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Construction Management and Economics (April 2006) **24**, 339–348

Six-sigma as a strategy for process improvement on construction projects: a case study

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Received 21 July 2004; accepted 10 June 2005

Significant expenditures of time, money and resources, both human and material, are wasted each year as a result of inefficient or non-existent quality management procedures. In an attempt to improve their market competitiveness, by limiting the extent of non-value-adding activities, some organizations are beginning to monitor the performance of internal and external engineering and construction processes. To achieve these bold aims, these organizations are looking to other industries such as manufacturing to examine the effectiveness of measuring and monitoring tools such as six-sigma. Only in recent years has the six-sigma method been utilized by some of the major players in the construction sector. To familiarize both researchers and practitioners on how to implement the six-sigma method and its potential benefits, the paper describes the outcomes of a six-sigma process improvement project (PIP) conducted for the construction of concrete longitudinal beams on the St Pancras raised railway station in London, UK. The outcome of the six-sigma PIP was the improved productivity of beam construction, enhanced interaction between project teams and reduced project delays. Moreover, interviews with key project participants were conducted to determine the success factors, barriers, suitability and advantages of the six-sigma approach compared with other TQM techniqes. In summary, the six-sigma approach provided the PIP team with a structured process improvement strategy to reduce waste and other non-value adding activities from the construction process.

Keywords: Six-sigma, process improvement, total quality management

Introduction

The construction industry is a business sector that plays a substantial role in many economies. However, the attainment of acceptable levels of quality in the construction industry has long been a problem. Significant quantities of resources, both human and material, are wasted each year as a result of inefficient or non-existent quality management procedures (Arditi and Gunaydin, 1997). There exists great potential for quality improvements in the construction industry; its importance cannot be understated, regardless of a nation's primary business, and organizations will always require interaction with the construction industry to source physical assets to house operations (Cox and Ireland, 2002). In recent years, globalization and deregulation of markets has led to increased foreign participation in domestic construction, placing further pressure on leading firms for major reforms. The cause of many problems lies in the organization of the industry and associated processes. Firms need to build on their competitive strengths through a deliberate and managed process to improve the capacity and effectiveness of the industry and to support sustained national economic and social objectives.

This study suggests that this development, in part, can be achieved by learning how to increase efficiency and productivity through process improvement. As a small step towards achieving this goal, we firstly present a review of a wide variety of existing process improvement techniques and then critically evaluate the use of six-sigma in other industries with a view to demonstrating how the phenomenon can be used as a strategy for construction firms. Six-sigma is a structured

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Construction Management and Economics
ISSN 0144-6193 print/ISSN 1466-433X online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01446190500521082

methodology that has found wide acceptance in the manufacturing sector by such firms as General Electric and Motorola. In essence, the principles of six-sigma have been derived from total quality management (TQM) theory. However, its structured and systematic framework, combined with the employment of statistical techniques, makes it an excellent tool for process diagnostics, which is an integral task of modern construction managers. The methodology has led to significant improvements in the manufacturing sector and it is believed that it should also assist construction firms to deliver projects on time, at the right cost and of superior quality (Wantanakorn *et al.*, 1999). Secondly, this article demonstrates the application of six-sigma in an industry-based case study to illustrate its usefulness in a complex site environment. Lastly, interviews with key project participants were conducted to extract six-sigma learning experiences and to determine the effectiveness of the method for achieving process improvement in the construction sector.

Process improvement in construction

The aim of process improvement in construction is to produce something of equal or better worth, at a lower cost. Brown and Adams (2000) reported that in the procurement of projects, leading clients are increasingly demanding a high quality product at a low cost, which is also reliable and delivered on the date required. The major feature of construction processes is that they are notorious for their complexity and changes during the construction process (Van der Aalst *et al.*, 2002). The industry has few structured frameworks on which to base process improvement initiatives and achieve total quality. The absence of clear guidelines has meant that improvements are often isolated and benefits cannot be coordinated or repeated. Sarshar *et al.* (2000) attribute this to the industry's inability to assess construction processes, prioritize process improvements and direct resources appropriately. Subsequently, the concept of process improvement varies for construction firms, unlike in manufacturing, where variation can be eliminated because the standards by which it is measured are themselves invariant – e.g. production lines. In construction, clients inevitably have variability in their requirements; consequently variation cannot be totally eliminated, but it can be managed (Shammas-Toma *et al.*, 1998). In recent years, a number of structured performance improvement methods have been adopted on construction projects. However, their degree of success has been somewhat less than that experienced in manufacturing industry. The following paragraphs provide a critical review of these models and examine their fitness-for-purpose for the construction sector.

