Part A

Six Sigma: Past, Present and Future

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Six Sigma: A Preamble

H. S. Yam

Six Sigma is a rigorous and highly disciplined business process adopted by companies to help focus on developing and delivering robust, near-perfect products and services. In this opening chapter, we first present the underlying motivation for Six Sigma. While Six Sigma has demonstrated itself to be of much value in manufacturing operations, its full potential is not realized till it has been proliferated and leveraged across the multitude of functions in a business entity. To achieve this end, a well-defined vision and roadmap, along with structured roles, are necessary. In this chapter, we present a brief description of the DMAIC roadmap and the organizational structure in a typical Six Sigma deployment. This is followed by a discussion of how to customize appropriate levels of Six Sigma training for these various roles. Finally, an example of a Six Sigma project is presented to illustrate the power of integrating existing technical expertise/knowledge with the Six Sigma methodology and tools in resolving leveraged problems.

1.1 INTRODUCTION

Six Sigma has captured the attention of chief executive officers (CEOs) from multi-billion corporations and financial analysts on Wall Street over the last decade. But what is it?

Mikel Harry, president and CEO of Six Sigma Academy Inc, defines it as 'a business process that allows companies to drastically improve their bottom line by designing and monitoring everyday business activities in ways that minimize waste and resources while increasing customer satisfaction'.[1] Pande *et al.* call it 'a comprehensive and flexible system for achieving, sustaining and maximizing business success, . . . uniquely driven by close understanding of customer needs, disciplined use of facts, data and statistical analysis, with diligent attention to managing, improving

Six Sigma: Advanced Tools for Black Belts and Master Black Belts L. C. Tang, T. N. Goh, H. S. Yam and T. Yoap

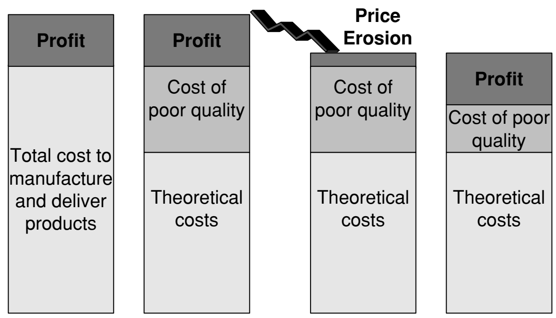

Figure 1.1 Relationship between price erosion, cost of poor quality and profit.

and reinventing business processes'.[2] Contrary to general belief, the goal of Six Sigma is not to achieve 6σ levels of quality (i.e. 3.4 defects per million opportunities). It is about improving profitability; improved quality and efficiency are the immediate by-products.[1]

Some have mistaken Six Sigma as another name for *total quality management* (TQM). In TQM, the emphasis is on the involvement of those closest to the process, resulting in the formation of *ad hoc* and self-directed improvement teams. Its execution is owned by the quality department, making it difficult to integrate throughout the business. In contrast, Six Sigma is a business strategy supported by a quality improvement strategy.[3] While TQM, in general, sets vague goals of customer satisfaction and highest quality at the lowest price, Six Sigma focuses on bottom-line expense reductions with measurable and documented results. Six Sigma is a strategic business improvement approach that seeks to increase both customer satisfaction and a company's financial health.[4]

Why should any business consider implementing Six Sigma? Today, there is hardly any product that can maintain a monopoly for long. Hence, price erosion in products and services is inherent. Profit is the difference between revenues and the cost of manufacturing (or provision of service), which in turn comprises the theoretical cost of manufacturing (or service) and the hidden costs of poor quality (Figure 1.1). Unless the cost component is reduced, price erosion can only bite into our profits, thereby reducing our long-term survivability. Six Sigma seeks to improve bottom-line profits by reducing the hidden costs of poor quality.

The immediate benefits enjoyed by businesses implementing Six Sigma include operational cost reduction, productivity improvement, market-share growth, customer retention, cycle-time reduction and defect rate reduction.

1.2 SIX SIGMA ROADMAP: DMAIC

In the early phases of implementation in a manufacturing environment, Six Sigma is typically applied in manufacturing operations, involving personnel mainly from process and equipment engineering, manufacturing and quality departments. For Six Sigma to be truly successful in a manufacturing organization, it has to be proliferated across its various functions – from design engineering, through materials and shipping, to sales and marketing, and must include participation from supporting functions such as information technology, human resources and finance. In fact, there is not a single function that can remain unaffected by Six Sigma. However, widespread proliferation would not be possible without appropriate leadership, direction and collaboration.

Six Sigma begins by identifying the needs of the customer. These needs generally fall under the categories of timely delivery, competitive pricing and zero-defect quality. The customer's needs are then internalized as performance metrics (e.g. cycle time, operational costs and defect rate) for a Six Sigma practicing company. Target performance levels are established, and the company then seeks to perform around these targets with minimal variation.

