SIX-SIGMA IN LEAN CONSTRUCTION SYSTEMS: OPPORTUNITIES AND CHALLENGES

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ABSTRACT

One of the tenants of lean construction states that achieving reliable workflow is possible when sources of variability are controlled. Under a lean paradigm, the effects of variability are buffered through excess inventory, flexible capacity, and/or work-ready backlogs. The common element between these three approaches to tackle production process variability is that they are all attempts to combat the effects of variability and not to reduce or eliminate variability altogether. Reducing or eliminating the variability that plague production processes requires the removal of the root causes of variability –a difficult but not impossible task. Six Sigma is a statistical-based methodology that provides a structured framework to organize and implement strategic process improvement initiatives to attain reductions in process variability. In this paper, the origin of Six Sigma is reviewed with a brief discussion of its methods and metrics. The application of the Six Sigma *rolled throughput yield* and sigma quality level metrics to the Last Planner System is demonstrated. Using the Lean Project Delivery System as a foundation, the paper suggests Six Sigma applications and research opportunities in Lean Construction.

KEY WORDS

Six-Sigma, Performance Metrics, Lean Construction, Lean Project Delivery System, Last Planner System

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INTRODUCTION

Koskela (1992) presented a production management paradigm where production was conceptualised in three complementary ways, namely, as transformation, as flow, and as value generation. This tripartite view of production has lead to the birth of Lean Construction as a discipline that subsumes the transformation-dominated contemporary construction management (Koskela and Howell 2002, Berteslen and Koskela 2002).

A profound implication of the TFV concept of production is that it changes the definition of Construction Management from "The judicious allocation of resources to complete a project at budget, on time, and at desired quality" (Clough and Sears 1994) to the "The judicious allocation of resources to transform inputs to outputs while maximizing flow and value to the customer".

Viewing production as flow of materials and information has led to the principle of waste (muda)[2] elimination, which was Ohno's number one enemy (Howell 1999). In fact, Ohno named seven sources of waste in a production process and tirelessly worked on eliminating them. The basic tenant was that removal of waste would result in better workflow (Womack and Jones 1996). This same maxim is emphasized in the lean construction literature (Everett 1992, Koskela 1993, Howell and Ballard 1994, and Howell 1999).

An associated principle with waste removal is variability reduction (Berteslen and Koskela 2002). This means that unreliable workflow is indirectly caused by variability (mura)[3] stemming from single or multiple causes that need to be targeted separately or collectively. In the construction industry, sources of variability include late delivery of material and equipment, design errors, change orders, equipment breakdowns, tool malfunctions, improper crew utilization, labor strikes, environmental effects, poorly designed production systems, accidents, and physical demands of work (Abdelhamid and Everett 2002).

While variability has a myriad of causes it manifests itself mainly in the form of poor workflow reliability between production processes. The damaging and corrupting[4] effects of variability on dependent processes has been addressed in Tommelein et al. (1999), Tommelein 2000, and Howell et al. 2001. Additional discussion on the topic can be found in Goldratt (1992), and Hopp and Spearman (2000).

Under a lean paradigm, the effects of variability on workflow reliability are mitigated through the use of surge piles, plan buffers, and/or flexible capacity (Ballard and Howell 1998). Surge piles could be in the form of raw and/or processed material. Plan buffers refer mainly to having a backlog of work for crews. Flexible capacity refers to intentional underutilization of a crew or the ability of using a resource in multiple ways by having cross-trained workers. Other examples of flexible capacity can be found in Hopp and Spearman (2000). These three approaches are attempts to combat the effects of variability and not to eliminate variability altogether. In current practice, surge piles or perhaps excess inventory

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2 Muda is Japanese for waste

3 Mura is Japanese for variability

4 Hopp and Spearman (2000) used this term in addressing the effects of variability

prevails over the other two approaches. Practitioners also use efficiency factors or the 45-minute productive hour to account for the effects of variability on crew productivity.

Schonberger (1986) emphatically states that "variability is the universal enemy" and that reducing variability increases predictability and reduces cycle times. Koskela (1992) adds that reducing process variability will also increase customer satisfaction and decreases the volume of non value-adding activities.

The elimination or, more realistically, the reduction of variability requires the identification and removal of the root causes of variability. Koskela (1992) mentions that implementing standard procedures is one strategy to reduce variability in conversion and flow processes. He also mentions Shingo's "poka-yoke" or mistake-proofing devices and techniques as another strategy to reduce variability. Koskela (1992) also states that statisticians have been battling variability through statistical quality control theory and techniques. This latter strategy has been reinvigorated in the industrial and business sectors through the Motorola-developed Six Sigma approach.

Six Sigma is a statistical-based methodology that provides a structured framework to organize and implement strategic product and process improvement initiatives to attain reductions in product and process variability. In this paper, the origin of Six Sigma is reviewed with a brief discussion of its methods and metrics. The use of the rolled throughput yield and sigma quality level metrics is demonstrated using the Last Planner System. Using the Lean Project Delivery System as a foundation, the paper suggests Six Sigma application and research opportunities in Lean Construction.

WHAT IS SIX SIGMA?

In 1985, Bill Smith of Motorola developed and implemented an approach to achieve near-perfection in product manufacturing called Six Sigma (Breyfogle et al. 2001). Six Sigma refers to a body of statistical and process-based (e.g., process mapping, value stream mapping, etc.) methodologies and techniques used as part of a structured approach for solving production and business process problems plagued with variability in execution (Harry and Schroeder 2000, Pande et al. 2000). Some researchers believe that Motorola developed Six Sigma in an effort to revive Philip Crosby's (one of the leaders of the quality movement) zero defects approach (Behara et al. 1995). Today, Six Sigma has become a way of life in many other manufacturing organizations (e.g., General Electric, Ford, and Eastman Kodak) as well as in the service industry (Breyfogle 2003).

Six Sigma has escaped canonical definition in both the academic and the practitioner literature (Hahn et al. 1999). This is primarily caused by a lack of an abstraction of the underlying theory of the Six Sigma approach. Using Goal theory, Linderman et al. (2003) developed useful theories for the Six Sigma phenomenon. The following definition, suggested by Linderman et al. (2003), embodies the concepts and principles underlying Six Sigma:

> Six Sigma is an organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates.

