Six Sigma-Based Approach to Improve Performance in Construction Operations

Seung Heon Han, M.ASCE¹; Myung Jin Chae, Ph.D., P.E.²; Keon Soon Im, P.E.³; and Ho Dong Ryu⁴

Abstract: Many researchers and project managers have attempted to improve project performance by applying new philosophies such as lean principle, just-in-time, pull scheduling, and last planner. However, very little research has been conducted on setting definite quantitative goals for performance improvement while considering the defect rate involved in the construction operations. This research explores practical solutions for construction performance improvement by applying the six sigma principle. This principle provides the metrics required to establish performance improvement goals and a methodology for measuring and evaluating improvement. The proposed approach is expected to achieve more reliable workflows by reducing process variability to fit in a desirable range—thereby improving the overall performance through the evaluation of the quality level in current construction operations. To verify the suggested methodology, two case studies have been presented and process simulation analyses are performed to observe the performance changes based on the six sigma principle. Critical total quality control, as the sigma level rises, is also discussed.


CE Database subject headings: Quality control; Simulation; Productivity; Construction management.

Introduction

In the pursuit of productivity improvement, it is important to ensure the quality of work processes to enhance the overall reliability and stability of construction operations. There have been a number of construction productivity improvement principles such as lean production, just-in-time (JIT), rapid machinery changeovers, pull scheduling, last planner, etc. (Thomas et al. 2003). Despite the successful applications, however, most of the results fell short of our expectations of a quantitative and practical method or metrics for assessing the defect rates of construction operations.

The defect rate in construction processes is largely caused by unreliable workflow when sources of process variability are involved (Tommelein 2000; Hopp and Spearman 2000; Howell et al. 2001; Thomas et al. 2002). The lean principle attempts to address the effect of variability, but not to eliminate or reduce variability by removing the root causes of the whole (Abdelhamid 2003). In order to estimate the defect rates involved in construction operations in a more quantitative and organized way, this research applies the six sigma principle. The six sigma principle has been an effective statistical-based methodology in measuring the defect rate in an attempt to maintain a high-standard quality level, particularly in construction materials. This study focuses on the development of the general methodology to apply the six sigma principles on construction operations rather than construction materials in terms of the barometers to measure, evaluate, and improve construction performance.

This study also pursues process effectiveness differently from an existing efficiency-oriented approach that is simply an average production divided by time or resources while disregarding the variation of the production rate and resource usage. We investigate the concept that the reduction of variability in view of process effectiveness (i.e., stable resource usage, reduced variation in cycle time, etc.) will improve project performance through such outputs as the drop of cycle time, enlargement of productivity, optimization of buffer size, etc.

Typically, project performance is measured after a project is completed so it might be difficult to improve process effectiveness without a definite goal for performance improvement. In this sense, a project manager must have a before-the-fact performance indicator to measure the project performance of an ongoing project. In this paper, this “performance indicator” is called six sigma. Project managers can use it to establish an explicit goal as well as to evaluate the level of project performance nearly perfectly.

To achieve its end, methodology requires several steps: (1) development of the six sigma principle strategy and procedure; (2) establishment of quantitative metrics based on the six sigma principle approach; (3) test of a series of case studies and process simulation analysis on six sigma principle applications to verify the principle; (4) discussion of the simulation results; and (5) provision of a generalized guideline to expand the application of six sigma principle for performance improvement. Among a variety of types of construction projects, this research is focused on a simple and repetitive construction process as an exploratory application. The proposed principle is also intended to be applicable to construction operations with more complex processes.
Background of Six Sigma Principle

Recently, many organizations have attempted to achieve customer satisfaction. One of the most important aspects of customer satisfaction is achieved through high quality product, which also means a low defect product. Traditionally, defects include products containing a flaw in the manufacturing process, customer dissatisfaction in the service department, or documentation errors in an office. Lindermann et al. (2003) stated that six sigma principle is a statistics-based methodology that relies on the scientific method to make significant reductions in customer-defined defect rates in an effort to eliminate defects from every product, process, and transaction.

