Six sigma quality management in engineering projects

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Past definitions of quality focused on conformance to standards, as companies strived to create products and services that fell within certain specification limits. Such definitions of quality assumed that if companies produced quality products and services, their performance standards were correct regardless of how those standards were met. The Six Sigma strategy broadens the definition of quality to include economic value and practical utility to both the company and the consumer. Quality is a state in which value entitlement is realized for the customer and provider in every aspect of the business relationship. A business process that allows companies to drastically improve their profit by designing and monitoring everyday business activities in ways that minimize waste and resources while increasing customer satisfaction. The purpose of this paper is to provide guidance and direction necessary to realize the value and potential of Six Sigma, a brief description of the basis and concept of Six Sigma, and its implementation in engineering projects.

إن التفسير القديم للجودة كان يتمحور حول كيفية تطبيق ومراقبة المعايير العالمية وكيفية الإنتاج ضمن هذه المعايير. وكانت الشركات تعتبر بأن هذه هي الطريقة المثلى للحصول على هذه جودة الإنتاج دون الخذ بالاعتبار الطرق المتبعة للوصول إلى هذه المعايير. إن استراتيجية الستة سيغما لمراقبة الجودة وسعت مفهوم الجودة لتتضمن القيمة الاقتصادية والعملية للشركات وللمستهلك على السواء. الستة سيغما هي طريقة مثلي لزيادة الربح مبنية على تصميم ومراقبة الأعمال اليومية لتخفيف الهدر والموارد إلى حدهما الأدني، وفي الوقت نفسه الحصول على رضى وامتنان المستهلك. إن الجدوى من هذا البحث هو شرح إمكانيات وكيفية إدارة الأعمال باستراتيجية الستة سيغما وكيفية تطبيق هذه الإستراتيجية على المشاريع الهندسية.

Keywords: Six sigma, Total quality management, Defect measurement, Performance measurement

1. Introduction

Performance standards for companies as they strived to create products and services that fell within certain specification limits are often achieved after considerable rework of a specific part or service. In addition, previous definitions of quality often overlooked the fact that products or services rarely consist of a single element. Even a product or service made up of as few as five different elements that individually conform to standard may not work properly when put together.

In the early 1980s with Chairman Bob Galvin at the helm, Motorola engineers decided that traditional quality levels of measuring defects in thousands of opportunities did not provide enough precision. Instead, they wanted to measure the defects per million opportunities. Motorola developed this new standard, created the methodology, and needed cultural change associated with it. Since then, hundreds of companies around the world have adopted six sigma as a way of doing business as evident by the many of America's leaders that have openly praised the benefits of Six Sigma. "The business media often describes Six Sigma as a highly technical method used by engineers and statisticians to fine-tune products and processes. Some people perceive Six Sigma as a means of achieving the goal reaching perfection in meeting customer requirements. Still others define six sigma as process to accomplish sweeping culture change to position a company for greater customer satisfaction, profitability, and competitiveness [1]".

The purpose of this paper is to provide guidance and direction necessary to realize the value and potential of Six Sigma, a brief description of the basis and concept of Six Sigma, and its implementation in engineering projects.

2. Literature review

Six sigma is relatively new concept in the general area of quality management. The following sections provide a review of quality systems that preceded the Six Sigma concept.

2.1. Total quality management

The first formal term associated with the general area of quality management is Total Quality Management (TQM). The concept of TQM was developed by an American, W. Edwards Deming after World War II. TQM improves the production quality of goods and services. The Japanese used this concept, in 1950, to re-establish their postwar business and industry, and using TQM, they dominated the market by 1980. When Japan first started using total quality management, Americans did not accept the concept. However, after Japan's domination of the market, US manufacturers realized that their assembly line factory models were too outdated for the new modern global economic market.

2.2. ISO 9000

ISO 9000 is an outgrowth of TQM. ISO stands for the International standardization Organization, a worldwide federation of national standard bodies from 100 countries. This group sets standards and guidelines for quality assurance systems. To develop an ISO strategy that puts the right activities in correct order, there are four key steps as described below:

1. Conduct a Needs Assessment, before beginning the ISO process. Sources of information include:
- Customer complaints,
- Process measurements, including a Cost of Waste analysis,
- Employee attitude surveys, and
- Benchmarking in key process areas.