While this definition may seem generic for any process improvement initiative, the focus on defect rates is what makes it unique. The defect rates, as defined by an internal or external customer, are caused by product and/or process variability. Reducing variability has been advocated by many of the quality movement leaders such as Deming, Conway, Juran, Crosby, Taguchi, and Shingo (Breyfogle 2003). Thus, Six Sigma emphasizes identifying and avoiding variation. But what also makes Six Sigma unique is the explicit recognition of the correlation among the number of product defects, wasted operating costs, and the level of customer satisfaction.

All 'sigmaists' know the framework used to achieve Six Sigma goals as DMAIC (Define, Measure, Analyze, Improve, Control). In its formative years, the DMAIC was practiced and perfected on performance improvement initiatives directed at existing processes that resulted in manufacturing defects. Today, the methodology is used for many business processes that fail to meet customer requirements. The DMAIC approach involves (Harry and Schroeder 2000):

1. Defining and understanding the problem being addressed by identifying the critical customer requirements and key factors affecting the process output.
2. Measuring relevant data to the problem primarily through Six Sigma metrics.
3. Analyzing, using statistical quality control tools, the production or business process associated with the problem to identify the root causes.
4. Improving the process using alternatives derived in the analysis phase.
5. Controlling and monitoring the process using statistical process control to sustain the gains and improvements.

Another emerging set of steps called Design for Six Sigma (DFSS)[5] is used when a product or a process does not exist (radical product or process design) or when incremental changes need to be incorporated into existing products or processes (Breyfogle et al. 2001). DFSS uses existing techniques, such as Quality Function Deployment (QFD), the Axiomatic Design (AD) method, and the theory of inventive problem-solving (TRIZ), to arrive at designs that consider a myriad of issues; performance, assembly, manufacturability, ergonomics, recyclability, reliability, and maintainability (Breyfogle 2003).

Companies implementing Six Sigma provide its employees with intensive and differentiated levels of training in six sigma methods (Pande et al 2000, Breyfogle et al . 2001, Linderman et al. 2003). Full-time 'black-belts' receive extensive training, usually 4-6 weeks, on the DMAIC or DFSS approaches and are prepared to lead Six Sigma improvement projects. Black belts are coached and instructed by experienced and specially trained individuals called Master Black Belts. Green belts are individuals who provide a supporting (part-time) role on improvement projects and thus receive less training compared to black belts. Six sigma projects are identified and selected by 'Six Sigma Champions' who receive macro-level training rather than detailed.

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[5] Known also as DMADV (Define-Measure-Analyze-Design-Verify)

STATISTICAL DEFINITION OF SIX SIGMA

Anyone who has had an elementary course in statistics knows that sigma, σ, is the Greek alphabet used by statisticians to denote the standard deviation of a set of data. The standard deviation (sigma) is (or should be) invariably associated with the calculation of the mean (average) value for a particular set of data. Reporting sigma with the mean value gives an indication of how all the data points vary from the mean. This is important because the mean value alone is misleading as demonstrated by the brilliant analogy of the person that had his/her two feet in a hot oven and the head in a bucket of ice but was on *average* doing 'ok' (Fellows and Liu 2003). However, in the context of the Six Sigma approach, 'sigma' has been used as a metric that reflects the ability of a company to manufacture a product or provide a service within prescribed specification limits (or with zero defects).

Understanding the statistical origins of the Six Sigma methodology requires an understanding of variability and the characteristics of the normal distribution, which represents many data sets in real life.

SIX SIGMA AND VARIABILITY

Deming (1986), the father and creator of TQM, stressed that because all things vary, statistical methods are required to control quality or defect rates. Underscoring the importance of variability, Deming (1986) stated: "Statistical Control does not imply absence of defective items. It is a state of random variation, in which the limits of variation are predictable".

Deming, and many others, further defined two kinds of variation: common cause and special cause variation (also known as chance and assignable variation, or chronic and sporadic variation). The former is an inherently random source of variation and addressing it involves a major change in the basic process and operating procedures. The latter is an unusual but controllable source of variation that requires a correction to bring the process or procedures back to its normal levels. Deming asserts that "the difference between these is one of the most difficult things to comprehend" and that it is a futile attempt to address quality problems without understanding the two types of variations. Therefore, Deming recommended that special cause variation be addressed first before addressing common cause variation.

To illustrate common cause and special cause variation, consider a manufacturer who produces a product using a single-stage or one-step process as shown in Figure 1. In Figure 1, X_n represents the inputs to the process and Y is the output. Due to variations in the inputs, the resulting Y will also be variable.

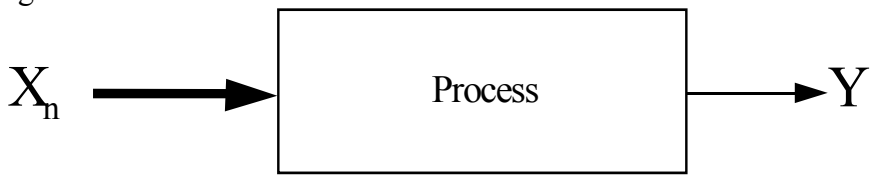

Figure 1: Typical single-stage manufacturing, business, or service process

Figure 2 shows the output Y assuming it follows a normal distribution where the ideal target is represented by the mean value. This normality assumption is frequently justified because

the inputs are mutually independent which allows invoking the central limit theorem, i.e., that the sum of mutually independent random variable approaches normality as the number of variables become larger (see Montgomery (2001) for further discussions).

Figure 2 is also showing that the manufacturer uses ± three sigma as the lower and upper specification limits for accepting the product Y. This is usually a reflection of the customer's input and requirements. Note that the use of USL and LSL as ± three sigma is for purposes of explaining the six sigma statistical origin. In real life, customers choose specification limits independent of the normal distribution, or any other distribution.

