofing, audit strategy, etc.

50.1.3 Key Tools to Support the DMAIC Process

This section presents the key tools to support the DMAIC process. Only a few key tools can be covered in this section and each method is outlined briefly with the basic ideas and mechanisms. The books and papers cited in this section give more details.

Business Process Mapping (SIPOC Diagrams)

Purpose. SIPOC stands for suppliers, inputs, process, outputs and customer. SIPOC diagrams are graphical tools to identify all relevant elements of a business process and map the process flow before the project begins. They are usually used in the define phase.

Definitions.

Supplier: Whoever produces, provides, or furnishes the products or services for the input of the process, either an internal or an external supplier.

Inputs: Material, resources and data required to execute the process.

Process: A collection of activities that take one or more kinds of input and creates output that is of value to the customer.

Outputs: The tangible products or services that result from the process.

Customer: Whoever receives the outputs of the process, either an internal customer or an external customer.

How to do it.

Step 1. Clear statement of CTQ and the process.
Step 2. Clear statement of start/end point.
Step 3. Identify major customers, suppliers, outputs, and inputs.
Step 4. Identify the five to seven major process steps using brainstorming and storyboarding.
Step 5. Decide what step to map in detail.
Step 6. Complete detailed map.

Quality Function Deployment (QFD)

QFD is a systematic approach to prioritize and translate customer requirements (i. e., external CTQ) into appropriate company requirements (i. e., internal CTQ) at each stage from product development to operations to sales and marketing to distribution. This method is usually used in the measure phase. It is also useful in design for Six Sigma (DFSS) and will be introduced in more detail in the DFSS section.

Failure Modes and Effects Analysis (FMEA)

Purpose. FMEA is a tool to reduce the risk of failures. It is also a tool to identify and prioritize CTQ at the measure phase.

Definitions.

Severity: the assessment of how severe a failure mode is. The severity usually scales from 1–10. Scale 1 means a minor failure mode that may not be noticed, and 10 means a very serious failure that may affect safe operations.

Occurrence: The likelihood that a specific cause will result in the failure mode, which scales from 1–10 with 10 being the highest likelihood.

Detection: The assessment of the ability to identify the failure mode. A 1–10 scale is often used with 10 being the lowest detectability.

RPN: The risk priority number (RPN) is the output of a FMEA. RPN = Severity × Occurrence × Detection.

How to do it [50.4].

Step 1: Identify the products, services, or processes.
Step 2: Identify the potential failure that would arise in the target process.
Step 3: Identify the causes of the effects and their likelihood of occurrence.
Step 4: Identify the current controls for detecting each failure mode and the ability of the organization to detect each failure mode.
Step 5: Calculate the RPN by multiplying the values of severity, potential causes, and detection.
Step 6: Identify the action for reducing or eliminating the RPN for each failure mode.

Measurement System Analysis (MSA)

Purpose. A statistical evaluation of the measurement system must be undertaken to ensure effective analysis of any subsequent data generated for a given process/product characteristic. MSA is usually used in the measure and control phases to validate the measurement system for the y and xs.

Definitions.

Gage R&R: is a tool to study the variation in the measurement arising from the measurement device and the people taking the measurement.

Repeatability: The variability that reflects the basic, inherent precision of the gage itself.

Reproducibility: The variability due to different operators using the gage (or different time, different environments) [50.5].

How to do it.

Step 1: Collect the data. Generally two to three operators, 10 units to measure, and each unit is measured 2–3 times by each operator.
Step 2: Perform the calculations to obtain %R&R [50.5].
Step 3: Analyze the results. A rule of thumb is that:

- %R&R $<$ 10%: measurement system is acceptable.
- %R&R between 10–30%: measurement system may be acceptable. We will make decisions based on the classification of the characteristics, hard applications, customer inputs, and the sigma level of the process.
- %R&R $>$ 30%: measurement system is not acceptable. We should improve the measurement system by finding problems and removing root causes.

Process Capability Analysis

Purpose. Process capability analysis is a statistical technique to quantify process variability, analyze this variability relative to customer requirements or specifications, and assist in reducing the variability [50.5]. It is used in the analyze phase.