For successful implementation of Six Sigma, the business objectives defined by top-level executives (such as improving market share, increasing profitability, and ensuring long-term viability) are passed down to the operational managers (such as yield improvement, elimination of the 'hidden factory' of rework, and reduction in labor and material costs). From these objectives, the relevant processes are targeted for defect reduction and process capability improvement.

While conventional improvement programs focus on improvements to address the defects in the 'output', Six Sigma focuses on the process that creates or eliminates the defects, and seeks to reduce variability in a process by means of a systematic approach called the *breakthrough strategy*, more commonly known as the *DMAIC methodology.* DMAIC is an acronym for Define–Measure–Analyze–Improve–Control, the various development phases for a typical Six Sigma project.

The *define* phase sets the stage for a successful Six Sigma project by addressing the following questions:

- What is the problem to be addressed?
- What is the goal? And by when?
- Who is the customer impacted?
- What are the CTQs in-concern?
- What is the process under investigation?

The *measure* phase serves to validate or redefine the problem. It is also the phase where the search for root causes begins by addressing:

- the focus and extent of the problem, based on measures of the process;
- the key data required to narrow down the problem to its major factors or vital few root causes.

In the *analyze* phase, practical business or operational problems are turned into statistical problems (Figure 1.2). Appropriate statistical methods are then employed:

- to discover what we do not know (exploratory analysis);
- to prove/disprove what we suspect (inferential analysis).

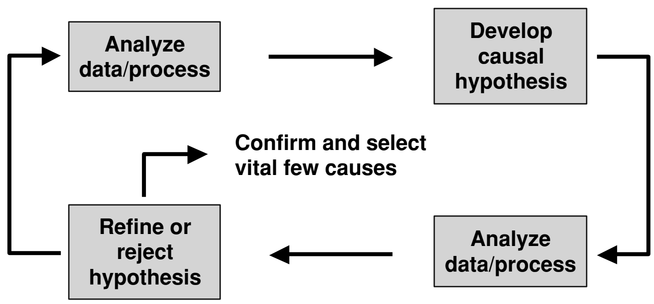

Figure 1.2 The analyze phase.

The *improve* phase focuses on discovering the key variables (inputs) that cause the problem. It then seeks to address the following questions:

- What possible actions or ideas are required to address the root cause of the problem and to achieve the goal?
- Which of the ideas are workable potential solutions?
- Which solution is most to likely achieve the desired goal with the least cost or disruption?
- How can the chosen solution be tested for effectiveness? How can it be implemented permanently?

In the *control* phase, actions are established to ensure that the process is monitored continuously to facilitate consistency in quality of the product or service (Figure 1.3). Ownership of the project is finally transferred to a finance partner who will track the financial benefits for a specified period, typically 12 months.

In short, the DMAIC methodology is a disciplined procedure involving rigorous data gathering and statistical analysis to identify sources of errors, and then seeking for ways to eliminate these causes.

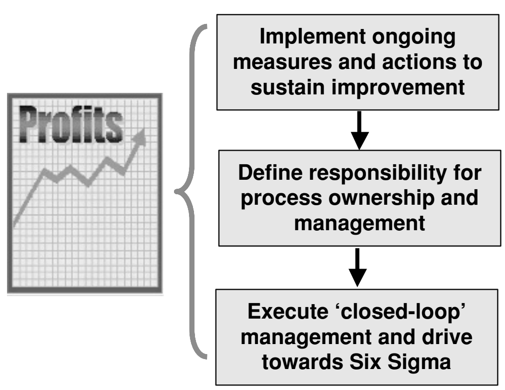

Figure 1.3 Six Sigma culture drives profitability.

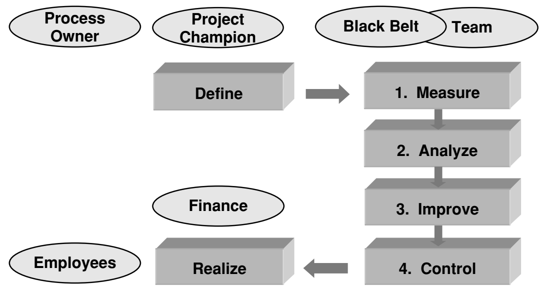

Figure 1.4 Interactions of stakeholders in various phases of a Six Sigma project.