The six sigma principle can be represented on a normally distributed product quality distribution curve. When the mean is located at the center of the normal distribution curve, the lower and upper limits are six times the standard deviation (sigma) from the center line. In other words, the range of the lower or upper limit defect is ±6 sigma from the mean. Ultimately, it aims to keep the defect rates under 0.002 parts per million (ppm) (1/106). If the data set falls within ±3 sigma from the mean as the upper and lower specification limits, it represents a 2,700 ppm (0.27%) defect rate that is considerably larger than 0.002 ppm. Specifically, assuming that the ideal mean is moved up to ±1.5 sigma, it adjusts the defect rate into 3.4 ppm within the quality level of ±6 sigma. Motorola used it (3.4 ppm) as the target level of the six sigma principle movement (Lindermann et al. 2003). It signifies only 3.4 defects/million parts or operations. Comparatively, this level is equivalent to one misspelled word in all the books in a small library, while the current quality level, as an example of 4 sigma, represents approximately one misspelled word per every 30 pages (Breyfogle et al. 2001). While the 3.4 ppm defect rate is considered an inappropriate goal for construction operations, the fundamental concept of taking the six sigma principle’s statistical definition associated with minimizing the defect rates along with different sigma levels and the continuous pursuit of performance improvement can be a drastic extension of the traditional approaches for achieving a high level of process quality.

Six sigma principle initiatives are implemented through a problem-solving framework such as “define-measure-analysis-improvement-control” (DMAIC) (Harry and Schroeder 2000; Ahn 2000). It emphasizes the identification and avoidance of variations. Moreover, six sigma principle underlines the explicit recognition of the root causes of defects and statistical process control to sustain continuous improvements (Abdelhamid 2003). Each step includes the following concepts: (1) Define: what problem needs to be solved and what are the critical customer requirements and key factors affecting process output? (2) Measure: what is the relevant data to the problem and what is the current performance based on a sigma calculation? (3) Analyze: why, where, and why do defects occur and what are the root causes? (4) Improve: how can the problem be solved using alternatives derived in the analysis phase? (5) Control: how can sustainable quality improvements be made through the institutionalization of the improved process?

In the construction industry, the use of the six sigma principle for performance assessments, particularly aimed at high quality and variability control, first appeared in 2000. Buggie (2000) introduced the six sigma principle as one of the approaches to augmenting productivity, which concentrated on reducing cycle time and eliminating any defects or errors engaged in the processes. Kroslid (2002) explained how six sigma principle and lean principle can be combined and used in a beneficial way to achieve outstanding performance. He also demonstrated that the synergies and advantages for such a merger have been assessed as strong. Abdelhamid (2003) also suggested a six sigma principle application and research opportunities to reduce the variability in lean construction. More recently, Cha and O’Connor (2005) described the six sigma principle as one of 44 state-of-the-practice tools for value management applicable to a construction project, based on the identification efforts conducted by the Construction Industry Institute (CII) project team 184. However, best research studies have been limited to the description of the six sigma principle and almost no project-oriented construction case study has been reported as a discipline to improve construction performance, while maintaining a high quality of products. Further, current applications of six sigma principle do not focus on construction operations, but rather on construction materials, safety, or health.

Framework for Six Sigma Principle Implementation

In contrast to the manufacturing industry, construction work is characterized by its fragmented and project-oriented work processes. For successful application of the six sigma principle, this paper presents a framework to provide guidelines for six sigma principle implementation for construction operations.

Integration of Six Sigma Principle and Lean Construction Technique

To take advantage of existing techniques, a combination of two techniques—the six sigma principle and lean construction—is suggested for both productivity and quality improvement at the same time. Combining these two principles is not a new idea. There are examples of combining lean manufacturing with the six sigma principle in a manufacturing process. Steelcase Co. achieved improvements in cost, quality, and time reduction through incorporating a lean manufacturing system and statistical tools (DFSS 2002). In addition, Kroslid (2002) concluded that integration of both lean and six sigma principle can result in an improved performance. More specifically, Abdelhamid (2003) suggested a conceptual six sigma principle application in lean construction using a lean project delivery system (LPDS) developed by Ballard (2000). He demonstrated how lean construction can show better results when combined with six sigma principle concepts.

Even though lean construction alone has provided the idea of viewing production as a flow and led to the principle of removing waste to achieve better workflow (Howell and Ballard 1994; Howell 1999), it does not clearly show the underlying mechanism of how to measure the level of defects in the current work processes. Lean construction also cannot set a quantitative goal to improve this workflow by removing the critical causes of defects in process variability.