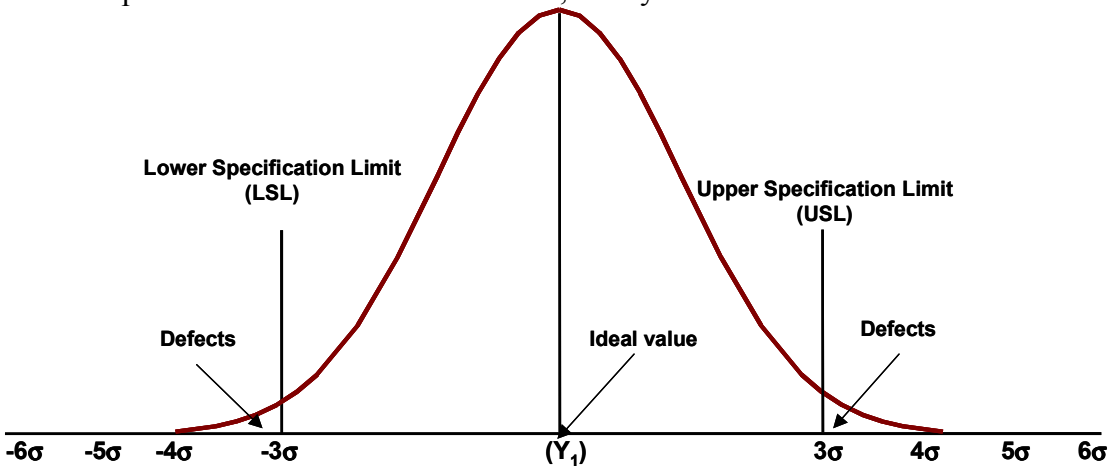

Figure 2: Normal Distribution with specification limits set at ± three sigma

Figure 3 is a statistical control chart used to *isolate* common from special cause variation. The chart shown in Figure 3 shows hypothetical dimension figures for the product Y plotted against time. The Upper and Lower Control Limits (UCL and LCL) shown are a function of the process mean, process range, and the standard deviation of the measured data. It is outside the scope of this paper to expand on the topic of control charts as the there are literally volumes written on the subject in the quality control literature. Montgomery (2001) and Breyfogle (2003) are excellent reference on the topic.

By considering the position of the data points on the control chart of Figure 3 relative to the upper and lower control limits, the manufacturer can determine whether the process is under *statistical control.* A process is considered under statistical control if all the data points fall within the LCL and UCL. Data points falling outside the LCL and UCL are caused by special cause variation. The variation of data points within the same bounds indicates common cause variation, which is inherently inevitable.

In the case shown in Figure 3, the process is not under statistical control because there is one measurement, that for part 3, falling below the LCL. This is caused by special cause variation. The reasons behind this should be investigated and eliminated. Because the measurements for the rest of the parts fall between the LCL and UCL, the variation seen is due to common cause variation. However, the common cause variation is excessive because the LSL and USL are violated on the 4^{th} and 5^{th} measurements. Hence, unlike the special cause variation, the reasons behind the variation for these two parts can only be eliminated

through a major change in the basic process. Processes exhibiting such performance are considered to be in *control* but *not capable* (Breyfogle 2003).

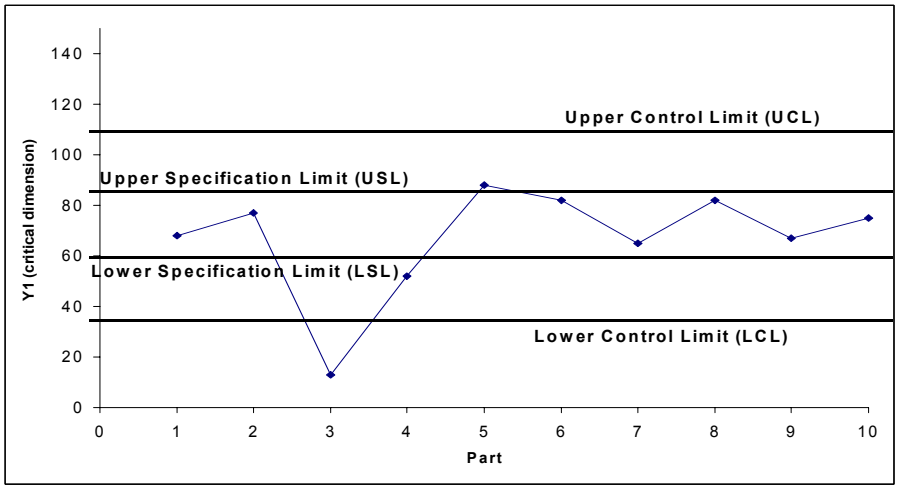

Figure 3: Statistical Control Chart -XmR[6] (Breyfogle 2003)

Turning attention back to Figure 2, it is known that when a data set follows a normal distribution that 99.73 percent of the data points fall within ± three sigma from the mean. Hence, the defects for the process shown in Figure 1 will represent 0.27% (100%-99.73%). When convened to a million 'Y' produced parts, the defect rate of the process in Figure 1 is 2700 defects per million parts (ppm). Similarly, if the design specifications allowed ± six sigma variation about the ideal mean, then the process under consideration will have a 0.002 [(100-99.9999998)*10^4)] parts per million (ppm) defect rate.

While, 0.002 ppm is considerably less than the 2,700 ppm defect rate, it has been found that the ideal mean value itself is subject to a variation or shift of up to ± 1.5 sigma as shown in Figure 4 (Montgomery 2001). This necessitates an adjustment to both defect rates reported. Hence, for the case shown in Figure 4, 93.32 percent instead of 99.73 percent of the data points now fall within ± three sigma from the mean, i.e., the defects for the process now represent 66,810 [(100-93.32)*10^4] ppm. In the same way, 99.99966 percent instead of 99.9999998 percent of the data points now fall within ± six sigma from the mean, which translates to a defect rate of 3.4 ppm. Motorola used this level of sigma quality as its goal and the Six Sigma movement was born.