2. Prioritize Improvement Targets, i.e. the 20% of the process areas that produce 80% of the unnecessary cost and waste.
3. Develop a Performance Improvement Strategy guided by a Steering Committee or Quality Improvement Team. Assure that employees are equipped with the knowledge, tools and skills for improving performance. The strategy should be to assure that key processes are analyzed and optimized before the ISO basics are implemented.
4. Institutionalize the Improvements: as projects are initiated and processes improved, use ISO documentation and training routines to lock in the changes. This foundation also serves as a basis for continuous improvement. To achieve both ISO certification and world-class performance, companies need to seek experienced help, develop the proper strategy, and take the time to make ISO 9000 work.

2.3. Comparison of TQM and Six Sigma

The difference between previous total quality approaches and the Six Sigma concept was a matter of focus. Total quality management programs focus on improvements in individual operations with unrelated processes. The consequence is that with many quality programs, regardless of how comprehensive they are, it takes many years before all the operations within a given process are improved. Six sigma has evolved over time. It's more than just a quality system like TQM or ISO. It's a way of doing business: "Six Sigma is many things, and it would perhaps be easier to list all the things that Six Sigma quality is not. Six Sigma can be seen as: a vision, a philosophy, a symbol, a metric, a goal, a methodology [3]". That why, one should navigate through the basics to fully understand the way it works.

3. Basics, concepts, and principles of Six Sigma

3.1. Definition

Σ is the Greek letter that staticians use to represent the standard deviation of a population. Sigma, or standard deviation from the mean, measures the variability in a process. Six Sigma uses Defects Per Opportunities (DPO) as a measurement tool. It uses the term opportunities rather than units because units tend to vary in complexity. Defects per Opportunities is a good measure of the quality of a process or product. It correlates to defects, cost, and time.

The sigma value indicates how often defects are likely to occur. The higher the sigma value, the lower the likelihood of defects. In this case, a defect is anything that results in customer dissatisfaction. Therefore, as sigma increases, cost and cycle time decrease while customer satisfaction increases.

Sigma levels of performance are expressed as Defects Per Million Opportunities (DPMO). DPMO indicates how many errors would show up if an activity were to be repeated one million times. Defects per million only describes what percentage of units will have defects that pass on to the customer. A base of one million is used instead of one hundred, as in percentages, because the numbers are usually small in relation to the systems they are meant to measure. Six Sigma, at a base level, is a way to simply and consistently track and compare performance to customer requirements (the Sigma measure) and an ambitious target of practically perfect quality (the Sigma goal). The goal of Six Sigma performance is to achieve what it is called 99.9997 percent perfect.

It is very important to understand that Six Sigma is a performance target that applies to what is referred to in Six Sigma parlance as a single critical-to-quality characteristic (CTQ). It is not a performance target that applies to the total product. A common example [4] of what this means is to consider an automobile. When an automobile is described as Six Sigma, this does not mean that only 3.4 automobiles out of one million will be defective. Six Sigma means that within a single automobile, the average opportunity for a defect of a critical-to-quality characteristic is only 3.4 defects per million [5]opportunities for such a defect to occur. The more complex a product is, the greater is the likelihood that a defect will exist somewhere with the product. So while a complex automobile may have more defects per unit than, say, typical audio speaker, at the opportunity level, the audio speaker and the automobile can easily have the same sigma capability. So rather than stating that a product is Six Sigma, it is better to say that the average opportunity for non-conformance within a product is Six Sigma. It is a measure not of the product, but of the performance of the product.

3.2. Method of calculation

To accurately calculate the capability of a process, one must properly define and quantify the process defect, unit, and opportunity. Every process should have definitions for defect, unit, and opportunity. In order to calculate the process sigma there are five steps that must be done.