A number of techniques and tools can be found under the TQM/Continuous Process Improvement (CPI) umbrella, including the process cost model, standardized process improvement for construction organizations, the balanced scorecard, *Kaizen* and statistical process control. Traditionally, businesses have tended to measure performance using only financial measures. As a result, organizations adopted techniques similar to the process cost model (PCM). This concept was developed in manufacturing industry and has been moulded into a workable strategy suitable to construction applications (Aoieong *et al.*, 2001). The PCM is a process-orientated approach that values client satisfaction and continuous process improvement. PCM uses financial theory to analyse and direct efforts for improvement; this has its advantages and disadvantages. Use of a single measure clearly illustrates the tangible benefits in a compatible format that is easy to interpret (Arditi and Gunaydin, 1997; Moen, 1998). However, the weakness of financial metrics stems from their failure to measure and monitor multiple dimensions of performance. Additionally, financial measures used in isolation create problems in that they are characterized as lagging measures, i.e. they are the result of past events. Consequently, PCM is a reactive approach, because waste and associated non-value adding activities have already transpired. For construction firms to succeed in the future they need to implement a more proactive approach to improving processes (Moen, 1998).

To look beyond financial measures, Sarshar *et al.* (2000) developed the standardized process improvement for construction enterprises (SPICE) framework. This framework was founded on the principles of the capability maturity model (CMM) and argues that the outcome of a process is a function of the maturity of the organization and its associated processes (Hutchinson and Finnemore, 1999; Sarshar *et al.*, 2000). The philosophy of this framework is that a process becomes more predictable and reliable as the organization and its processes simultaneously mature. SPICE provides a structured framework with a definite starting point that assists the process improvement teams to prioritize areas for improvement. The SPICE framework provides a good process diagnostics tool with a strong process focus. Sarshar *et al.* (2000) demonstrated the application of the SPICE framework in two case studies aimed at improving construction processes. An interesting outcome of these studies was that an organization does not have the capability to capture best practices until 'level 3 (defined)' of the framework. In light of this, the SPICE framework has many similarities with six-sigma, particularly in its ability to address priority processes.

Although the two previous techniques provide an indication as to the success or failure of a project, they do not provide a balanced view of a project's performance. Kaplan and Norton (1992) developed the balanced scorecard (BSC) to capture both the tangible and intangible perspectives of performance. The BSC provides information on four perspectives, including customer perspective, internal business perspective, learning and growth perspective and financial perspective. However, this approach is far from simple and requires a comprehensive understanding of the fundamental characteristics of performance measurement as well as a significant commitment from top management and employees (Chan *et al.*, 2002). Moreover, construction firms may find implementation difficult due to the diversity of their projects (Sommerville and Robertson, 2000). Hubbard (2000) also felt that the BSC was too generic in design and did not consider a specific industry's needs or the strategic desires of individual organizations.

Another process improvement technique that was developed by the Japanese and was a contributor to their economy's rapid growth in the second half of the twentieth century was *Kaizen*. This technique was formed from a quality culture that emphasizes continuous process improvement through standardization – i.e. establish a standard, maintain it and then improve it (McGeorge and Palmer, 2002). However, the technique tends to be difficult to adopt for firms that have already implemented the TQM culture. In view of this, the authors do not believe that *Kaizen* can offer the construction industry substantial benefits since it merely promotes similar ideals already created through TQM. What the industry needs is a structured data-driven approach to direct its efforts.