1.3 SIX SIGMA ORGANIZATION

For best results, the DMAIC methodology must be combined with the right people (Figure 1.4). At the center of all activities is the Black Belt, an individual who works full-time on executing Six Sigma projects. The Black Belt acts as the project leader, and is supported by team members representing the functional groups relevant to the project. The Champion, typically a senior manager or director, is both sponsor and facilitator to the project and team. The Process Owner is the manager who receives the handoff from the team, and is responsible for implementation and maintenance of the agreed solution. The Master Black Belt is the consultant who provides expert advice and assistance to the Process Owner and Six Sigma teams, in areas ranging from statistics to change management to process design strategies.

Contrary to general belief, the success of Six Sigma does not lie in the hands of a handful of Black Belts, led by a couple of Master Black Belts and Champions. To realize the power of Six Sigma, a structure of roles and responsibilities is necessary (Figure 1.5). As Six Sigma is targeted at improving the bottom-line performance of a company, its support must stem from the highest levels of *executive management*. Without an overview of the business outlook and an understanding of the company's strengths and weaknesses, deployment of Black Belts to meet established corporate-level goals and targets within an expected time frame would not be possible.

The *Senior Champion* is a strong representative from the executive group and is accountable to the company's president. He/she is responsible for the day-to-day

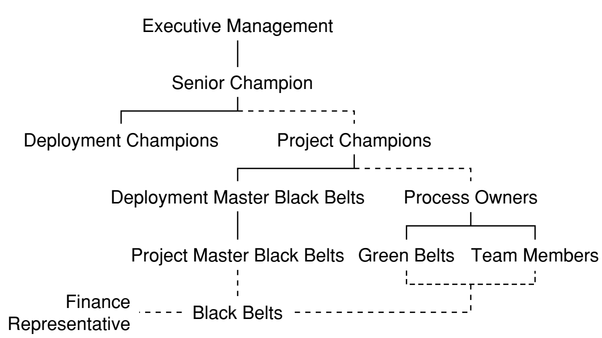

Figure 1.5 The reporting hierarchy of the Six Sigma team.

corporate-level management of Six Sigma, as well as obtaining the business unit executives to commit to specific performance targets and financial goals.

The *Deployment Champions* are business unit directors responsible for the development and execution of Six Sigma implementation and deployment plans for their defined respective areas of responsibility. They are also responsible for the effectiveness and efficiency of the Six Sigma support systems. They report to the Senior Champion, as well as the executive for their business unit.

The *Project Champions* are responsible for the identification, selection, execution and follow-on of Six Sigma projects. As functional and hierarchical managers of the Black Belts, they are also responsible for their identification, selection, supervision and career development.

The *Deployment Master Black Belts* are responsible for the long-range technical vision of Six Sigma and the development of its technology roadmaps, identifying and transferring new and advanced methods, procedures and tools to meet the needs of the company's diverse projects.

The *Project Master Black Belts* are the technical experts responsible for the transfer of Six Sigma knowledge, either in the form of classroom training or on-the-job mentoring. It is not uncommon to find some Project Master Black Belts doubling up as Deployment Master Black Belts.

The *Black Belts* play the lead role in Six Sigma, and are responsible for executing application projects and realizing the targeted benefits. Black Belts are selected for possession of both hard technical skills and soft leadership skills, as they are also expected to work with, mentor and advise middle management on the implementation of process-improvement plans. At times, some may even be leading cross-functional and/or cross-site projects. While many companies adopt a 2-year conscription for their Black Belts, some may chose to offer the Black Belt post as a career.

The *Process Owners* are the line managers of specific business processes who review the recommendations of the Black Belts, and ensure that process improvements are captured and sustained through their implementation and/or compliance.

Green Belts may be assigned to assist in one or more Black Belts projects, or they may be leaders in Six Sigma mini-projects in their own respective areas of expertise. Unlike Black Belts, Green Belts work only part-time on their projects as they have functional responsibilities in their own area of work.

The *Finance Representatives* assist in identifying a project's financial metrics and potential impact, advising the Champion on the approval of projected savings during the define phase of a project. At completion of the project (the end of the project's control phase), he/she will assist in adjustment of projected financial savings due to changes in underlying assumptions (market demand, cost of improvements, etc.). The Finance Representative will also track the actual financial savings of each project for a defined period (usually one year).

1.4 SIX SIGMA TRAINING

All Six Sigma practicing companies enjoy the benefits described earlier, with financial savings in operating costs as an immediate return. In the long run, the workforce will transform into one that is objectively driven by data in its quest for solutions as Six Sigma permeates through the ranks and functions and is practiced across the organization. To achieve cultural integration, various forms and levels of Six Sigma training must be developed and executed. In addition to the training of Champions and Black Belts (key roles in Six Sigma), appropriate Six Sigma training must be provided across the ranks – from the executives, through the managers, to the engineers and technicians. Administrative functions (finance, human resources, shipping, purchasing, etc.) and non-manufacturing roles (design and development, sales and marketing, etc.) must also be included in the company's Six Sigma outreach.