The first step is to define the opportunities. Opportunities are the total number of chances per unit to have a defect. Each opportunity must be independent of other opportunities and, like a unit, must be measurable and observable.

The second step is to define the defects. A defect is defined as any part of a product or service that does not meet customer specifications or requirements.

The third step is to measure opportunities and defects once a clear definition of what an opportunity and defect is established.

The forth step is to calculate the Yield. The process yield is calculated by subtracting the total number of defects from the total number of opportunities, dividing by the total number of opportunities, and finally multiplying the result by 100.

The final step is to look up for sigma on a Sigma conversion table, using the process yield calculated in Step 4 (table 1).

To get the values in table 2 the following equations are used:

Defects Per Million Opportunities (DPMO)= (Total Defects/Total Opportunities) x 1,000,000 "For a closer look at the difference between three sigma and six sigma processes,one can consider the following example. Fig. 1 below illustrates a three sigma (centered) process and a Six Sigma (+1.5 σ shifted) process. Both process distributions appear to be entirely within the product specifications.

The LSL means Lower Specification Limit and USL means Upper Specification Limit, and μ means the mean. The target, T, equals [(USL + LSL)/2]. We will chose T = 0, USL = -6, and LSL = +6. In this example we are considering that we have worked at a three sigma level up to this point and that, further, given the specifications, the process variation (σ) must be small enough so that the base of the normal

Table 1
Yield to sigma conversion table [5]

Yield %	Sigma	Defects per million opportunities
99.9997	6.00	3.4
99.9995	5.92	5
99.9992	5.81	8
99.9990	5.76	10
99.9980	5.61	20
99.9970	5.51	30
99.9960	5.44	40
99.9930	5.31	70
99.9900	5.22	100
99.9850	5.12	150
99.9770	5.00	230
99.9670	4.91	330
99.9520	4.80	480
99.9320	4.70	680
99.9040	4.60	960
99.8650	4.50	1350
99.8140	4.40	1860
99.7450	4.30	2550
99.6540	4.20	3460
99.5340	4.10	4660
99.3790	4.00	6210
99.1810	3.90	8190
98.9300	3.80	10700
98.6100	3.70	13900
98.2200	3.60	17800
97.7300	3.50	22700
97.1300	3.40	28700
96.4100	3.30	35900
95.5400	3.20	44600
94.5200	3.10	54800
93.3200	3.00	66800
91.9200	2.90	80800
90.3200	2.80	96800
88.5000	2.70	115000
86.5000	2.60	135000
84.2000	2.50	158000
81.6000	2.40	184000
78.8000	2.30	212000
75.8000	2.20	242000
72.6000	2.10	274000
69.2000	2.00	308000
65.6000	1.90	344000
61.8000	1.80	382000
58.0000	1.70	420000
54.0000	1.60	460000
50.0000	1.50	500000
46.0000	1.40	540000
43.0000	1.32	570000
39.0000	1.22	610000
35.0000	1.11	650000
31.0000	1.00	690000
28.0000	0.92	720000
25.0000	0.83	750000
22.0000	0.73	780000
19.0000	0.62	810000
16.0000	0.51	840000
14.0000	0.42	860000
12.0000	0.33	880000
10.0000	0.22	900000
8.0000	0.09	920000

Table 2
Simplified sigma conversion table [6]

5	1 Sigma = 690,000 DPMO = 30.9% Yield
6	2 Sigma = 308,537 DPMO = 69.2% Yield
7	3 Sigma = 66,807 DPMO = 93.2% Yield
8	4 Sigma = 6,210 DPMO = 99.4% Yield
9	5 Sigma = 233 DPMO = 99.98% Yield
10	6 Sigma = 3.4 DPMO = 99.9997% Yield