For example, in the specific case of inventory management, typical lean production or JIT philosophy attempts to attain “near zero inventories” rather than finding an optimal level of inventory so many researchers raised the question about the size of resource buffers to achieve the best performance in a volatile and uncertain construction environment (Ballard and Howell 1995; Al-Sudairi et al. 1999; Pheng and Chuan 2001; Sakamoto et al. 2002). Specifically, based on the observations from three real projects, Horman and Thomos (2005) concluded that productivity deteriorated when inventory size and time lag became zero. This fact implies that inventory management aiming at JIT is a challenging task in
A performance measurement system should be developed prior to the six sigma principle deployment. The key activities of the performance measurement system are: (1) setting up a company-wide quality control strategy and policies; and (2) arranging performance indicators based on that strategy. In order to set up performance indicators, it is necessary to identify activities and key factors that are critical to the success of the project at each construction phase. Toward this end, critical total quality (CTQ) is the most closely related element to a process performance indicator. For example, if “productivity” is a performance indicator for a certain project, the reliability of the resource flow can be assumed to be a main CTQ because it has the closest association with productivity. In implementing six sigma principle, CTQ is a main input variable, particularly in the phases of DMAIC. Through defining and measuring the status of various CTQs such as variations in cycle time, idle, or waiting time of labor/equipment, excess or shortage of inventory (buffer size), and percent of earned value achieved, we can evaluate the level of sigma in the work process and identify the root causes of defects that deteriorate the work performance.

To compare the quality level of the work process associated with CTO, a six sigma principle metric should be clarified. Of the several available six sigma principle metrics, this paper adopts the process capability index \( (C_p) \) because it provides upper and lower boundaries based on the company’s quality control strategy and policies. According to Ahn (2000), sigma level is obtained by \( C_p \) that is described by the following expression on the assumption that quantitative data for the CTQ evaluation can be collected continuously without any serious bias. If only the upper bound is given for the purpose of controlling the defect rate of CTQ, we can calculate the \( C_p \) by setting up a goal for the allowable performance level (so-called, upper specification level) and then by using the mean and standard deviation from the collected data. Based on the estimated \( C_p \), we can evaluate the sigma level of the current CTQ of a specified work process

\[
C_p \text{ (process capability index)} = \frac{USL - \text{MEAN}}{3 \times \text{STDEV}} \quad (1)
\]

If only USL given

\[
\sigma \text{ (sigma level)} = 3 \times C_p \quad (2)
\]

where \( USL = \) upper specification limit; \( \text{MEAN} = \) mean of the data; and \( \text{STDEV} = \) standard deviation of the data.

As an example, suppose that the cycle time for earthmoving is highly variable due to various external factors such as traffic and access road conditions. The mean and standard deviation value

### Table 1. Comparative Views in Inventory Management

<table>
<thead>
<tr>
<th>Items</th>
<th>Lean</th>
<th>Six sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource management objectives</td>
<td>Near zero resource buffer</td>
<td>Optimum resource buffer for maximum productivity</td>
</tr>
<tr>
<td>Methods</td>
<td>Minimization of the cost of redundant resources and increasing the reliability of the process through JIT technique</td>
<td>Reduction of the total project cost by maintaining the optimum resource buffer and eliminating the loss of productivity caused by the resource shortage</td>
</tr>
<tr>
<td>Usefulness</td>
<td>Inadequate for the construction process which has many uncertainties and discontinuous activities</td>
<td>Adequate for the construction process and useful for a resource management plan</td>
</tr>
</tbody>
</table>

To reduce the process variability through the evaluation of quality level (six sigma indicator) in current construction operations, it is necessary to identify activities and key factors that are critical to the success of the project at each construction phase. Toward this end, critical total quality (CTQ) is the most closely related element to a process performance indicator. For example, if “productivity” is a performance indicator for a certain project, the reliability of the resource flow can be assumed to be a main CTQ because it has the closest association with productivity. In implementing six sigma principle, CTQ is a main input variable, particularly in the phases of DMAIC. Through defining and measuring the status of various CTQs such as variations in cycle time, idle, or waiting time of labor/equipment, excess or shortage of inventory (buffer size), and percent of earned value achieved, we can evaluate the level of sigma in the work process and identify the root causes of defects that deteriorate the work performance.

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### Fig. 1. Concept of six sigma integrated approach
are estimated as 30 and 20 min, respectively. In this case, the CTQ is defined as the variation in cycle time. The allowable performance level for the cycle time variation is arranged to a maximum of 25 min from the mean time to maintain quality workflow. Based on these assumptions, the current $C_p$ is measured as 0.42 $[(55−30)/(3×20)]$. Accordingly, due to the fact that the current sigma level of CTQ is very low ($\sigma=3×0.42=1.26$ sigma), the next target should focus on how to improve the quality level of CTQ to achieve a better work performance.