Definitions.

Cp: Process/product capability index, is the relationship of the process/product variation to the upper and lower specification limits. It is related to the potential process capability and not a measure of how centered the data are.

Cpk: It compares process variability with the specification's width and location. It takes into account that the sample mean may be shifted from the target. Since both the mean shift and the variability of the characteristics are considered, Cpk is better related to the capability of the current process.

How to do it. The detailed calculation and analysis is given by *Montgomery* [50.5].

Cause–Effect Diagram (Fishbone Diagram)

Purpose. This is a graphical brainstorming tool to explore the potential causes (i. e., xs) that result in a significant effect on y. It is usually used in the analyze phase.

How to do it.

Step 1: Define clearly the effect or analyzed symptom (y) for which the possible causes (xs) must be identified.
Step 2: Place the effect or symptom (y) being explained on the right of a sheet of paper.
Step 3: Use brainstorming or a rational step-by-step approach to identify the possible causes.
Step 4: Each of the major areas of possible causes should be connected with the central spine by a line.
Step 5: Add possible causes (xs) for each main area.
Step 6: Check for completeness.

Design of Experiments (DOE)

Purpose. DOE is a major tool in the improve phase. It is used for screening the few, vital xs, characterizing the relationship between y and xs, and optimizing the setting of the vital xs.

Definitions.

Factor: An independent variable (i. e., xs) whose state can be varied.

Level of a factor: The state of the factor.

Full factorial experiments: Discover the factor effects and relationship between y and xs by running all the combinations of factor levels.

Fractional factorial experiments: An economical approach to discovering the factor effects and to screening the vital few xs by running only part of the combinations of factor levels.

Response surface methodology (RSM): A DOE technique that is useful for modeling and optimization in which a response of interest y is influenced by several factors xs and the objective is to optimize this response. This method will be discussed more in the DFSS section.

How to do it [50.6, 7].

Step 1: State the problem.
Step 2: Choose the response variable (y).
Step 3: Choose the factors (xs) and their levels and ranges.
Step 4: Determine the experimental plan (i. e., the design matrix).

1. To screen the xs to obtain the few, vital xs, we often use factorial experiments. In such cases, if the number of runs is moderate and we have enough time and resources, we may conduct a full factorial experiment; if the number of runs is large or time and resources are limited, we may consider a fractional factorial experiment.
2. To obtain the optimal response, we may conduct RSM, which is usually conducted after variable screening.

Step 5: Run the experiments under the prescribed conditions and collect the response data.
Step 6: Analyze the data collected using main effect plots, interaction plots, ANOVA, etc.
Step 7: Conclude the experiment and make recommendations. A confirmation run or a follow-up DOE is usually needed.

Statistical Process Control (SPC)

Purpose. SPC is a major tool in the control phase. It is used to control and monitor the stability and capability of the few, vital xs for CTQ.

How to do it. This method will be discussed in more detail in the DFSS section. For a general introduction to SPC, see *Montgomery* [50.5]. For recent advances in SPC, the reader may refer to http://qlab.ielm.ust.hk and references therein.

50.2 Design for Six Sigma

The success of Six Sigma's DMAIC methodology has generated enormous interest in the business world. One of the basic ideas is to measure existing defective processes quantitatively and then to improve them. Compared with this defect-correction methodology, design for Six Sigma (DFSS) is a proactive methodology, which focuses on the new product/service development to prevent quality defects from appearing instead of solving problems when they happen in existing processes.

DFSS is a disciplined and statistical approach to product and service design that ensures that new designs can meet customer requirements at launch. The objective of DFSS is to eliminate and reduce the design vulnerabilities in both the conceptual and operational phases by employing scientific tools and statistical methods.

Unlike the DMAIC methodology, the phases of DFSS are not universally defined. There are many methodologies, such as Woodford's identify, design, optimize, validate (IDOV), El-haik's identify, characterize, optimize, verify (ICOV), Tennant's define, customer concept, design, and implement (DCCDI), and so on. All these approaches share common themes, objectives, and tools. In this section, we refer to above methodologies, especially General Electric's DFSS approach called define, measure, analyze, design and verify (DMADV):

Define the project goals and customer requirements.
Measure and determine customer needs and specifications.
Analyze the options of conceptual solutions to meet customer needs.
Design the product/service to meet customer needs.
Verify the design performance and ability to meet customer needs.