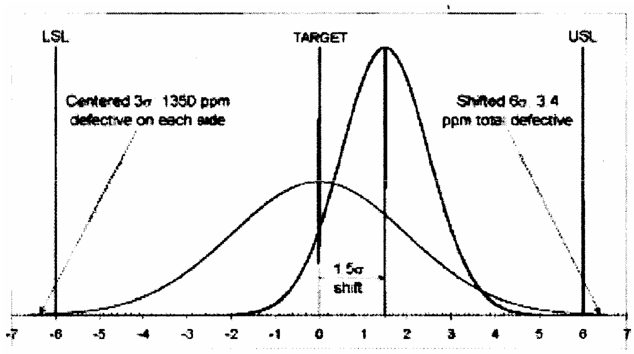

Fig. 1. Six Sigma process with +1.5σ shift vs.centered three sigma process 7.

distribution fits within the specifications, when the mean equals the target. That is, the length from μ - 3σ to μ + 3σ, a length of 6σ, must be less than USL - LSL. Hence σ = [(USL - LSL)/6] is the largest variation allowable. The above chart illustrates this situation with a normal distribution where the mean, μ, equals 0, and the variation, σ, equals 2. A process operating in this mode will produce 2,700 Parts Per Million (PPM) defectives, with 1,350 PPM beyond each specification limit. And should the process mean shift to $\mu = \tau \pm 1.5\sigma$ (which would be ± 3), then it would produce 66, 807 PPM defectives.

Following the same reasoning as was given for the three sigma process, a process variation of σ = 1 or smaller is required to achieve the six sigma objective σ = [(USL - LSL)/12]. If the six sigma process mean were centered on the target value, the process would produce defectives at a rate of two parts-per-billion, which is one part-per-billion beyond each specification limit. Should the process mean shift by 1.5 sigma, the defective rate would increase to 3.4 parts-per-million defectives. The chart illustrates the latter situation, with a normal distribution where the mean, μ, equals 1.5, and the variation, σ, equals 1. Every process has a variation that can be estimated through a process capability study. It is not determined by the specifications of the product being produced. With this example we are determining how precise a process must be to accomplish a three or six sigma objective for the product[7]". The objective of Six Sigma Quality is to reduce process output variation so that ±six standard deviations lie between the mean and the nearest specification limit. This will allow no more than 3.4 defect Parts Per Million (PPM) opportunities, also known as Defects Per Million Opportunities (DPMO), to be produced.

3.3. Principles of Six Sigma

Six Sigma is a quality methodology that can produce significant benefit to businesses and organizations. Not much text, however, has been written about the structure needed to successfully implement Six Sigma quality within business or organization. The inverted pyramid (fig 2) is a powerfull metaphor for the support of Six Sigma needs to succeed. The inverted relationships that result from this triangle have strong implications for the way Six Sigma infiltrates an organization. At the bottom of the pyramid, supporting and balancing the strucure, is the executive leadership.

3.3.1. Roles and responsibilities

Six sigma is not just having people work in teams. Teams alone can't change orporate structures. They must be part of an infrastructure designed to assist in the redesign of the organization. One way to understand this renovation structure is to review the roles of people in the evolving Six Sigma organization (fig 3). There are five functions and roles that must be developed:

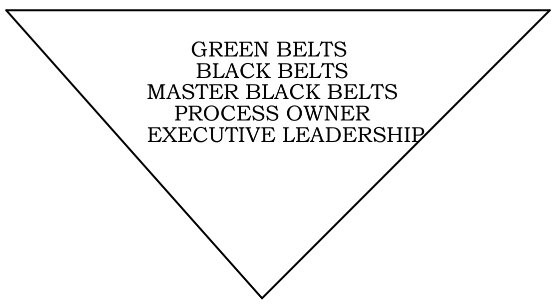

Fig. 2. Six Sigma pyramid [3].