**Basic Framework for Six Sigma Principle-Based Management**

Based on existing techniques in manufacturing process improvement, the six sigma principle is used in construction operations according to the strategies described in the previous sections. As shown in Fig. 2, the six sigma principle concept can be applied to the construction process control within the basic framework of CTQ inputs, DMAIC procedures, and output measures.

The process activities that cause production drops or defect increases are identified by continuously monitoring the outputs of the DMAIC steps while the input values change. Since construction projects have more uncertainties than manufacturing processes, a strict six sigma principle level for factor variability control should be appropriately modified. Instead, it is more importantly considered an application of new management thinking that takes the six sigma principle’s statistical definition associated with minimizing the defect rates through a control of CTQ. In this view, Fig. 2 shows the modified DMAIC in a six sigma principle process to fit in the construction operations. As stated earlier, this research integrates the advantage of lean and six sigma principle thinking in an attempt to improve the performance output. Fig. 2 also defines the input indices and subsequently measures the sigma level of CTQ. Then, appropriate means for the improving the quality level of CTQ through minimizing wastes and reducing variability are provided. Finally, the framework presents the quantitative improvement targets based on the six sigma principle metrics by controlling CTQ as the sigma level rises.

**Case Study 1: Iron-Reinforced Bar Assembling Process**

To demonstrate the six sigma-based management strategy integrated with lean construction, we have conducted two case studies. The assembling process is common in both manufacturing and construction work. In this research, the assembling process in a construction project that builds 765 kV power transmission lines was chosen as the first sample application to the lowest-level activities. These construction processes include site mobilization, foundation, steel tower assembly and erection, and attaching a power line to a tower. We focused on the assembly of the iron tower for process analysis and sigma-level controls.

The assembly work has the following characteristics: (1) the activity needs 13 crew members including tower assembling engineers, tower erecting engineers, helpers, and crane operators; (2) the current storage weight of iron bars is 8.4 t; (3) the maximum size of the field space to store iron bars is less than 20 t of capacity due to the limited site accessibility around a mountainous area; (4) the cost to store 1 t of iron bar is about $25/day; (5) delivery and other process cost for iron bars is estimated at $6/t; (6) the cost for extending storage space exceeding current capacity of 8.4 t is $365/t; and (7) field data were collected for 10 working days.

In this paper, the iron bar assembling process was chosen for its receptiveness in process activities. A simulation model is developed for the proof-of-concept. For process flow development and process analysis, EXTEND was employed in the development of the simulation models. This tool is the versatile visual computer simulation software that allows one to test proposed changes to the current processes and predict "what-if" change scenarios (Imagine That 2002). The primary model components that connect the main work process associated with the iron bar assembly consist of delivery of iron bars to the storage area (inventory management), classification of steel members, preassembling on the ground, transportation of assembled parts to the specified location, and assembling each part. Fig. 3 shows the part of the EXTEND model that indicates the interrelated objects to depict the function of inventory management for iron bars. Two models are made: one for before the six sigma principle application and the other for after the application. By comparing two models and sensitivity analysis, the benefit of the six sigma principle in conjunction with lean construction is quantified. First, observed data were compared with the outputs of modeling to verify the simulation model. The result showed that the real observed productivity (0.046–0.054 t/min) and simulation result (average 0.049 t/min) match each other within an allowable tolerance.

**Definition of CTQ (Critical Total Quality)**

The first step to define the CTQ is to set principle indices. The productivity improvement level was set as the principal indices of process performance quality. Then the factor that is most closely linked with productivity is identified. Through the complete analysis and observation of process variations with many independent factors, changes (or variations) of the work cycle time are assumed to be the CTQ because it was found that the productivity is closely related to the reliability of the cycle time for assembly work. Subsequently, the target CTQ needs to be determined in order to evaluate the process status and establish the quality improvement goal. Fig. 4 shows the cycle time variations for assembly works from 80 observations during 10 working days. The target CTQ is assumed to be within a maximum 40-min variation. This target CTQ is the tool to achieve the productivity goal.

Following the definition of CTQ and its goal, the current defect rate is calculated by Eqs. (1) and (2). It was found that the target CTQ, 40-min variation, can be represented as the 1.41-
The current process has a sigma level of 1.41, which is far below the 6-sigma level and indicates a need for improvement. We have developed a fishbone diagram (Fig. 5) to identify the cause-and-effect chains that affect the cycle time. Surveys and interviews with engineers and field supervisors revealed that the resource buffer size has the most critical influence on the cycle time variation of assembly work. This means that optimizing the buffer size will increase the sigma level through CTQ improvement. Accordingly, the sigma level improvement will increase the process performance as well.