A more data-driven technique is statistical process control (SPC), which has an emphasis on numbers, fact-based analysis and tangible decision-making. Consequently, due to its technical nature, it has never been fully embraced (Dale *et al.*, 2000). With managements becoming more interested in performance and profitability, they are beginning to divert attention back to the analysis of process variation and elimination through root cause analysis and problem solving. Use of SPC identifies overall process capabilities and areas that need improvement. Although SPC equips the users with an extensive array of measurement techniques it appears to lack a strong organizational supportive framework. The tools employed by SPC have, to a large extent, fuelled the development of the latest addition to the TQM/CPI umbrella: six-sigma.

Six-sigma in construction

Six-sigma is a new way of managing business processes. Since its publicized adoption at Motorola and General Electric in the early 1980s, six-sigma has evolved into a leading method for managing process efficiency, not just in manufacturing industry but increasingly in other areas close to project managements' 'heart' such as construction management. It is a formal and disciplined method for defining, measuring, analysing, improving and controlling (DMAIC) processes (see Figure 1). These five steps form the backbone of the six-sigma methodology and work on the principle of a stage/gate process that requires certain deliverables to be met at the gate before the firm can proceed to the next stage or phase (Marves, 2000). While traditional quality programmes have focused on detecting and correcting mistakes, six-sigma encompasses something broader: it provides specific methods to re-create the process itself so that the defects are never produced in the first place. The concept seeks to continually reduce variation in processes with the aim of eliminating defects from every transaction (Hahn *et al.*, 1999; Tennant, 2001). Antony and Banuelas (2002) define six-sigma from both a *business* and *statistical* perspective. From a *business* perspective, they describe six-sigma as a strategy used to improve profitability, reduce quality costs and improve overall operations to exceed the customer's expectations. In a *statistical* vocabulary, six-sigma refers to 3.4 defects per million opportunities (DPMO), where sigma represents the variation about the process average. Six-sigma executioners progress to become qualified experts, trained in six-sigma philosophy and methodology, and are referred to as 'black belts'. As process improvement project (PIP) leaders these experts carry in-depth knowledge of techniques such as process mapping, measurement analysis, analysis of variance, supply chain management and so on.

Six-sigma has different interpretations and definitions for different applications; in this case we refer to its proposed application to the construction/engineering sector. For this sector, six-sigma improvement methods are not about being totally defect-free or having all processes and products at six-sigma levels of performance – another misconception of the six-sigma philosophy (Linderman *et al.*, 2003). The appropriate level will depend on the strategic importance of the process and the cost of its improvement relative to the benefit (Brue, 2002). In the application of six-sigma there are typically a number of common features, which include: it is a top-down rather than bottom-up approach; it is a highly disciplined approach that typically includes five stages (i.e. DMAIC); and it is a

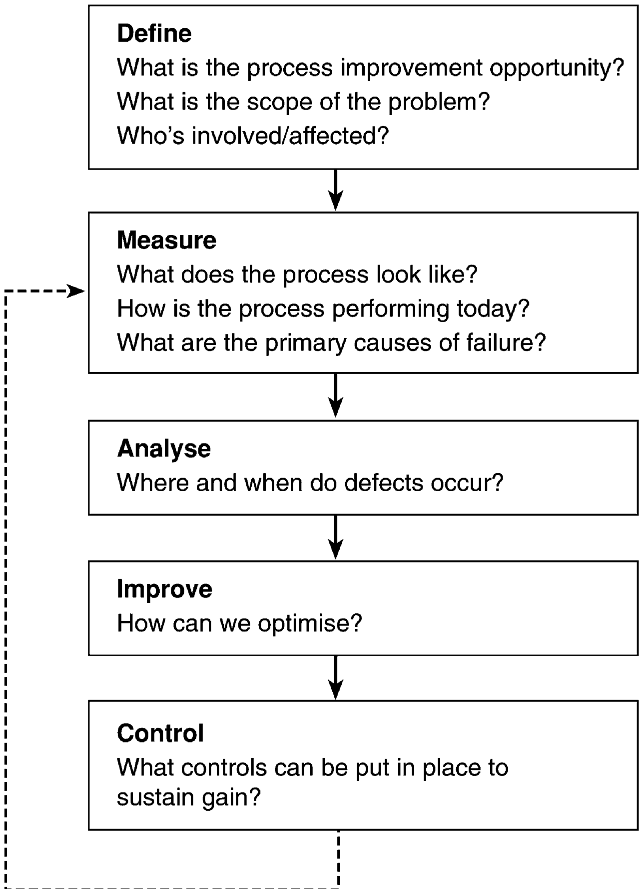

Figure 1 Six-sigma's structured methodology – DMAIC (adopted from Brue, 2002)

data-oriented approach using various statistical and non-statistical decision tools (Klefsjo *et al.*, 2001).