As mentioned earlier, in the Six Sigma approach a 'sigma' quality level is used as a metric that reflects the ability of a company to manufacture a product or provide a service within prescribed specification limits (or with zero defects). Figure 5 shows the defective parts per million (ppm) and the associated sigma quality level (Breyfogle 2003)[7]. As shown in Figure 5, the relation between the defect rates and the sigma quality level is not linear. For example, a 6 sigma quality level indicates that a company is operating with only 3.4 defects

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[6] XmR stands for a control chart that uses process values obtained from one sample set to calculate process mean. A moving range is typically also constructed. Hence, the designation XmR.

[7] Sigma Quality Level = $0.8406 + [29.37\text{-}2.221 \times \ln(\text{ppm})]^{\wedge 1/2}$

per million parts, units, or operations, while a company operating at 3 sigma quality level has a defect rate of 66,810 ppm.

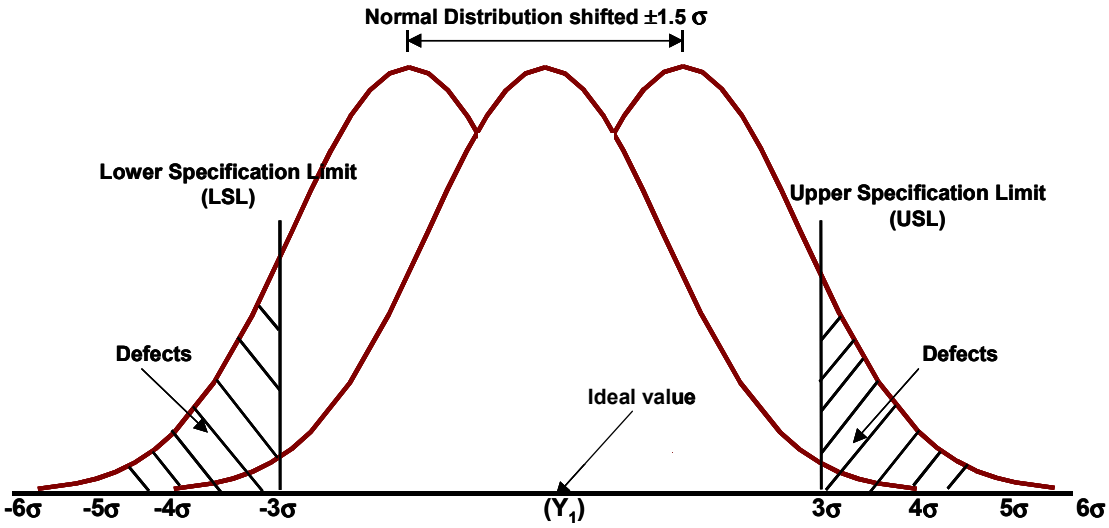

Figure 4: Normal distribution with ±1.5 sigma shift

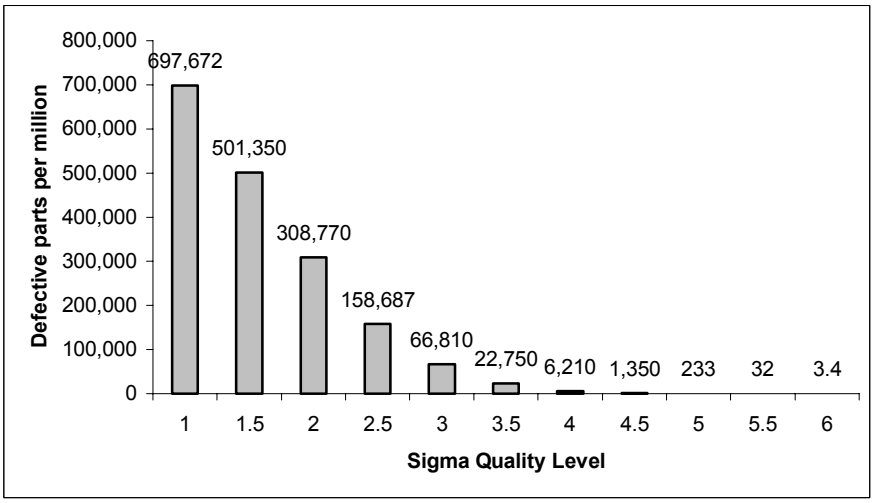

Figure 5: Defects per million and Sigma quality level

To better appreciate the magnitude of difference between the different sigma levels, the following spelling mistakes are provided as an example (Breyfogle 2001):

- Sigma level one: 170 misspelled words per page in a book
- Sigma level two: 25 misspelled words per page in a book
- Sigma level three: 1.5 misspelled words per page in a book
- Sigma level four: 1 misspelled words per 30 pages in a book

- Sigma level five: 1 misspelled word in a set of encyclopaedias
- Sigma level six: 1 misspelled word in all the books in a small library
- Sigma level seven: 1 misspelled word in all the books in several large libraries

On average, most US manufacturing and service industry firms rate between three and four sigma. Companies operating at the six sigma level in the short term and at the 4.5 sigma level for the long term are considered to be 'best in class'. It is worth noting that the US domestic airline flights fatality rate is between 6 and 7 sigma, i.e., at 0.43 ppm (Breyfogle 2003).

Thus far, the discussion has only addressed a single-step process. For multi-step processes, each step will have its associated sigma quality level or defect rate. The statistically independent *yields* for each step are multiplied to arrive at the overall yield or defect rate (Behara et al. 1995). Table 1 shows the overall yield for a single process up to a process with 1000 steps. As an example, consider a 10-step process with a desired 4 sigma level. The overall yield for the process as shown in Table 1 is 93.96 percent. Hence, 6.04 percent will be the resulting defect rate (or 60,400 ppm). Note that this defect rate is roughly ten times more compared to that from a single process at the same sigma level (at 6,210 ppm).

The numbers shown in Table 1 underscore the importance of simplifying and reducing the number of processes involved in producing a part, completing a service, building a structure, etc. In addition, having multi-stage processes makes it rather difficult to achieve a six sigma quality level. However, not all companies should consider this as the appropriate level. Rather the appropriate sigma quality level should be based on the strategic importance of the process and the cost to benefit ratio expected (Linderman et al 2003, Breyfogle 2003).