50.2.1 Why DFSS?

Proactive versus Retroactive

During the product/service design process, conceiving, evaluating and selecting good design solutions are difficult tasks with enormous consequences. Usually organizations operate in two modes: *proactive*, that is, conceiving feasible and healthy conceptual solutions the first time; and *retroactive*, that is, an after-the-fact practice that drives design in a design–test–fix–retest cycle and creates what is broadly known as the *fire-fighting* mode of design. If a company follows this practice, it suffers from high development costs, longer times to market, lower quality levels, and marginal competitive edge [50.8].

Compared to retroactive approaches such as DMAIC, which apply performance improvement in the later stages of the product/service life cycle, DFSS shifts the attention to improving performance in the front-end design stages. That is, the focus is on problem prevention instead of problem solving. This action is motivated by the fact that the design decisions made during the early stages of the product/service life cycle have the largest impact on both total cost and quality of the system. It is often claimed that up to 80% of the total cost is committed in the concept development stage. Also, at least 80% of the design quality is committed in the early design stages. According to a study of the design community [50.8], at the early design stage, the impact (influence) of design activity is much higher than a later stage, while the correction cost in the early stage is much lower.

Experience Dependency versus Scientific and Systematic Methodology

Currently, most design methods are empirical in nature, while the work of the design community is often based on experience. This experience-based tradition often leads to unnecessary variation and is difficult for project manager to control. As a result, vulnerabilities are introduced into the new design that makes it impossible for the product/service to achieve Six Sigma performance. This is another motivation for devising DFSS as a scientific and systematic design method to address such needs.

50.2.2 Design for Six Sigma: The DMADV Process

Generally speaking, DFSS has five phases spread over product development. They are called: define, measure, analyze, design and verify (DMADV).

Phase 1: Define (D)

The process of product/service design begins when there is a need (internal or external), which can be a problem to be solved or a new invention. In this phase, design objectives, scope and available resources should be simply and clearly defined in the design project charter as the key deliverables.

Phase 2: Measure (M)

In particular, the voice of customer (VOC) is the critical input in customer-oriented design. Based on VOC, the internal CTQ measures (critical to quality or critical to satisfaction, i. e., the y), such as cost, performance, reliability, aesthetics and serviceability, need to be identified quantitatively and to be prioritized according to their importance to customers. This kind of information can help to define the function requirements in a later phase.

Phase 3: Analyze (A)

In this phase, the CTQs will be decomposed into measurable and solution-free functional requirements (FRs). Then, a number of conceptual-level design alternatives should be produced by the design team for the FRs, considering cost, physical properties, the difficulties to operate/manufacture and maintenance, etc. Through summarizing the design requirements and conceptual-level design alternatives, an overall set that contains high-potential and feasible solutions can be produced to help the design team to decide on the best solution considering the original design charter including the performance, the constraint of cost and available resources.

Phase 4: Design (D)

Once the design team fixes the selection of the conceptual solutions, they need to decompose the FRs into design parameters (DPs). At the same time, they need to consider the potential risk to achieve CTQs when they create detailed designs to the level of design parameters. Then, optimization tools will be used to get optimal values for the design parameters. In DFSS, optimization can be reached statistically, and by using statistical tools, the transfer functions can be generated to mathematically represent the relationships between the input and output of a product or a service process. Then, the design team can rely on the transfer function to optimize the design solutions so that the product/service can achieve a target performance and be insensitive to uncontrollable factors (noise factors), such as the environment and production case-to-case variation.

Phase 5: Verify (V)

In this phase, the design team makes a model formed by the simulation of a service process or a physical prototype that is the first working version of the product. Based on these few prototypes, the design team evaluates and tests the whole design to predict if the future product's performance can meet the design charter and how to improve the solution when failure occurs.