### Improvement of CTQ

The CTQ improvement was achieved in two phases: (1) modification of the current assembling process by lean construction; and (2) resource buffer size optimization for the reduction of cycle time variation through the six sigma principle. Before the process modification and resource optimization, the initial resource level for iron bars was determined as 8.4 t and its sigma level was 1.41. After only implementing the process modification without modifying the buffer size (Columns 1 and 2 of Table 2), productivity improved by 0.003 t/min, while the sigma level reached only to 1.72, which is not a sufficient improvement both in productivity and sigma level. In this phase, the process modification included the change of preassembling location on the ground for facilitating the assembling operation of a hydraulic crane by removing the interference between on-ground preassembling and hydraulic crane work. In addition, we revised the work sequence in order to increase the reliability of cycle time by classifying categories and sizes of iron bars prior to transporting them to the assembling locations. These modifications are all relevant to the lean construction to eliminate waste.

After the process modification, the targeted sigma level was obtained through buffer size optimization to stabilize the cycle time. By increasing the buffer size from 8.4 to 11.5, 14.5, and 19.2 t to its nearly maximum capacity, the productivity improved to 0.055, 0.060, and 0.061 t/min, respectively. The sigma level
also improved to as high as 6 when the buffer size is 19.2. However, the productivity rose by only 0.001 by adding 4.7 t resource storage area and US$2,900 additional cost. Therefore, it is suggested that around 14.5 t is the most efficient range of a buffer size while maintaining reasonable productivity and sigma level.

**Summary of First Case Study**

The simulation result showed the changes of sigma level that vary along with the process reliability, which was measured by variations of the performance indices. The process was evaluated based on the relationship of productivity and cost. It was found that about 20 t of iron bars should be in stock to keep the process from stopping and keep the defect rate (variation of cycle time) from fluctuating.

However, due to the limited storage space and additional cost for maintaining increased storage volume, a resource buffer of around 14.5 t was considered as the most efficient size for keeping the process reliability as stable as possible while also keeping the additional cost for the extra inventory buffer as low as possible. Fig. 6 indicates that the cycle times are apt to be almost the same while the sigma level rises. However, it should be noted that process reliability in terms of variation in cycle time is enhanced as the sigma levels of the CTQ are improved. This implies that the defect rate is minimized to attain a reliable work flow and performance improvement.

Fig. 7 shows another relationship of the sigma level in CTQ over productivity. Productivity improves as the sigma level in CTQ increases. The cycle time variation below 40 min is a target performance measurement criterion and at around the 4-sigma level the improvement is maximized through the control of variability in CTQ. In order to verify the simulation result, we investigated the same problem from a different point of view. Fig. 8 shows the relationship of material storage size versus productivity. The shape of the curve is very similar to the curve in Fig. 7. This means that the productivity is dependent both on CTQ and storage size.

On the other hand, Fig. 9 shows the linear relationship between storage size and additional cost. The cost information of the process is the basis for finding the optimum resource buffer size and the most efficient process control to maintain a higher sigma level. As a result, the six sigma principle has shown many benefits compared with traditional productivity control.

**Table 2. Performance Index by Buffer Sizes**

<table>
<thead>
<tr>
<th>Item</th>
<th>Average buffer size (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8.4 (As-is)</td>
</tr>
<tr>
<td>Productivity (t/min)</td>
<td>0.049</td>
</tr>
<tr>
<td>Total cost (US$10/days)</td>
<td>9,400</td>
</tr>
<tr>
<td>Additional storage cost (US$10/days)</td>
<td>3,500</td>
</tr>
<tr>
<td>Throughput (t/10 days)</td>
<td>236</td>
</tr>
<tr>
<td>Cycle time (min)</td>
<td>162</td>
</tr>
<tr>
<td>Sigma level of cycle time (CTQ)</td>
<td>1.41</td>
</tr>
</tbody>
</table>

^Additional cost of United States $2,000 for increasing buffer size from 8.4 to 11.5 t (3.1 t × $25/day × 10 days = $775; (2) the cost for extending a storage area = 3.1 t × $365 = $1,130; and (3) delivering and other processing cost for producing more throughput (268−252=16 t)=16 t × $6=$96 (all in united states dollars).
improvement techniques. Table 3 summarizes the distinct comparison between the six sigma principle integrated with lean and the traditional approaches.