Champions training typically involves 3 days of training, with primary focus on the following:

- the Six Sigma methodology and metrics;
- the identification, selection and execution of Six Sigma projects;
- the identification, selection and management of Black Belts.

Black Belt training is stratified by the final four phases of a Six Sigma project – Measure, Analyze, Improve and Control. Each phase comprises 1 week of classroom training in the relevant tools and techniques, followed by 3 weeks of on-the-job training on a selected project. The Black Belt is expected to give a presentation on the progress of his/her individual project at each phase; proficiency in the use of the relevant tools is assessed during such project presentations. Written tests may be conducted at the end of each phase to assess his/her academic understanding.

It is the opinion and experience of the author that it would be a mistake to adopt a common syllabus for Black Belts in a manufacturing arena (engineering, manufacturing, quality, etc.) and for those in a service-oriented environment (human resources, information technology, sales and marketing, shipping, etc.). While both groups of Black Belts will require a systematic approach to the identification and eradication of a problem's root causes, the tools required can differ significantly. Customized training is highly recommended for these two major families of application. By the same token, Six Sigma training for hardware design, software design and service design will require more mathematical models to complement the statistical methods.

In addition to the standard 4 weeks of Black Belt training, *Master Black Belt training* includes the Champions training described above (as the Master Black Belt's role bridges the functions between the Black Belt and his/her Champion) and 2 weeks of advanced statistical training, where the statistical theory behind the Six Sigma tools is discussed in greater detail to prepare him/her as the technical expert in Six Sigma.

To facilitate proliferation and integration of the Six Sigma methodology within an organization, appropriate training must be available for all stakeholders – ranging from management who are the project sponsors or Process Owners, to the front-line employees who will either be the team members or enforcers of the proposed solution(s). Such *Green Belt training* is similar to Black Belt training in terms of syllabus, though discussion of the statistics behind the Six Sigma tools will have less depth. Consequently, training is reduced to 4 days (or less) per phase, inclusive of project presentations.

1.5 SIX SIGMA PROJECTS

While Six Sigma tools tend to rely heavily on the use of statistical methods in the analysis within their projects, Black Belts must be able to integrate their newly acquired knowledge with their previous professional and operational experience. Six Sigma may be perceived as fulfilment of the Shewhart–Deming vision:

> *The long-range contribution of statistics depends not so much upon getting a lot of highly trained statisticians into industry as it does in creating a statistically minded generation of physicists, chemists, engineers, and others who will in any way have a hand in developing and directing the production processes of tomorrow.*[5]

The following project is an example of such belief and practice. It demonstrates the deployment of the Six Sigma methodology by a printed circuit board assembly (PCBA) supplier to reduce defect rates to best-in-class levels, and to improve cycle times not only for the pick-and-place process of its surface mount components but also for electrical and/or functional testing. Integration of the various engineering disciplines and statistical methods led to reduction in both direct and indirect material costs, and the design and development of new test methods. Working along with its supply chain management, inventory holding costs were reduced significantly.

1.5.1 Define

In this project, a Black Belt was assigned to reduce the cycle time for the electrical/functional testing of a PCBA, both in terms of its mean and variance. Successful realization of the project would lead to shorter manufacturing cycle time, thus improving the company's ability to respond to customer demands (both internal and external) in timely fashion, as well as offering the added benefit of reduced hardware requirements for volume ramp due to increasing market demand (i.e. capital avoidance).

1.5.2 Measure

To determine the goal for this project, 25 randomly selected PCBAs were tested by six randomly selected testers (Figure 1.6). The average test time per PCBA across all six testers t_{Ave} (*baseline*) was computed, and the average test time per unit for the 'best' tester t_{Best} was used as the *entitlement*. The opportunity for improvement ($\Delta = t_{\text{Ave}} - t_{\text{Best}}$) was then determined. The goal t_{Goal} was then set at 70% reduction of this opportunity, $t_{\text{Goal}} = t_{\text{Ave}} - 0.7\Delta$.

The functional testing of a PCBA comprises three major process steps:

- loading of the PCBA from the input stage to the test bed;
- actual functional testing of the PCBA on the test bed;
- unloading of the tested PCBA to the output stage.

To identify the major contributors of the 'hidden factory' of high mean and variance, 20 randomly selected PCBAs were tested by two randomly selected testers, with each unit being tested three times per tester. The handling time (loading and unloading) and test time (actual functional testing) for each of these tests were measured (see Figures 1.7 and 1.8).