50.2.3 Key Tools to Support the DMADV Process

Below is a summary of the key tools used to support the DMADV process.

Voice of Customer (VOC)

Purpose. Define customer needs/requirements for the new product/service design or existing product/service redesign.

Input. Market segment defined – who the customers are and their environment.

Output. Detailed customer requirements.

How to do it [50.9].

Step 1: Define market segments – to understand who the customers are and where to go to gather their needs.
Step 2: Identify objective for interviews of customer – to learn what of their needs are new, unique, and difficult (NUD).
Step 3: Select customer groups within the target market segments.
Step 4: Decide on the customer visit team – divide into three roles: leader, subordinate interviewer that helps adding balance and diversity in the discussion, and statement writer that writes down the VOC needs statement.

1. Create an interview guide based on objectives – to get customers' responses that are rich in description of needs.
2. Listen, probe, and observe customers by asking stimulating questions and open-ended statements to gather the VOC. Image data can be gathered by actual observation of customers' responses to existing products or services.

Kawakita Jiro (KJ) Method [50.10]

Purpose. Structure and rank the customer requirements.

Input. The detailed VOC.

Output. Organized customer requirements.

How to do it [50.11].

Step 1: Write down customer descriptions as *statements of customer requirements* on a POST-IT note and put them on the wall.
Step 2: Group the similar customer requirements together.
Step 3: Review the customer requirements statements and throw out redundant ones.
Step 4: Write a summary to express the general idea for each group. For those that do not relate to anything else, label it as *independent*.
Step 5: Vote for the most important groups and rank the top three groups and assign some relationships. If a group supports another group in a positive manner, we add an arrow pointing from the supporting group to the supported group. If the relationship is contradictory, we add a line pointing between the two groups with blocks on the end.
Step 6: Look at each detailed customer requirement and highlight the new, unique, or difficult ones.
Step 7: Ask customers to rank (on a scale of 1–10) the strength of importance for each requirement.

The result of these ranked and structured customer requirements will flow into the QFD process.

Quality Function Deployment (QFD): the houses of quality [50.12]

QFD is a methodology that establishes *bridges* between qualitative, high-level customer needs/requirements and the quantitative engineering terms that are critical to fulfilling these high-level needs. By following QFD, relationships can be explored among customer requirements, CTQ measures, function requirements (FRs), design parameters (DPs) and process variables (PVs). And the priorities of each CTQ, FR, DP and PV can be quantitatively calculated.

Generally, the QFD methodology is deployed through a four-phase sequence.

Phase 1 – critical-to-satisfaction planning (HOQ1)
Phase 2 – functional requirements planning (HOQ2)
Phase 3 – design parameters planning (HOQ3)
Phase 4 – process variable planning (HOQ4)

In this chapter, HOQ1 will be introduced in detail as an example.

Input. Structured and ranked new, unique and difficult (NUD) VOC from the KJ diagram.

Key Output. The priorities of each CTQ.

How to do it [50.8].

Step 1: Convert NUD VOC (“WHATs”) into a list of CTQs (“HOWs”) in terms of the engineering perspective to support customer requirements along the roof of the house. There may be more then one CTQ to achieve each customer requirement.
Step 2: Quantify the relationship between each customer requirement to each CTQ on a $1-3-9$ scale ($9 =$ strong fulfillment, $3 =$ moderate fulfillment, $1 =$ weak fulfillment, or $0 =$ no relationship). These values help to identify which CTQs are critical and which are not.
Step 3: Identify the correlation between each pair of CTQ to address the cooperative and conflicting relationships among CTQs to develop the design to be as cooperative as possible.
Step 4: Conduct a competitive assessment with a main competitor. The comparison with the key competitor on each customer requirement is on a 1–5 scale, with five being high.
Step 5: Prioritize customer requirements. These priorities include importance to customer from the KJ method, improvement factor, and absolute weight. Customer requirements with low completive assessments and high importance are candidates for improvement, which will be assigned improvement factors on a 1–5 scale, with five being the most essential target to improve. The absolute weight can then be calculated by multiplying the customer importance and the improvement factor.
Step 6: Priority CTQs. The CTQs are prioritized by determining absolute weight and relative weight. The absolute weight is calculated by the sum of the products of the relationship between customer requirements and CTQs and the importance to the customer. The relative weight is the sum of the products of the relationship between customer requirements and CTQs and customer requirement absolute weights. The relative and absolute weights are evaluated to prioritize and select CTQs for improvement.