Case Study 2: Deck Plate Installation Process

The second case study for six sigma principle application was performed on a typical deck plate installation process in building construction, which is more complicated and less repetitive than operations in the first case study. It usually takes 2 days to install deck plates for one floor of a building. Typical deck plate assembly work has the following characteristics: (1) the activity needs six crew members (two for delivery, one for cutting and assembly, and three for welding); (2) the floor size is 1,665 m² (17,922 ft²) and each floor consists of 462 deck plates (the size of each deck plate is 0.6 m × 6 m); (3) the cycle time of installing one floor’s deck plates is around 14 h (840 min); and (4) the labor costs for delivery, cut and assembly, and welding activity are $11, $9, and $23/h, respectively.

Definition of Process CTQ for Deck Plate Installation

The process of defining CTQ includes various activities such as collecting opinions of field engineers, internal customer needs, process mapping techniques, characteristic analysis diagrams, etc. The deck plate installation process requires only two types of resources: the number of workers involved in process activities and the type of deck plate material. Thus, the productivity improvement strategy can be formed based on the optimum use of the resources, which provides the basis to define the CTQ for deck plate installation. As the result of an in-depth survey, interviews, and process analysis, variations of the crews’ working time on plate assembling and welding are set as the fundamental sigma level governing CTQ.

Measuring CTQ and Six Sigma Process Improvement

Based on the 25-min observation of installing 12 deck plates, we developed an EXTEND simulation model representing the productivity changes over time. First, cutting and assembling activities were tested for measuring the CTQ level. The crew’s average working time for cutting and assembling one deck plate was 1.8 min and its standard deviation was 0.19 min. The target CTQ is supposed to be within a maximum of 2 min of working time. Accordingly, the $C_P$ (process capability index) is calculated by the following equation

$$C_P = \frac{USL - MEAN}{3 \times STDEV} = \frac{2 - 1.8}{3 \times 0.19} = 0.35$$

(5)

$$\sigma = 3 \times C_P = 1.05$$

(6)

By the same method, the average welding time for one deck plate was 1.8 min and its standard deviation was 0.22 min. The sigma level for welding activity was 0.9, which means that working time for welding will be over 2 min with the probability of 6,210 times out of 1 million activities.

A fishbone diagram (Fig. 10) shows the items that cause the variations of the crew’s working time. Based on the surveys and interviews with engineers and field supervisors, and from the analysis of the crew balance chart, we found that the hauling direction of deck plates and balanced rations of workers are the major areas that mostly affect the variation of labor working time.
Subsequently, improving the process includes three major modifications as shown in Table 4. As a result of the process modifications, an average of 50% working time can be saved based on the simulation models developed using the same method as the first case study.

Sigma level and performance index were calculated and are shown in Table 5. In the second case study, we used the adjusted sigma levels based on the theory and practice of the six sigma principle. According to Lindermann et al. (2003), adjusted sigma levels are calculated by adding a certain movement (1.5 sigma) from ideal means to reduce biases in the specific cases where observation was for a relatively short time span. The adjusted sigma levels were improved from 2.5 and 2.4 to 4 and 4.5, respectively, while increasing the productivity from 0.55 to 0.63 t/min and reducing the cost from $675 to $485 per product cycle.

**Summary of Second Case Study**

The second case study revealed that the productivity, sigma level, and performance index were improved by the CTQ modifications, which were the working time variations of cutting, assembling, and welding activities. The modification procedure started from setting the standard performance index level. Any process that exceeded a 2-min limit was considered a defect in controlling sigma level and it is controlled by the CTQ indices such as the

<table>
<thead>
<tr>
<th>Process modifications</th>
<th>Purposes</th>
<th>Simulation results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relocation of deck plate loading area</td>
<td>For better material hauling and distributing</td>
<td>Hauling distance shortened.</td>
</tr>
<tr>
<td>Adjustment of deck plates stacking direction to correspond to the construction route</td>
<td>Hauling/assembling/welding ration changes from 2:1:3 to 2:1:2</td>
<td>Assembling time saved by 50%</td>
</tr>
<tr>
<td>Reallocation of related workers</td>
<td></td>
<td>Welding time saved by 50%</td>
</tr>
<tr>
<td>Adjustment of deck plate size</td>
<td>Cutting deck plate in small and light pieces enough to be carried by one person</td>
<td>No improvement</td>
</tr>
</tbody>
</table>