Table 1: Overall yield and associated sigma quality level (Behara et al. 1994)

Number of stages/parts	± 3 sigma	± 4 sigma	± 5 sigma	± 6 sigma
1	93.32	99.379	99.9767	99.99966
10	50.08[8]	93.96	99.768	99.9966
100	0.10	53.64	97.7	99.966
1000	0.0	0.20	79.24	99.661

SIX SIGMA AND TQM

Despite the success of Six Sigma and its role in rejuvenating the quality movement, it has come under fire from the quality community itself. Some have criticized the used of the 1.5 sigma shift and considered it an attempt to correct for the ubiquitous use of the normal distribution with its inherent oversimplifications. Others considered the 3.4 ppm defects rate an inappropriate goal for all businesses. Proponents of six sigma acknowledge that six sigma is not perfect but that it has shown deserved success and that taking six sigma's statistical

[8] 50.08% = (93.32%)^10

definition literally overlooks that it has now become associated with the tireless pursuit of customer satisfaction through higher levels of quality and lower levels of cost (Hammer and Goding 2001). In fact, not only did Six Sigma break away from its statistical definition of quality, it has also managed to break away from its initial focus on minimizing the variations or defects of manufactured products where it is now being applied to many business and service processes (e.g., billing, patient care, software programming, payroll, etc.)

Perhaps the most common mischaracterization of six sigma is that it is "TQM on steroids" and that it is nothing new. Breyfogle et al. (2001) quotes Tom Pyzdek saying: "Six Sigma is such a drastic extension of the old idea of statistical quality control as to be an entirely different subject….In short, Six Sigma is ….an entirely new way to mange an organization…Six Sigma is not primarily a technical program; it's a management program". Many others have dismissed the TQM uplift as irrelevant especially that six sigma does not place the same preeminence TQM placed on quality at the expense of all other business aspects (Harry and Schroeder 2000, Pande et al. 2000, Breyfogle 2003).

SIX SIGMA METRICS

Organizations implementing Six Sigma must select metrics against which progress and improvements can be assessed. To facilitate comparison and benchmarking to competitors or even other industries, a number of six sigma metrics have been created and are in use. Rolled throughput yield (Y_{RT}), defects per million opportunities (DPMO), process capability (C_k and C_{pk}) and process performance (P_k and P_{pk}) are examples of these metrics. Of these, rolled throughput yield (Y_{RT}) will be discussed as conceived under Six Sigma and then later adapted for use in the Last Planner System.

SIX SIGMA YIELD

For most organizations, yield (Y) represents the percentage of units that pass final inspection relative to the number of units that were processed. Mathematically, the yield represents the area under the probability density curve between design specification limits (Breyfogle 2003). Using the Poisson distribution as an approximation of the normal distribution (see Figure 6), the yield denotes the probability of having zero defects. Breyfogle (2003) shows yield in equation form as

$$Y = P(x = 0) = \frac{e^{-\lambda}\lambda^{x}}{x!} = e^{-\lambda} = e^{-DPU} \qquad (1)$$

where λ is the mean of the distribution equal in this case to the defects per unit, DPU. Note also that x represents the number of failures.

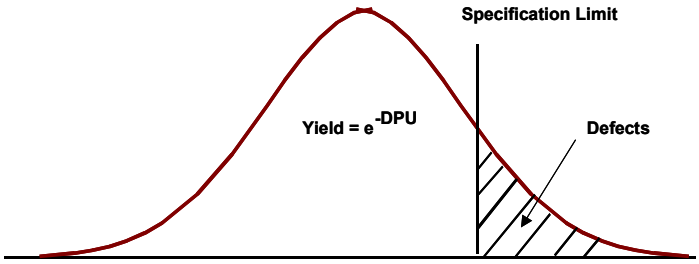

Figure 6: Process Yield and Defects (Breyfogle 2003)

The definition of the yield should not be associated with manufacturing operations only. In any industry where a product or service is provided, a process yield can be identified. This metric, however, can mask the rework that takes place prior to final release, which is the metaphoric 'hidden factory' that Lean and Six Sigma advocate identifying and eliminating. Exposing the 'hidden factory' is facilitated in Six Sigma projects through the use of rolled throughput yield (Y_{RT}). Y_{RT} is the product of the yield of each process (or sub-process) required to produce a unit or a service. To illustrate the difference between Y and Y_{RT}, Figure 7 shows a 3-stage process with the yield, rework, and scrap at each stage.

The process shown in the dashed box of Figure 7 represents how the yield is calculated using conventional means. For example, when 100 units are processed through the first process, which has an established yield of 90%, only 90 units will be acceptable or accomplished. The remaining 10 are re-routed through the 'hidden factory' where, as assumed here, 6 are re-worked successfully and 4 are scrapped. In this case, the final units reported, or that will end-up showing as 'finished goods', will be 96 (90+6) and not 90. This same calculation is used for process 2 and 3. Finally, the 3-stage process appears to have a yield rate of 90% (90/100).

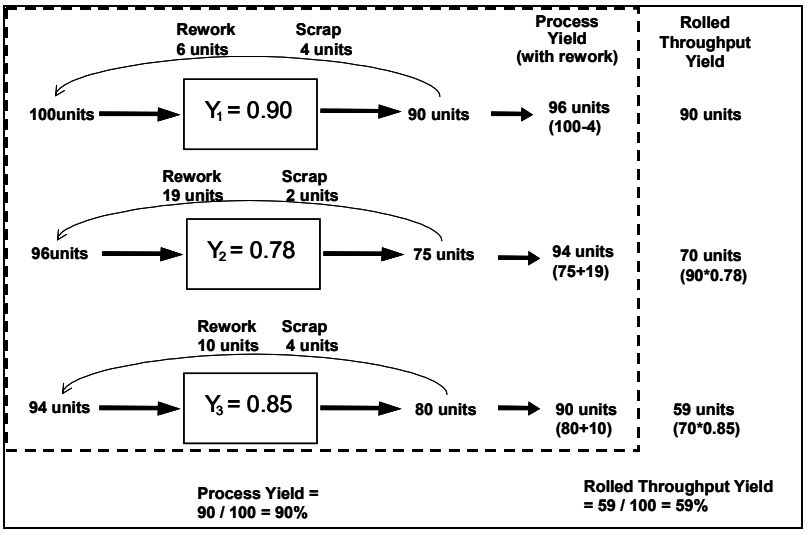

Figure 7: Conventional process yields vs. Six Sigma's rolled throughout yield

Using the Six Sigma rolled throughput yield metric gives an entirely different perspective on the yield. In this case, the output from the first process (the 90 units) is used as the input for