Furthermore, the design team can apply the same method for identifying the relationship among CTQs, functional requirements, design parameters and process variables.

The Pugh Concept Evaluation and Selection Process [50.13]

The Pugh concept evaluation is a solution-iterative selection process. The method alternates between generation and selection activities. The *generation* activity can be enriched by the TRIZ (theory of inventive problem solving, [50.14]) methodology to generate conceptual solutions for each functional requirement. The *selection* activity can use a scoring matrix called the *Pugh matrix* or the *criteria-based matrix* to evaluate the concepts.

Input. Functional requirements and conceptual solutions to achieve corresponding FRs.

Output. The conceptual solutions, which are selected and ready to go forward into the design phase.

How to do it [50.15].

Step 1: Define concept selection criteria from a clear and complete set of requirements.
Step 2: Define a best-in-class benchmarked datum concept.
Step 3: Provide candidate concepts to evaluate against the datum.
Step 4: Evaluate each concept against the datum using (+)s, (−)s, and (S)s to rank the fulfillment of the concept selection criteria.
(+) means the concept is better than the benchmarked datum concept;
(−) means the concept is worse than the benchmarked datum concept;
(S) means the concept is the same with the benchmarked datum concept.
Step 5: Refine criteria as necessary during the first cycle of evaluation.
Step 6: Analyze the results from the first cycle of evaluation: the sum of (+)s, (−)s, and (S)s.
Step 7: Identify weakness in concepts that can be turned into (+)s.
Step 8: Create hybrid *super-concepts* by integrating the strengths of similar concepts to remove (−)s and (S)s.
Step 9: Select a new datum based on the scoring that suggests a superior concept after the first cycle of evaluation.
Step 10: Add any new concepts that have been developed.
Step 11: Repeat the evaluation process through the second cycle.
Step 12: The superior concept is selected and ready to go forward into the development or design phase.

Design Failure Modes and Effects Analysis [50.16]

DFMEA is applied to define qualitatively and rank quantitatively the failure modes and effects for new products and service processes across all the phases of DMADV. In particular, the design team can use DFMEA in a design concept for potential failure modes so it can address them early in the design. Usually DFMEA is conducted on the superior concept, which is chosen from all the candidate concepts in the Pugh concept-selection process.

Input. Superior concept architectures, functional requirements, the physical form, etc.

Output. Causes of failure and corrective action.

How to do it [50.8].

Step 1: Develop a block diagram of the design element or function being analyzed (at system, subsystem, subassembly, or component level).
Step 2: Determine the ways in which each design element or function can fail (failure modes).
Step 3: Determine the effects of the failure on the customer(s) for each failure mode associated with the element or function.
Step 4: Identify potential causes of each failure mode.
Step 5: List the current design controls for each cause or failure mode.
Step 6: Assign severity, occurrence, and detection ratings to each cause.
Step 7: Calculate risk priority numbers (RPN) for each cause.
Step 8: Apply tools and best practices to reduce the sensitivity to root causes of failure or eliminate root causes of failure and recalculate RPNs.
Step 9: Document causes of failure and corrective action results qualitatively and quantitatively.

Response Surface methods [50.6,17]

Purpose. Optimize the system performance in the *design* phase by constructing a statistical model and response surface map that represents the relationship between the response and the critical design parameters. If the design parameters are quantitative and there are only a few of them, RSM is an effective tool for modeling and optimization.

Input. Critical design parameters.

Output. Surface map and equations that determine the level of the factors.

How to do it [50.18].

Step 1: Choose a CTQ response to be studied by experimentation.
Step 2: Determine the critical parameter to be modified with the experiments. Focus on the significant factors that affect the response.
Step 3: Select the measurement system used to analyze the parameters.
Step 4: Create the transfer function from the experimental data. The transfer function is a mathematical description of the behavior of the system that can be used to create surface plots and optimize the system's performance.
Step 5: Plot the response surface maps to observe the system behavior.
Step 6: Final output: a surface map and an equation that is used to determine the level of the factors. Sensitivity of the factors can also be analyzed.