- *Executive leadership:* The Executive Leadership's primary responsibility is to represent the needs of the customer and to improve the organization's operational effectiveness. Without commitment from Executive Leadership, Six Sigma is subjected to failure. The Executive Leadership must create a vision that is clearly understood by the entire organization. The Executive Leadership is part of the CEO/President's staff, and has the power and resources to make decisions and implement the changes brought about by Six Sigma.
- *Process owner:* Process Owners (PO) is normally the individual responsible for a specific process. They are the people who receive the solution created by an improvement team and become the owners responsible for managing the improved process. For example, there may be a chief marketing officer for business, that is the process owner for marketing. Process Ownership makes sense in an organization that has implement process management as a way of doing business.
- *Master black belts:* Master Black Belts (MBBs) devote 100% of their working time for projects, with the collaboration of Process Owners to coordinate project selection and training. MBBs are assigned to a specific area or function of an organization. MBB training is extensive and includes training in statistical problem solving. MBBs train Black and Green Belts, and spend most of their time utilizing soft skills, such as organizing people, designing cross functional experiments, structuring and coordinating projects and meetings, teaching, coaching, and collecting informations on ways to improve their Six Sigma organization.
- *Black belt:* Black Belt (BB) label is drawn from the martial arts, and suggests a perfection of skills and discipline, while the different levels, Green, Black, and Master recognize depth of training and experience. Black Belts dedicate 100% of their time to working on Six Sigma projects. BB can

typically complete one to six projects per year with savings of approximately $230,000 per projects. Black belts are seen as leaders and must possess both management and techical skills. BBs also coach Green Belts on the projects.

- *Green belt:* Green Belts (GB) employees involvement in Six Sigma projects is not 100% of their working time. GB have less Six Sigma responsibility. GB have two primary tasks to achieve: first to help implement the success of Six Sigma techniques, and second to lead small scale improvement project within their prospective areas. GBs at the beginning dedicate only part of their overall job time to the Six Sigma project in their daily activities. As Six Sigma quality program evolves, the GB employees will begin to include the Six Sigma methodology in their daily activities and it will be the way their work is accomplished 100% of the time.

3.3.2. Rewards and recognition

Role assignments are not enough to start and maintain a successful Six Sigma quality program. Rewards and recognition must be part of a sustained program. The question is: How to reward the different roles within the organization. The following paragraph describes the various Six Sigma participitants in the organization.

- *Green belts*: The Green Belts motivation comes from gift certificates, cash, and stock options, but the most effective way to motivate the Green Belts is to publically praise amd recognize them in front of their peers: Esteem or Ego as defined by Maslow's Hierarchy of needs. So those who bring a significant improvement to their business units profit margins, deserve a salary compensation that rewards their achievement.
- *Black belts and master black belts:* BBs and MBBs compensation is an important consideration when implementing Six Sigma. Their salaries must be standardized in a way that recognizes their roles within the company. Productivity, loss reduction, improved quality, and reduced overhead are factors in determining the proper compensation for performance. At the same time, whenever their performance is not meeting company standards, instead of being praised, they will be instructed on how to modify their behaviors and actions for improved performance.
- *Process owners:* This is one of the key roles that needs to be defined properly. The Process Owner's compensation (salary and bonus) must be tied directly to quality efforts within their organization. Their metrics and efforts need to be utilizing all of the quality tools appropriately. For example, 25% of their bonus could be tied to meeting their quality initiative goals and objectives, then have them report on how they did before determining the bonus payout.
- *Quality leadership*: As with all of the other Six Sigma participitants, Quality Leadership should be compensated based on their performance. The leadership responsibilities are of great importance, and the quantitave (savings, projects, training,ect.) aspects and efforts should be measured.
- *CEO*: The CEO is crucial to a successful program. The CEOs and those at the executive level, should have a minimum of 30% of their incentive compensation tied to Six Sigma.

It is essential to tie compensation to the Six Sigma Quality initiative, in order to have the entire organization focused around the customer and the quality of his processes and deliverables.

3.3.3. DMAIC Six Sigma approach

The Six Sigma approach for projects as presented in many references is DMAIC (Define, Measure, Analyze, Improve and control). These steps are the most common Six Sigma approach to project work.