the second process without reflecting the rework. Consequently, the output for the second process is considered as the input of 90 units multiplied by the yield Y_2 (at 78%) giving a total of 70 units. These 70 units are again considered as the input for the third process, without the rework, and so on. The use of rolled throughput yield indicates that the 3-stage process has a 59% yield and not the 90% reported by conventional yield calculations. This exposes the hidden factory and gives more insights into process performance.

It is worth noting that the rolled throughput yield shown in Figure 7 is also the product of the three individual yield values, i.e. 0.90*0.78*0.85 = 59%. Hence, in equation form, rolled throughput yield is

$$Y_{RT} = \prod_{i=1}^{m} Y_i \qquad (2)$$

where m is the number of processes involved and Y_i is the throughput yield of process *i*. To facilitate comparison of processes performed at different locations, e.g., by peer companies or even across industries, the rolled throughput yield is normalized and a sigma quality level is calculated. This is performed using the following set of equations (see Breyfogle (2003) for more discussion):

$$Y_{norm} = \sqrt[m]{Y_{RT}} \qquad (3)^{9}$$

and using (1) it can be shown that

$$DPU_{norm} = -\ln(Y_{norm}) \qquad (4)$$

where DPU stands for the defects per unit. To determine the sigma quality level, also called $Z_{benchmark}$, for the processes under consideration, the following equation is used:

$$Z_{benchmark} = Z_{DPU_{norm}} + 1.5 \qquad (5)$$

where $Z_{DPUnorm}$ is the standard normal value corresponding to the DPU_{norm} found using Equation 4. To illustrate the use of Equations 3-5, the 3-stage process in Figure 7 is used:

1. Using Equation 3, $Y_{norm} = \sqrt[m]{Y_{RT}} = \sqrt[3]{0.59} = 0.8387$
2. Equation 4 gives a $DPU_{norm} = -\ln(Y_{norm}) = -\ln(0.8387) = 0.1759$
3. The standard normal table shows that $Z_{DPU_{norm}} = 0.93$, hence,
   $Z_{benchmark} = Z_{DPU_{norm}} + 1.5 = 0.93 + 1.5 = 2.43$

Therefore, the 3-step process shown in Figure 7 is operating at a 2.43 sigma quality level. This can be converted to a parts per million rate using

$$PPM = e^{\left(\frac{29.37-(SigmaQualityLevel-0.8406)^2}{2.221}\right)} \qquad (6)$$

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9 This equation is essentially the geometric mean of a set of data.

Using Equation 6, the ppm rate of this process is 177,435.

For a single step process, the same equations can be used but without normalizing the yield and noting that the rolled throughput yield is the same as the throughput yield. For example, consider that the sigma quality level of stage 2 in Figure 7 was of interest. To determine that, the following steps are followed:

1. Using $Y_2 = 0.78$ in Equation 4 gives a $DPU = -\ln(Y_2) = -\ln(0.78) = 0.2484$
2. The standard normal table shows that $Z_{DPU} = 0.68$, hence, $Z_{benchmark} = Z_{DPU} + 1.5 = 0.68 + 1.5 = 2.18$

Hence, stage 2 is operating at a 2.18 sigma quality level that, using Equation 6, gives a ppm rate of 246,725.

YIELD AND THE LAST PLANNER SYSTEM®

The Last Planner System® (LPS) provides a framework for management and workers to plan and control daily production assignments (Ballard 1999). Daily assignments are viewed as commitments that a production unit makes to other downstream units. A detailed explanation of the LPS is beyond the scope of this paper and can be found in Ballard (2000).

The Last Planner System uses Percent Plan Complete (PPC) as a metric to measure the quality of the commitments made and the reliability of workflow. PPC is the number of completed assignments expressed as a ratio of the total number of assignments made in a given week. This metric is usually reported for a particular trade or crew on a daily or weekly basis. Figure 8 shows PPC data collected by Chitla (2003) for a paint ceiling job in a manufactured housing facility where houses are built on an assembly line. The average daily PPC for the crew in Figure 8 is 68%.

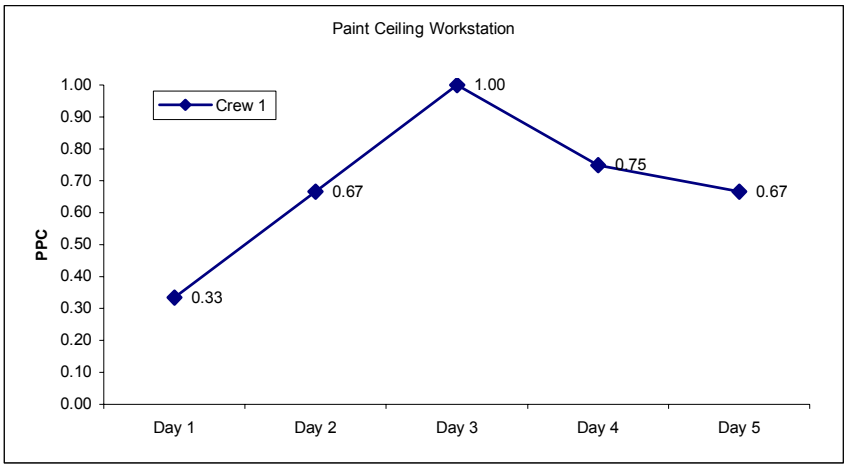

Figure 8: PPC for Paint Ceiling

Figure 9, also from Chitla (2003), shows PPC for 10 different workstations along the assembly line of the same plant. The PPC in Figure 9 was calculated using data collected

over 10 days for each station. According to the PPC data in Figure 9, the average PPC for the entire plant is 78%.