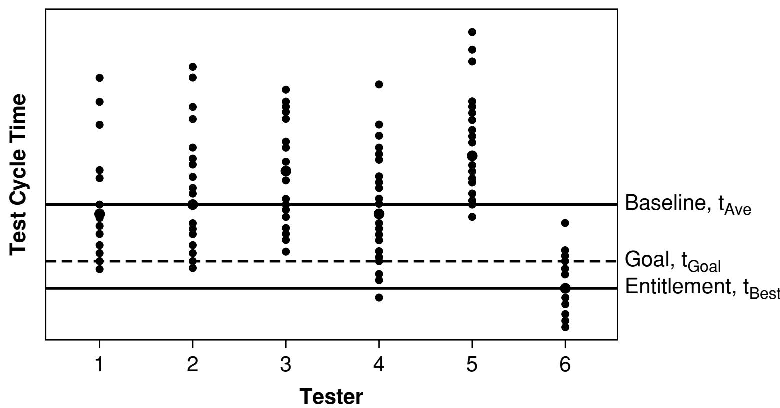

Figure 1.6 Test cycle times for different testers.

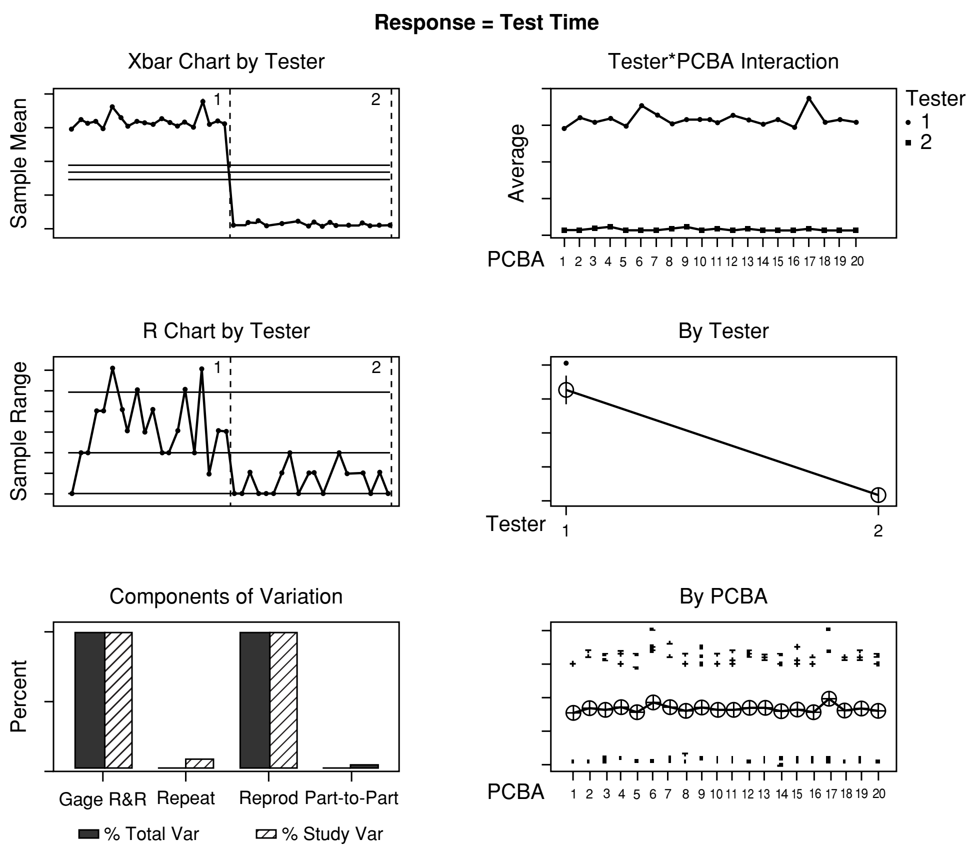

Figure 1.7 Sixpack analysis of test time.