Inferential Statistics

Inferential statistics are often employed in the *verification* phase.

Purpose. Identify and control variation in the critical responses.

Input. The new product/service's performance data.

Output. The decision on which factors have an effect on the design's response.

Hypotheses and risk: There are null hypothesis and alternate hypothesis. Once we have data, we can determine whether we should accept or reject the null hypothesis, by calculating a test statistic.

The t-test: Used to compare two samples, or one sample with a standard. The null hypothesis is that the means are equal and the difference between the two population means is zero.

Analysis of variance (ANOVA): We use ANOVA when there are more than two samples to compare. ANOVA is used to test whether the means of many samples differ.

H. Statistical Process Control [50.5]

Purpose. Monitor the critical response of the new product/service in the *verify* phase to assess stability and predictability and detect important changes.

Input. The new product/service's performance data.

Output. Assessment of the new product/service's stability, predictability, sigma level and capability for commercialization readiness.

Main considerations. Sample size considerations – sample size should be large enough to provide good sensitivity in detecting out-of-control conditions

Sampling frequency – sampling should be frequent enough to ensure opportunities for process control and improvement.

Concepts. A production/service process that is operating with only chance causes (common causes) of variation present is said to be *in statistical control*. A process is out of control if there exists assignable causes (special causes) that are not part of the chance cause pattern such as improperly adjusted or controlled machines, operator errors, or defective raw material [50.5]. An SPC chart is used to distinguish these two types of causes by upper and lower control limits (UCL and LCL). As long as all the sample points plot within the control limits, the process is assumed to be in statistical control. If a charting point is out of the control limits, this implies that there is evidence that the process is out of control. We then should investigate the assignable causes and take corrective actions.

We can use SPC charts to determine if a new product/service's CTQ measure is in control. If it is, the product/service may move to the mass-production phase.

How to do it [50.5].

Step 1: Select the environment in which the data will be collected.
Step 2: Select the responses and parameters that will be monitored.
Step 3: Select the measurement systems used to acquire the data.
Step 4: Run the system in the prescribed environment

and acquire the data.

Step 5: Plot the data using the appropriate type of SPC chart.

Step 6: Assess the plots for stability and predictability.

Step 7: Calculate the estimates of sigma level and process capability.

50.3 Six Sigma Case Study

In this section, a case study on printed circuit board (PCB) improvement by the author is used to demonstrate the application of Six Sigma, which is digested from *Tong* et al. [50.2] where a more detailed report of this case may be found. This study was conducted in reference to the DMAIC approach, and the objective is to improve the sigma level for a series of products called PSSD in the screening process.

50.3.1 Process Background

This case study was conducted in an electronic company, which is located in an industrial park in southern China. The company manufactures multilayer PCBs by using the surface-mount technology (SMT), which is a technique for placing surface-mount devices (SMDs) on the surface of a PCB. SMDs are micro-miniature leaded or leadless electronic components that are soldered directly to the pads on the surface of the PCB. The major manufacturing processes in the company are solder screen, component placement, and solder reflow. As any defect in any of the solder joints can lead to the failure of the circuit, the screening process is regarded as the most critical process in PCB manufacturing.

The screening process is a manufacturing process that transfers solder paste onto the solder pad of a PCB. The application method for solder paste is printing, and the printing technique used is off-contact printing, in which there is a snap-off distance between a stencil and a PCB. The type of screening machine used to manufacture PSSD products is semiautomatic. During a printing process, two PCBs are placed side-by-side on the holder of a screening machine. The solder paste is then placed onto a stencil manually before printing. The front/back blade makes a line contact with the stencil and a close contact with the given amount of solder paste. The solder paste is then rolled in front of the front/back blade. In this way, solder paste is pressed against the stencil and transferred onto the solder pad through the stencil openings. More detailed operation of a screening process is described in *Tong* et al. [50.2].