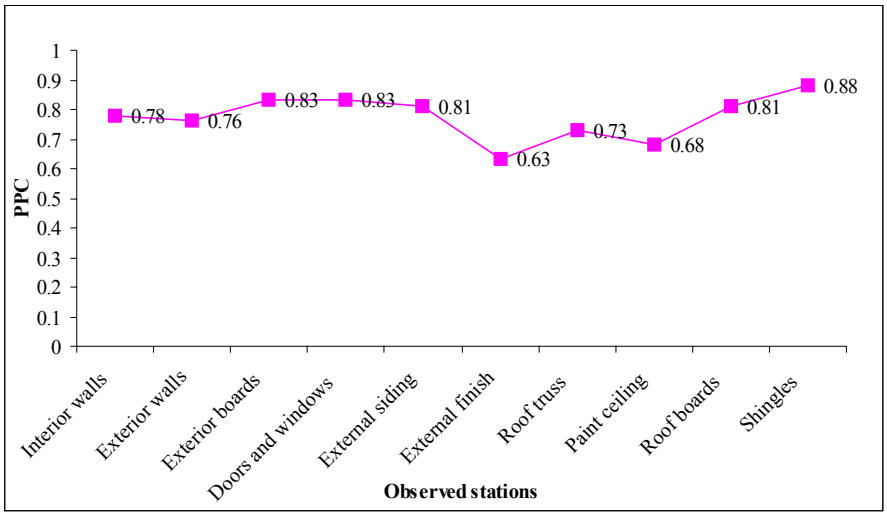

Figure 9: Manufacturing Plant PPC

The PPC averages reported at both the crew level and the plant level reflect fluctuations in production planning and workflow reliability. Recall that the yield (Y) represented the percentage of units that pass final inspection relative to the number of units that were processed. Contrasting the PPC metric to the definition of the yield reveals similarities because both reflect a 'completion rate'. Consequently, using an average PPC to report the overall plant throughput would also mask the 'hidden' factory as discussed before in the case of the yield. Therefore, it seems prudent to extend the Six Sigma rolled throughput yield (Y_{RT}) to the PPC metric. This is accomplished by adapting equations 2-5 as follows:

$$PPC_R = \prod_{i=1}^{m} PPC_i \qquad (7)$$

where PPC_R is *rolled PPC,* m is the number of processes involved, and PPC_i is the PPC of process *i.*

$$PPC_{norm} = \sqrt[m]{PPC_R} \qquad (8)$$

$$MAPP_{norm} = -\ln(PPC_{norm}) \qquad (9)$$

where MAPP stands for *missed assignments per plan*.

$$Z_{benchmark} = Z_{MAPP_{norm}} + 1.5 \qquad (10)$$

where $Z_{MAPPnorm}$ is the standard normal value corresponding to the $MAPP_{norm}$ found using Equation 9.

To illustrate the use of equation 7-10, the 10-stage process in Figure 9 was considered and the following results were obtained:

4. Equation 7 gives a $PPC_R = 0.085$

5. Using Equation 8, $PPC_{norm} = \sqrt[10]{PPC_R} = \sqrt[10]{0.085} = 0.782$
6. Equation 9 gives a $MAPP_{norm} = -\ln(PPC_{norm}) = -\ln(0.782) = 0.246$
7. The standard normal table shows that $Z_{MAPP_{norm}} = 0.69$, hence, $Z_{benchmark} = Z_{MAPP_{norm}} + 1.5 = 0.69 + 1.5 = 2.19$.

Therefore, the 10-step process shown in Figure 9 is operating at a 2.19 sigma quality level that, using equation 6, is equivalent to 243,757 ppm. The average PPC reported for the single process of painting the ceiling can be also converted to a sigma quality level as follows:

1. Using PPC = 0.68 in Equation 9 which gives a $MAPP = -\ln(PPC) = -\ln(0.68) = 0.3857$
2. The standard normal table shows that $Z_{MAPP} = 0.29$, hence, $Z_{benchmark} = Z_{MAPP} + 1.5 = 0.29 + 1.5 = 1.79$. Hence, the ceiling painting process is operating at a 1.79 sigma quality level that is equivalent to a ppm rate of 368,773.

Using the Six Sigma based rolled PPC metric facilitates the comparison of performance against other plant locations as well as other companies. In addition, the rolled PPC exposes the hidden factory that was masked by the average plant-level PPC. While the average PPC value reported for painting the ceiling could be used for comparisons with other operations on the line, the principle benefit of finding the sigma quality level is to give a better sense of the magnitude of the process performance failure. In other words, reporting that the process is 32% off-target is not the same as stating that the process is operating with a defect rate of 368,773 ppm.

SIX SIGMA AND LEAN CONSTRUCTION

The synergy, or lack thereof, between six sigma and lean production is a point of contention between people on either camp. The balanced perspective on this issue states that by working in unison, Lean and Six Sigma represent a potent framework in eliminating process variation. Breyfogle et al. (2001) states: "In a system that combines the two philosophies, lean creates the standard and Six Sigma investigates and resolves any variation from the standard". Stated in a different way, while lean identifies *Muda*, Six Sigma eliminates *Mura.* Moreover, Six Sigma is considered a great tool for problems that are 'hard to find but easy to fix'. Problems of the 'easy to find but hard to fix' category are better addressed using lean production tools (Hammer and Goding 2001).

To find candidates for the implementation of the Six Sigma methodology, the Lean Project Delivery System (LPDS) was used. LPDS is a conceptual framework developed by Ballard (2000) to guide the implementation of lean construction on project-based production systems, i.e., the structures we build. LPDS was depicted as a model with 5 main phases, where each phase is comprised of three modules. The inter-dependence between the phases (e.g. that design of product and process should be performed concurrently) was represented

by sharing one module between two subsequent phases. Production control and lean work structuring were both shown to extend throughout the 5 main phases. Learning or (post-occupancy evaluation) was introduced to underscore the need to document lessons learned from one engagement to another. The reader is referred to Ballard (2000) for a detailed account of the LPDS model.