- *Define:* Define is the first step in six sigma approach of DMAIC. DMAIC first asks leaders to define the core processes. It is important to define the selected project scope, expectations, resources and timelines, and this is done by mapping a product or service process. All processes consist of series of steps or events. Define, identifies what is part of the project and what is not, and explains the scope of the project. For process improvement, the problem should be identified, all requirements should be defined, and finally the goals should be set.
- *Measure:* Measure is the second step in DMAIC and measures the capability of each process. Most organizations fail to recognize

the importance of measure. A company that cannot express how well a process is performing in the form of a measure doesn't understand its process. The Six Sigma approach asks the Black Belt project manager to quantify and benchmark processes, using actual data. BBs need to calculate the average process performance and consider some estimate of dispersion or variation to reveal trends and cycles.

- *Analyze:* Analyze is the third process of DMAIC. In the analyze phase, data are collected to determine the relationship between the variable factors in the process to determine the direction of improvements. In this step, statistical tools are applied to discover the root of problems. The data analyzed can reveal the basic nature of the process, and show the process stability over a period of time. At this stage, the BBs play a major role whether the process capability is poor and should be terminated or there is a potential for improvement and progression to the next phase.
- *Improve:* During the improve step of the Six Sigma approach, ideas and solutions are put to work. Once the defects are identified, it is the job of the Black Belt to focus on the critical to quality characteristics by searching for variables that have the greatest impact on the processes, and trying to develop ideas to remove root of causes. As part of the Six Sigma approach, BB must have the ability to test the solutions, sometimes more than one trial may be required to check and ensure that the desired results are achieved.

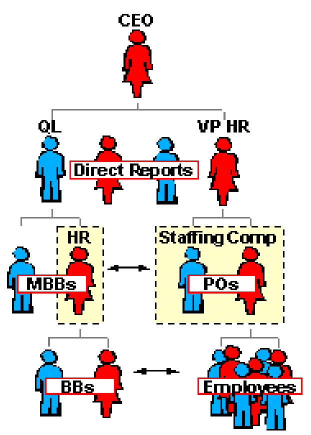

Fig. 3. Organizational structure of six sigma [1].

- *Control:* Control is the final phase or step in the DMAIC process. Once the process has been improved, Black Belts must implement measures that will control the key variables within the operating limits overtime. As part of the Six Sigma approach, to make sure that a new process is monitored and continuously improved, first one has to make sure that the problems are corrected as needed, and then establish standard measures to maintain performance.

3.3.4. The DMAIC methodology in engineering

For engineering, a project starts as a need by the owner for the design and construction of a facility to produce a service. A project consists of three components: scope, budget, and schedule. A lack of definition of one of these components is always the problem for changes in projects. Using the concept of DMAIC, one can solve this kind of problem. Applying the Six Sigma concepts to engineering changes are illustrated below:

Define: Large number of changes from client after approving engineering design schedule slipping.

Measure: Number of changes, time involved in changes, compliance to critical path schedule, number of changes to correct errors, number of changes due to owner requests.

Analyze: No clear authority on client team to establish scope, any of client team could make changes, verbal communication of changes, conflicting changes by client team members. Language issues between client and engineers.

Improve: Regular engineering/client meetings where topics included: scope for each section and desired objective, known limitations defined, unclear requirements were questioned and options discussed. Written plan signed by client representative and engineering lead. Change requests in writing and signed by client representative.

Control: Change requests all in writing. Shared approach with other disciplines on project.

For a manufacturing process, there is always a possibility for some products to be out of spec. The following example gives us an idea how DMAIC deals with this problem.

Define: Amount of product out of specification and being automatically removed is high. No recycle or salvage value.

Measure: Quantified the amount of out of spec product for each product grade.
Analyze: Operations and Engineers identified the variables that affect the production of out of spec material. Several of these are preventive actions performed by operations. Ranges for the levels and frequencies for the variables were determined. Designed experiments were run and acceptable levels and frequencies determined. *Improve:* Levels for the variables and frequencies for operator preventive actions established. Out of spec material dropped by 50%.
Control: Operating procedures were modified, schedules for operator corrective actions instituted, and control charts for the amount of out spec material are being kept.

3.3.5. Designs for Six Sigma

Companies can expect to make one sigma shift improvement per year up to 4.7 sigma. The closer companies come to achieving Six Sigma, the more demanding the improvements become. At 4.8 sigma, companies hit a wall; the only way to get beyond the five-sigma wall is to redesign their products and services from scratch using Design For Six Sigma (DFSS).