Fig. 10. Factors influencing changes of working time

<table>
<thead>
<tr>
<th>Table 3. Comparison of Six Sigma to Traditional Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Items</td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>Goal</td>
</tr>
<tr>
<td>Measurement of current performance (t/min)</td>
</tr>
<tr>
<td>Definition of CTQ for performance improvement</td>
</tr>
<tr>
<td>Defect rate of CTQ (sigma level)</td>
</tr>
<tr>
<td>Analysis of main causes for low performance</td>
</tr>
<tr>
<td>First phase of process improvement</td>
</tr>
<tr>
<td>Improved performance after first phase improvement (t/min)</td>
</tr>
<tr>
<td>Improved defect rate of CTQ after first phase improvement</td>
</tr>
<tr>
<td>Targeted area for CTQ improvement</td>
</tr>
<tr>
<td>Achieved sigma level for CTQ improvement</td>
</tr>
<tr>
<td>Finally achieved performance improvement (t/min)</td>
</tr>
</tbody>
</table>

<sup>a</sup>N/A=not available.
Table 5. Improvement Results Overview

<table>
<thead>
<tr>
<th>Items</th>
<th>Sigma level</th>
<th>Workers idle time (%)</th>
<th>Productivity (t/min)</th>
<th>Total cycle time for each floor (min)</th>
<th>Labor cost (United States $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-is&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Hauling</td>
<td>N/A&lt;sup&gt;b&lt;/sup&gt;</td>
<td>48</td>
<td></td>
<td>675</td>
</tr>
<tr>
<td></td>
<td>Cutting &amp; assembling</td>
<td>1.05 (2.5)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25</td>
<td>0.55</td>
<td>836</td>
</tr>
<tr>
<td></td>
<td>Welding</td>
<td>0.9 (2.4)</td>
<td>51.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>To-be</td>
<td>Hauling</td>
<td>N/A&lt;sup&gt;b&lt;/sup&gt;</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cutting &amp; assembling</td>
<td>2.5 (4.0)</td>
<td>5</td>
<td>0.63</td>
<td>727</td>
</tr>
<tr>
<td></td>
<td>Welding</td>
<td>3.0 (4.5)</td>
<td>9</td>
<td></td>
<td>485</td>
</tr>
</tbody>
</table>

<sup>a</sup>The data of “as-is” are obtained from the real observations on site, collected for around 25 min. Sigma levels in parentheses are the adjusted values based on the theory and practice of six sigma principle in the case of short-term observation.

<sup>b</sup>N/A = not available.

number of workers and working times on such activities as cutting, assembling, and welding. Comparing the results from before and after the process modification, the number of process time variations that exceeds 2 min were reduced through the process stabilization and subsequently a higher sigma level is obtained. Fig. 11 shows the relationship of the average sigma level (mean value among those of cutting, assembling, and welding) in CTQ over productivity. The productivity improves as the sigma level in CTQ increases. At around a 3–4 sigma level the improvement reaches its maximum through the control of variability in CTQ.

**Practical Implications for Applications**

On the basis of these case studies, we drew valuable findings regarding the six sigma principle application to construction operations. The six sigma principle can evaluate the quality of the current operation and quantify the goals of improvements for the targeted work flow so as to control the critical sources of variability. The previous case studies explored the feasible solutions for enhancing construction performance by adopting the six sigma principle as a statistical-based methodology to make significant reductions in customer-defined defect rates. With the aid of a simulation tool, it is verified that the overall performance improved as the degree of sigma level was advanced through the control of CTQ. Expectedly, we can arrive at the point which implies that the results of improvement through the six sigma principle will be large if it is applied to more complicated, volatile, and multistep processes with a linkage to the lean principle.

However, the construction process is an outdoor activity that is affected by external conditions and is less repetitive than the manufacturing process. Often, quality control in construction projects focuses on materials rather than on work flows. Therefore, in adopting the six sigma principle to construction projects, it is required to choose relatively simple and repetitive construction activities in which productivity is immediately reflected by the process variation factors such as resource level, workers proficiency, etc. For a smooth application of the six sigma principle onto construction work, this research suggests a two phased six sigma application. The first phase is to apply the six sigma principle to a simple and repetitive construction process similar to a manufacturing process. Industrial/plant construction and equipment installation projects are usually similar to manufacturing processes as is demonstrated in the first case study. The second phase is to apply the principle to a real construction process which is more complicated and less repetitive. The second case is a typical example that is considered as high-level six sigma principle applications.