Figure 10 represents the author's adaptation of the LPDS model. This depiction of the LPDS model as compared to its original 'triad'-based illustration was primarily a response to suggestions by graduate students in a Lean Construction course taught by the author at Michigan State University. In addition, using the format of Figure 10, it was easier to superimpose the Six Sigma methodology most suited for the different modules of the LPDS model. It is worth noting that the numbers in the encircled and octagon bound modules represent the phase that the module belongs to. The modules with two numbers represent the modules that are shared between two different phases. For example, the module 'Product Design' is part of both the 'Lean Design' and the 'Lean Supply' phases.

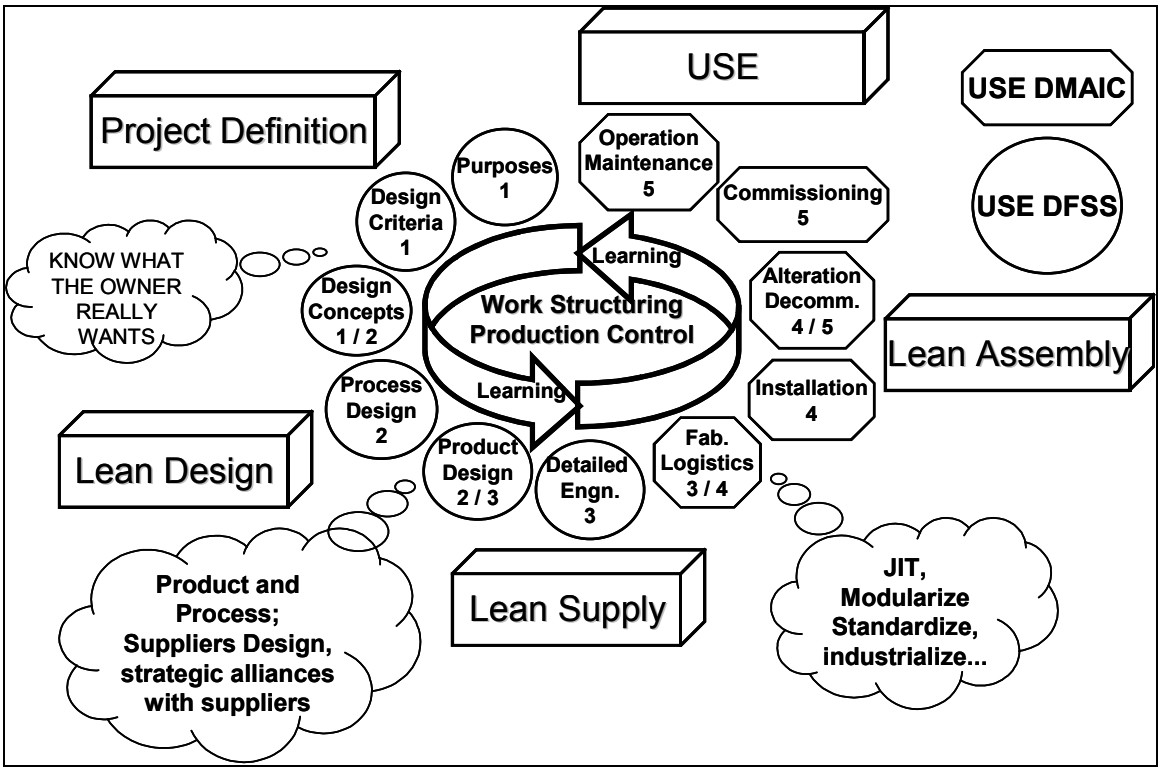

Figure 10: Lean Project Delivery System and Six Sigma

In Figure 10, modules bounded by an octagon are candidates for the DMAIC approach because this approach is suited for investigating and improving existing processes. For example, fabricators can utilize this approach to investigate and improve processes that exceed the allowable tolerances (the Doors and Frames case study in Tsao et al. 2000). Another example is on-site assembly or installation processes suffering from variability in performance due to late delivery of material and equipment, design errors, change orders, machine breakdowns, environmental effects, occupational accidents, and poorly designed

production systems. The DMAIC approach can help in identifying and eliminating the root causes behind these problems.

Similarly, encircled modules in Figure 10 are candidates for the DFSS approach which is most suited for new products or processes or when incremental changes need to be incorporated into existing products or processes. The methods used in DFSS are an extension of those used in DMAIC for existing (repetitive) processes. The goal of DFSS is to meet customer (internal and external) requirements from the start. This is especially important for project-based production systems where a customer requirement is usually met under a tight budget and schedule constraints.

Recognizing the role that Six Sigma initiatives are playing and will play in the future, the Primavera group has developed a software called TeamPlay which provides organizations with the tools to select and implement Six Sigma projects. TeamPlay has a host of tools that allow the identification of 'key improvement areas', and applying the DMAIC and the DFSS method. This is not in any way an endorsement of this software product but it is a resource that could be investigated.

CONCLUSION

This paper described the Six Sigma methodology that was developed at Motorola in 1985 and is now used by many organizations to attain reductions in process variability. The paper discussed the definition of Six Sigma and its statistical origin. The DMAIC and DFSS methods and metrics used in Six Sigma were briefly presented. A Six Sigma modification was also introduced to the Last Planner System through the use of the rolled throughput yield metric and sigma quality levels. Using the Lean Project Delivery System as a foundation, the paper suggested Six Sigma application opportunities in Lean Construction.

This paper considered the tip of the iceberg when it comes to the ever expanding and evolving area of Six Sigma. Additional research is needed to investigate the implementation of Six Sigma methods in Lean Construction. Some researchers may consider starting with the LPDS-identified areas as presented in this paper. Others may choose other avenues. In general, in any implementation effort of Six Sigma it must be recognized that it is a *tool* among many and that it is suited for a particular type of business problems while entirely useless for others. Six Sigma is a great tool for problems that are 'hard to find but easy to fix'. Lean tools are great for 'easy to find but hard to fix' problems (Hammer and Goding 2001).

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