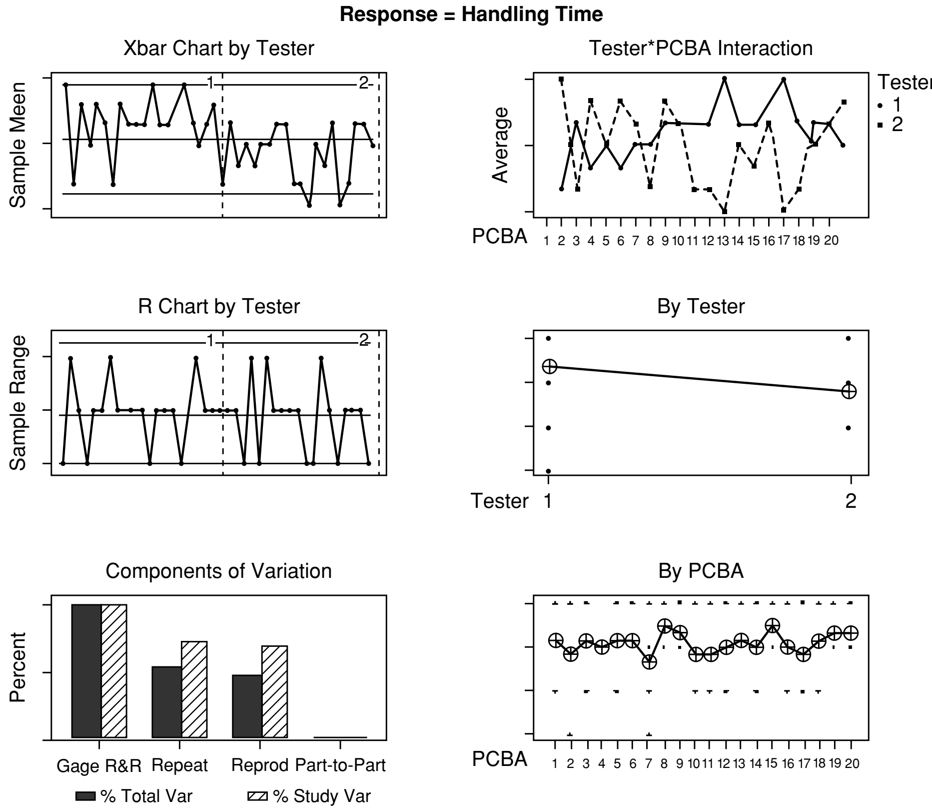

Figure 1.8 Sixpack analysis of handling time.

The following observations were noted:

- Test time was about 6–8 times as large as handling time.
- Variance in handling time between the two testers was negligible.
- Variance in test time between the two testers was significantly different.
- The average test time for Tester 1 was about 25% higher than Tester 2.
- The variance in test time for Tester 1 was nearly 20 times higher than for Tester 2.

The team unanimously agreed to focus their efforts on understanding the causes of variation in test time.

The *fishbone diagram* (also called an *Ishikawa diagram*) remains a useful tool for brainstorming of the various possible causes leading to an effect of concern (Figure 1.9).

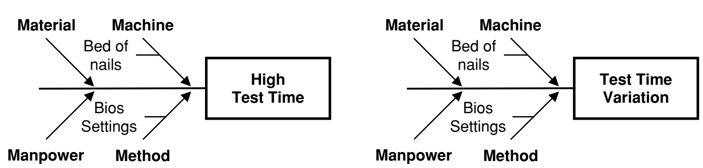

Figure 1.9 Cause-and-effect diagrams for long test time and large variation.

Table 1.1 Cause-and-effect matrix.

Key process input variables	Key process output variables: High test time	Key process output variables: Test–time variation	Score	Rank
	w_1	w_2		
BIOS settings	r_{11}	r_{12}	S_1	R_1
⋮	⋮	⋮	⋮	⋮
Bed-of-nails	r_{k1}	r_{k2}	S_k	R_k

However, one of its drawbacks is that generally too many possible causes will be listed. To facilitate a somewhat objective selection of important causes for further investigation, the *cause-and-effect matrix* was employed (Table 1.1). A derivative of the *House of Quality*, the importance of the key process output variables – high mean and variance in test time – were reflected in the different weights assigned to them.

The measure s_{ij} reflects the relationship between a *key process input variable* i and the *key process output variable* j. The score of each input variable, $S_i = r_{i1}w_1 + r_{i2}w_2$, was computed and ranked in descending order (i.e. highest score first), with further statistical analysis to be performed on the shortlisted input variables, selected via a *Pareto chart*.

At the end of this phase, the team were confident that they had the solution to their challenge, but they were surprised by what they were to learn.

1.5.3 Analyze

During this phase, statistical experiments and analyses were performed to verify the significance of the shortlisted input variables (Figure 1.10).

Input variables may fall under either of two categories:

- Control factors. Optimum levels for such factors may be identified and set for the purpose, of improving a process's response (e.g. clock speed, BIOS settings).
- Noise factors. Such factors are either uncontrollable, or are costly to control at desired levels (e.g. tester variation).

Regression analysis was performed to identify the effect of clock speed on the PCBA test time (Figure 1.11). While the test time decreased at higher clock speed, there is

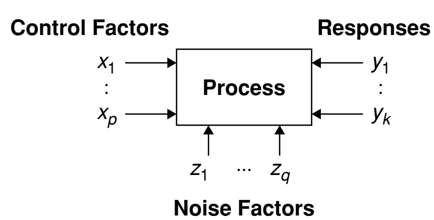

Figure 1.10 Model to facilitate statistical analysis.