Following the procedural applications, the systematic process of the six sigma principle requires several phases such as defining CTQ, process modification, simulation modeling, and model verification. Fig. 12 explains the procedural steps and key reflections in applying the six sigma principle to construction processes and operations. Unlike the manufacturing industry, the construction industry has lacked a systematic methodology to assess the defect rate and evaluate performance improvement as the defects are removed in the production processes. This leads to an incomplete objective for the performance improvement at the construction job site level. The six sigma principle can have greater effects on maintaining stable work quality by controlling various factors that are required to ensure project requirements such as safety, quality, cost, or duration under the conditions of diverse and dissimilar project participants.

In this view, Table 6 summarizes the skeleton of the criterion when the users decide the motives of performance improvement and set out the measuring indicators, which is applicable to construction operations. The previous cases are typical examples, particularly in the event of an additional supply of resource buffers to reduce the variation of cycle time and the rearrangement of workers’ rations to minimize inefficient idle time. This method can be expanded to other construction operations by the aforementioned procedures. Above all, the definition of CTQ and evaluation of the results to select the critical factors that govern the level of CTQ should be made in accordance with the following steps: (1) CTQ is the one that is most closely linked with

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Fig. 11. Sigma level in CTQ versus productivity
productivity so the process of defining CTQ includes various qualitative and experience-based activities such as opinions of field engineers, process mapping techniques, characteristic analysis diagrams, and prior simulation tests, etc; (2) the factors that critically affect the quality level of CTQ can be investigated through a fishbone diagram. Based on the cause-and-effects chains that affect the CTQ and additional subjective information from interviews and surveys with engineers and field supervisors, the factors can be found; and (3) effects of those factors can be evaluated and verified based on the simulation results and “what-if” scenario analysis. The factor identification is finally obtained by the complete analysis with many independent variables and sensitivity to the CTQ.

Conclusions and Recommendations

As stated, the construction industry has endeavored to improve project performance by applying a number of new philosophies. However, reliable workflows were not achieved sufficiently up to this point. This is largely due to the lack of methodological metrics to quantitatively set out the definite goal of improvements and to reduce the process variability through the evaluation of quality level in the current construction operations. To achieve this purpose, this paper explored the feasible strategies for the improvement of the construction processes and operations by combining the six sigma principle with the idea of lean construction.

We have performed in-depth comparative analyses on the existing methods for performance improvement and identified the advantages of the six sigma principle over the traditional techniques. Consequently, process simulation models have shown that construction performance improved as the sigma level advanced by enhancing the condition of CTQ. In addition, the six sigma principle provided more benefits by obtaining the optimized solution sets from performance indices, especially when the target processes are complicated and extended. In short, the six sigma principle is not only a managerial tool for productivity and quality improvement but also a systemized tool for quality and process control. With the aid of the six sigma principle method, quality variances or defects involved in construction processes can be controlled in more practical ways to fit in a desirable range.

Encouraged by the benefits of six sigma principle application, future research will concentrate on developing detailed guidelines on the CTQ control of target factors based on the diverse characteristics of many different companies because the customization of the six sigma principle strategy facilitates construction firms to achieve their own process evaluation paradigm. For these objectives, advanced financial feasibility analysis should be developed before the implementation of the six sigma principle to a real construction operation. Furthermore, as a basis for getting more effective results from the six sigma principle, various aspects of construction operations and processes must be investigated in many different projects. Finally, base information must be provided from which the improvement targets can be selectively chosen based on the level of practical benefits. Eventually, an integrated management system should be established to control the variations of all the process activities as a whole, rather than the separated process, through the overall performance quality assessment.

Acknowledgments

The writers would like to thank the Korea Ministry of Construction and Transportation for the funding (Grant No. 05-CIT-D05-01) that made this research possible and the anonymous survey respondents for their valuable contribution to our study.
Table 6. Typical Criterion for Applying Six Sigma to Construction Operations

<table>
<thead>
<tr>
<th>Performance improvement initiatives (independent variables)</th>
<th>Measuring indices</th>
<th>Objectives/Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>How reliable is human and material resource variance?</td>
<td>Sigma level</td>
<td>Productivity and effectiveness of the process</td>
</tr>
<tr>
<td>Is resource buffer size enough?</td>
<td>Changes of performance index in accordance with sigma levels</td>
<td></td>
</tr>
<tr>
<td>Is the size of human resource queue appropriate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How does the project cost change?</td>
<td>Cost changes in accordance with sigma level changes</td>
<td></td>
</tr>
</tbody>
</table>

References