DFSS is a rigorous approach to designing products and services and their enabling processes from the very beginning to ensure that they meet customer expectations. The primary goal of DFSS is to create a design that is resource efficient, capable of very high yields regardless of complexity and volume, and sensitive to process variations.

3.3.5.1. The main tools used in DFSS: It is very important to have practical experience of Six Sigma, as DFSS builds on the concepts and tools from a typical DMAIC approach. Since DFSS works with products/services rather than processes, and since design and creativity are important, a few new tools are common to any DFSS methodology. Strong emphasis is placed on customer analysis, the transition of customer needs and requirements (of the product/service) down to process requirements, and on error and failure proofing. Since the product/service is often very new, modeling and simulation tools are important, particularly for measuring and evaluating in advance the anticipated performance of the new process.

The main tools include: Quality Function Deployment (QFD), Failure Mode Effect Analysis (FMEA), Design Of Experiment (DOE), and simulation techniques. However, like in Six Sigma the ability of the approach to be successful in use does not depend entirely on the tools used.

If DFSS is to work successfully, it is important that it covers the full life cycle of any new product or service. This begins when the organization formally agrees the requirement for something new, and ends when the new product is in full commercial delivery.

4. Six sigma in the construction industry

4.1. Definition of a process

Almost all companies involve a process. A process is an activity or group of activities that takes an input, adds value to it, and provides an output to an internal or external customer. Companies, regardless of their size, utilize thousands of processes every day to create their products and services. For example, an industrial process is any process that depends on machinery for its creation. A commercial process, such as ordering materials, payroll, etc, supports industrial processes, or may stand on its own as a separate and unique business.

4.2. Six sigma and construction

Six Sigma focuses on the process as the key means to meet customer requirements, whether dealing with a new product or service, measuring performance, improving efficiency, or customer satisfaction. Six Sigma first, focuses on is process improvement. Process improvement refers to a strategy of finding solutions to eliminate the root causes of performance problems in processes that already exist in the company. The process improvement team can use DMAIC methodology to attack the problem.

Another application of Six Sigma is process management where a focus on managing processes across the organization replaces managing individual functions by different internal departments. Process management tends to evolve as a business expands its Six Sigma effort and deepens its knowledge of its processes, people, and customers.

Construction, like manufacturing, is a collection of processes. Usually, there are many choices of processes, one has to take into consideration the advantages and the disadvantages of each one, and apply the most appropriate one to his company. In construction, the process chosen has a big impact on many things, including the project cost, quality, schedule, budget, and quality of people forming the team members. A typical example of a process in construction is paving. Actually, paving is formed of many functions, but all related to each other, and the output of the work is the paving process. Fig. 4 shows simplified function of the paving process.

The goal of Six Sigma is to reduce variability in construction processes and construction quality by giving good measurement systems. The following paragraphs show how to implement a good measurement system in construction.

4.3. Measurement systems

The construction industry suffers from a lack of a good measurement system and a lack of understanding concerning the importance of a good measurement system. Reasons for having a poor measurement system include highly variable and non-homogeneous materials and processes, high technical training requirements for testing products, and poor sampling techniques. Another reason for a poor measurement system is hidden factory. Too often companies that produce products and services spend an extraordinary amount of time and money practicing detection and correction of mistakes and errors.

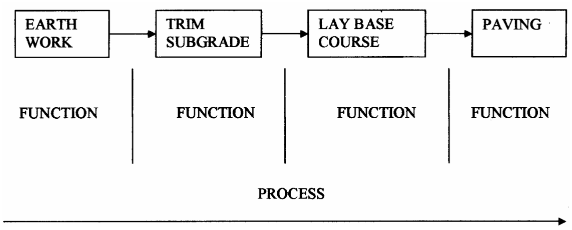

Fig. 4. Paving process.