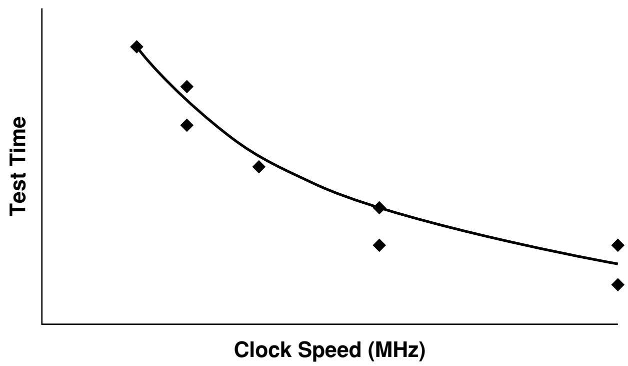

Figure 1.11 Nonlinear relationship between test time and clock speed.

an optimal speed for the existing tester design, beyond which value would not be returned for investment in higher clock speed.

Given the results from the Measure phase, which showed that the variation between testers was highly significant, the team went on to explore two primary sub-systems within a tester, namely the interface card and the test fixture. Five interface cards and six test fixtures were randomly selected for the next experiment; this was to yield results which came as a pleasant surprise.

Before the experiment, it was believed (from experience) that test fixture would result in greater inconsistency due to variation in the contact between the test pins and the test pads, as well as noise due to inductance in the conductors. However, reviewing the results using a *two-way ANOVA Type-II model* reveal that the interface card was the primary cause of variation, not the text fixture.

The *multi-vari chart* in Figure 1.12 illustrates that interface cards A and D can provide robustness against the different test fixtures used, while yielding a shorter test time.

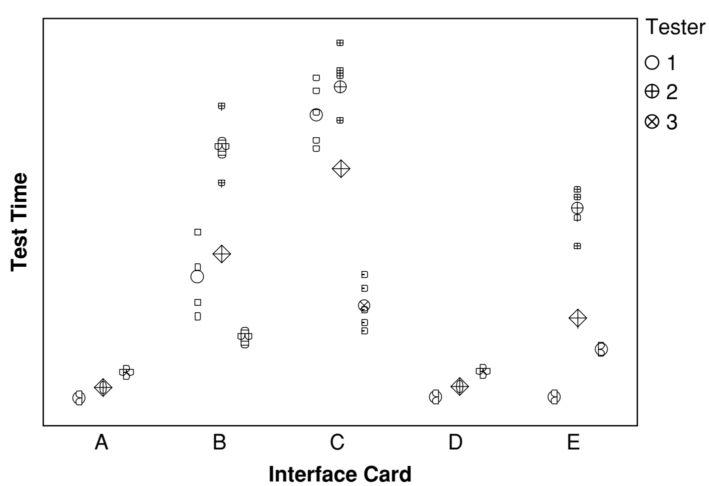

Figure 1.12 Multi-vari chart for test time with different testers and interface cards.

Applying their engineering knowledge, the team narrowed the cause down to the transceiver chip on the card. Examination revealed that cards A and D had transceivers from one supplier, with cards B and C sharing a second transceiver supplier, while card E had its transceiver from a third supplier. Cross-swapping of the transceiver with the interface cards confirmed that the difference was due to the transceiver chip.

1.5.4 Improve

During this phase, the effect of four control factors and one noise factor on two responses was studied.

Response (Y)	y_1	: Average Test Time
	y_2	: Standard Deviation in Test Time
Control Factors (X)	x_1	: Internal Cache
	x_2	: External Cache
	x_3	: CPU Clock Speed
	x_4	: Product Model
Noise Factor (Z)	z_1	: Transceiver on Interface Card

A 2^4 *full factorial design*, with two replicates, blocked by the two transceivers, was employed.

While an optimal combination of control factor levels was identified to minimize both the mean and variance in test time, the results showed that the noise factor (transceiver type) was the largest contributor to improvement.

Engineering analysis was employed to understand the difference between the transceiver chips. Oscilloscope analysis revealed that the 'better' transceiver (from Supplier 1) had a longer propagation delay, that is, it was actually slower than the chip from Supplier 2 (Figure 1.13).

The team verified their finding by acquiring slower transceivers from Supplier 2 (with propagation delay similar to that of Supplier 1). The test time for transceivers

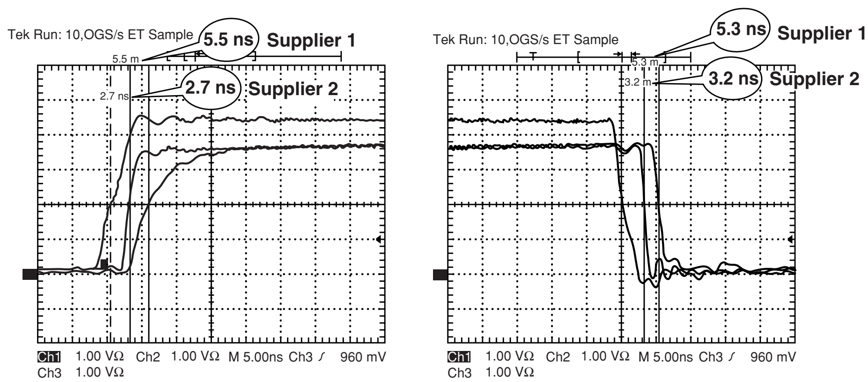

Figure 1.13 Results of oscilloscope analysis on propagation delay for Suppliers 1 and 2.