50.3.2 Define Phase

In this case, we specifically focus on the improvement of the sigma level of the PCB screening process. In the screening process, the solder paste volume (height) transferred onto the PCB is the most important factor that needs to be controlled carefully. This is because too little solder paste can cause open circuits and too much solder paste can cause bridging between solder pads in the subsequent processes. As a result, the solder paste height on the solder pads is identified as a critical-to-quality (CTQ) characteristic (i. e., the y) that needs to be controlled in a very precise way by the company. According to that, a project team is formed and a project charter is constructed.

50.3.3 Measure Phase

To control the screening process, the project team in the company has asked operators to measure the solder paste height for the PSSD product on five different points on a PCB. The solder paste height on the five points is measured by using the Cyberoptics Cybersentry system every four hours. The gage repeatability and reproducibility (R&R) of the measurement system was verified before the study on the solder paste height is conducted. The gage R&R results ensured that the data from the current measurement system are accurate enough for the following analysis.

50.3.4 Analyze Phase

Currently, six semiautomatic screening machines are used to manufacture the PSSD product. Therefore, the data on solder paste height of these six machines was collected from the company, and the process capability analysis was conducted for these screening machines in order to analyze the current printing performance. According to the analytical results, the process capability in machine number 12 was not satisfactory because the capability index Cp was only 1.021, which was smaller than 1.33 (the four-sigma level). Moreover, another capability index Cpk was 0.387. This showed that the screening process was off-center. Based on the process capability study, we concluded that there exist both a high variance and a mean shift in the solder paste process. Therefore, we list all the potential factors (xs) that may cause this through brainstorming and constructing a cause and effect diagram.

50.3.5 Improve Phase

In the analysis of the current printing performance, the result showed that the screening process capability of machine number 12 was not satisfactory. After brainstorming with the mechanical engineers in the company, the designed experiments were decided to conduct on machine number 12 in order to determine the optimal settings of all the input factors (xs) in the screening process. In this phase, DOE was used as a core statistical tool for the sigma level improvement.

In the initial experiments, several possible factors that might have influence the printing performance were taken into account. These experiments were used to screen out new factors that have influence on the printing performance. These significant factors would then be included together with the already-known significant factors (solder paste viscosity, speed of squeegee, and pressure of squeegee) in the further experiments. The aim of the further experiments was to determine the standard settings of all the significant factors (i. e., the few, vital xs). By using these optimal settings in the screening process, the printing performance could be improved. As a result, the sigma level can also be enhanced significantly. The detailed DOE setting, analysis, and result can be found in *Tong* et al. [50.2].

50.3.6 Control Phase

To sustain the improvement of the sigma level in the screening process, control plans for all the important xs were proposed to the company. For example, both the CTQ y and the vital xs should be monitored by SPC charts over time, so that the solder paste height variation and the sigma level can be controlled and sustained continuously. Also, the financial benefits through the reduction of COPQ were calculated.

The comparison of the printing performance before and after the project was reported in *Tong* et al. [50.2]. After using the optimal settings, the sigma level of the screening process can be improved from 1.162 to 5.924. This shows that a nearly six-sigma performance can be achieved. According to *Harry* and *Schroeder* [50.19], the level of defects per million opportunities (DPMO) would reduce to near 3.4 and the COPQ would be less than one percent of the sales. As a result, after the Six Sigma practice, the COPQ of the process for this company has been significantly reduced.

50.4 Conclusion

As Six Sigma is evolving over time, the advantages and benefits of other business-excellence approaches can still be learned and utilized in future Six Sigma programs. According to *Hahn* [50.20], combining other tools or methodologies and the Six Sigma methodology may be a future trend. For example, combining lean tools with the Six Sigma methodology has become popular during the last few years. And there are expected to be more combinations in the future.

Recently, Six Sigma efforts have been pushed to both the external suppliers and external customers along a supply chain, which has resulted in even larger overall business impacts and cost savings. I have also observed an increasing trend outside the US, where more and more companies in Asia and Europe, including small-to-medium-sized enterprizes, have implemented various stages of Six Sigma deployment and discovered its far-reaching benefits.

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