Measurement is a key transitional step on the Six Sigma road, one that helps the team refine the problem and begin the search for root causes. Any data collected should reveal why or how the process does or does not meet customer requirements and profitability. Measurement in Six Sigma is based on some basic concepts. The first concept is "observe first then measure". This observational experience will help in deciding what and where to measure the process. The second concept is to understand the difference between "continuous data and discrete data". Continuous measures are data that can be measured on an infinitely divisible scale. Discrete measures are those where one can sort items into separate, non-overlapping categories. The third concept is to "measure for a reason". Always, there should be a clear reason to collect data, a key variable to track, and a goal to achieve. The forth concept is "a process for measurement". It is important to get the measures right the first time. This can be accomplished by treating data collection as a process that can be defined, documented, studied, and improved.

5. Six sigma in civil engineering

5.1. Variability of compressive strength

The compressive strength testing is used to determine the ultimate compressive unit stress of concrete. The test consists of placing concrete into the mold in three equal layers and each layer rodded a specified number of times (25 times for each layer for 6" diameter molds) with a bullet nosed rod. The top layer is struck or floated level and then protected from rapid evaporation by a suitable top place such as glass. Generally, three specimens are molded for a test. The specimens are cured in a moist condition for a specified number of days (3, 7, and 28 days).

The American Association of State Highway and Transportation Officials (AASHTO), and the American Society for Testing and Materials (ASTM) define the procedure for the concrete test cylinders AASHTO, and ASTM C 192 agreed that if:

Slump is less than 1” → we must vibrate the specimen.

Slump is between 1” and 3” → we can either rod or vibrate the specimen.

Slump is greater than 3” → we must rod the specimen.

The problem presented was whether we should rod or vibrate the specimens when the slump is between 1” and 3”, or does it have any relation with the compressive strengths. Experts say, “Vibrating would yield higher compressive strengths”. Using the Six Sigma approach, we cannot rely on advices; instead, experimentation and data are the tools to give an answer for the problem presented. Providing the same conditions for all tests, and fixing the other variables like technician, methods of consolidation, and methods of capping, the results were as follows:

Psi range	No of rodded specimens	No of vibrated specimens
4000	1	1
4100	2	2
4300	9	4
4350	5	5
4450	3	6
>4450	2	5

- Vibrating yield higher strengths, (vibrating provides 150 psi more than rodding)
- Vibrating yields higher variability in strengths, (standard deviation of vibrating is 150 psi more than that of rodding)

Specifications were percent within limit, up to 3% bonus for consistent high quality concrete, and variability was twice as important as bias (the difference between the average value and a reference value). Fig. 5. presents the scenario graphically:

According to the calculation, the areas below the lower limit for Rodding and Vibrating were respectively 2.28% and 6.7%. Final decision according to the graph is to rod all specimens with slump greater than 1” to minimize risk of penalty due to testing errors.

6. Conclusions

This paper is to enlighten the readers

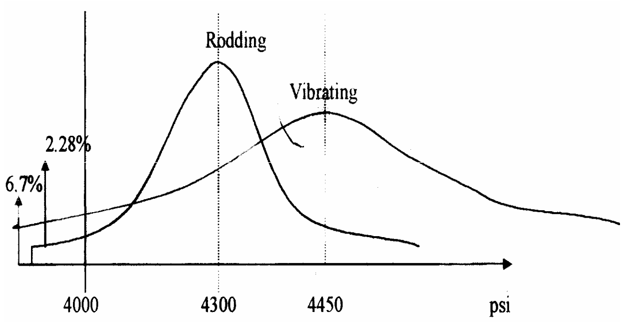

Fig. 5. Rodding and vibrating strengths.

about the concept of Six Sigma in the area of quality management. Six sigma is not all new. It combines some of the best techniques of the past with recent breakthroughs in management thinking, and for sure, common sense.

Six sigma has been successfully applied in the manufacturing industry, particularly because manufacturing is process intensive. Since construction is also process intensive, then many of the Six Sigma concepts and principles should be applicable to construction and engineering projects. However, because of the presence of many variables in those fields, Six Sigma application may seem harder, and needs additional care.

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