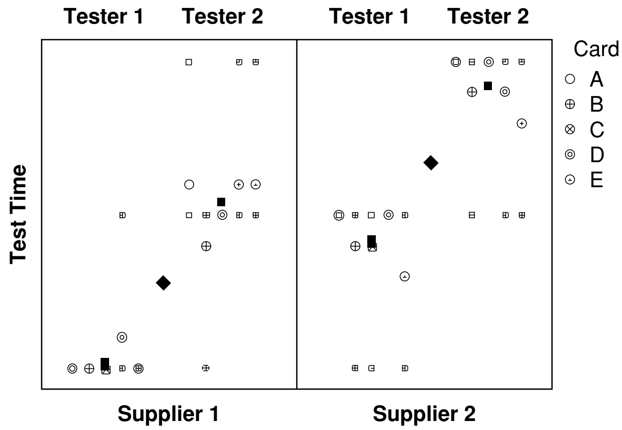

Figure 1.14 Multi-vari chart for test time by testers, interface cards and suppliers.

from both suppliers yielded similar results; verification was performed across two testers and five interface cards (Figure 1.14).

1.5.5 Control

The findings and recommendations were presented to the Process Owner, along with agreed trigger controls. These were documented in a *failure mode and effects analysis* document and *control plan*.

1.5.6 Realize

The results were astounding. Not only did the team exceed the established goal, they actually beat the original entitlement (Figure 1.15). In terms of variation, the variance in test time was reduced to a mere 2.5% of its original value. An unexpected benefit,

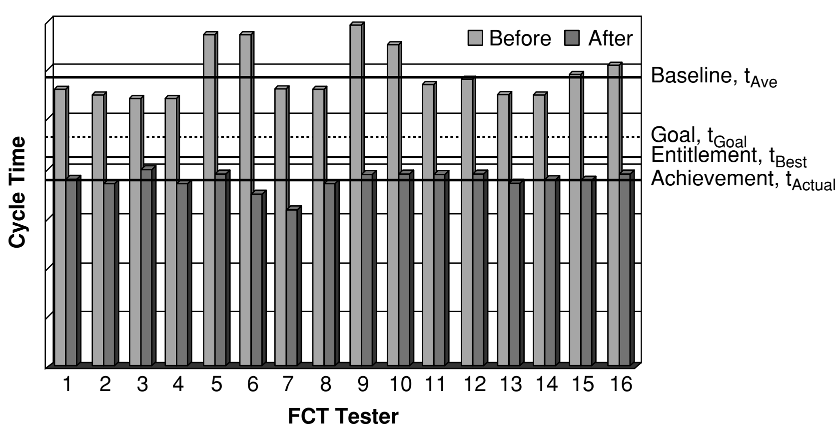

Figure 1.15 A before-and-after comparison of the cycle time.

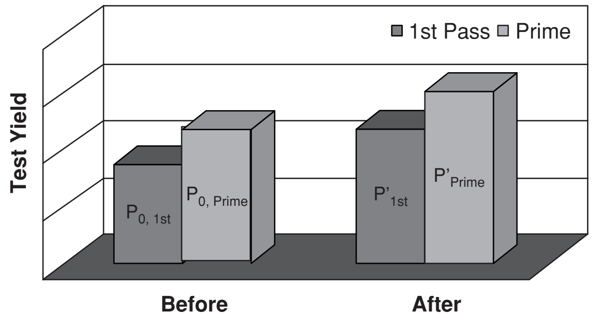

Figure 1.16 A before-and-after comparison of the test yield.

shown in Figure 1.16 was the improvement in first pass yield and prime yield (retest without rework).

The power of Six Sigma was evident in this project. Through the integration of engineering experience/knowledge with the Six Sigma tools and methodology, a data-driven and optimized solution was derived for a highly leveraged problem.

1.6 CONCLUSION

To summarize, Six Sigma involves selecting a highly leveraged problem and identifying the best people to work on it, providing them the training, tools and resources needed to fix the problem, while ensuring them uninterrupted time, so that a data-driven and well-thought-out solution may be achieved for long-term sustenance of profitability.

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