This use of a structured approach to improving processes in construction helps to reduce task complexity while increasing performance and commitment from team members (Linderman *et al.*, 2003). The DMAIC methodology simplifies the process improvement project because it acts like a road map for the improvement team. In the manufacturing industry, six-sigma has typically been applied in an organization-wide manner, choosing macro opportunities as six-sigma projects. Consequently, in manufacturing, we have tended to witness revolutionary changes. These projects have tended to involve the design and development of an entirely new product or service or the major redesign of an existing one. Conversely, at this stage, the deployment of six-sigma in the construction industry has been predominately aimed at micro-opportunities. This means that six-sigma projects would be smaller in scope and likely to relate to a sub-task within a macro opportunity.

Keeping with the philosophy of CPI and TQM, the application of six-sigma at this early stage of its development is to argue enhancements for evolutionary rather than revolutionary changes (Maleyeff and Kaminsky, 2002). Applying six-sigma in construction typically involves breaking down large tasks into smaller ones that can be re-engineered and improved. The main advantage of the six-sigma method is that it shares much of the same *values* and uses similar *tools* to TQM. The tools are nothing new, but the strategic way that the six-sigma programme proactively uses them, within its structured framework, is what generates improved results. Like TQM, six-sigma is a people-focused management system that aims to continually increase customer satisfaction by reducing real costs through a reduction in variation and causes of poor quality (Klefsjo *et al.*, 2001). It works by involving all employees, top-to-bottom, as a structured team. In order to efficiently use statistical tools to base decisions on fact, substantial effort is required to train employees. In doing so, authority is allocated through a 'karate belt' system, creating a comprehensive infrastructure of resources to achieve quality and process improvements. Team members are equipped with knowledge of six-sigma and, most importantly, the processes that they are analysing. In this manner six-sigma emphasizes the involvement of people who carry out the processes on a daily basis. For construction organizations this promotes the collection of data from a level close to the data source. Moreover, the participation of process owners is essential to ensure that the process improvement teams formulate more creative and practical responses.

Case study

The purpose of this case study was to demonstrate the potential of six-sigma to achieve CPI in construction and to highlight the benefits of introducing a structured assembly-line doctrine to construction processes. The case study was based on a PIP for a contract in the United Kingdom. The contract, Contract 105 (C105) of the Channel Tunnel Rail Link (CTRL) includes the construction of an extension to the existing St Pancras Station, London. The contract for construction included participants from the following companies: Costain, O'Rouke, Bechey and Emcor Rail (CORBER). Following completion, this station will become the main London terminal for international rail passengers using the Eurostar service in 2007. The platform extension was built in two halves, the east and west deck. This paper examines the construction of the east deck, which comprises the following major civil engineering activities: diversion of underground services (utilities); demolition of existing road and rail infrastructure; construction of piles, pile caps and columns to support the station extension platforms; and construction of beams that will comprise the new station platforms and tracks.

This research project was conducted to achieve two primary objectives: (1) describe the application of the six-sigma method on a construction project; and (2) evaluate the effectiveness of this method for achieving CPI in the construction sector. The research method adopted to achieve these objectives consisted of two parts. Firstly, the decisions made and their outcomes for two PIPs were recorded under the five stages of the six-sigma philosophy – define, measure, analyse, improve and control. Secondly, six of the PIP team members (i.e. six-sigma black belt consultant, site engineer, site foreman, design manager, construction coordinator and station extension manager) were interviewed to determine their perceptions of the barriers, critical success factors and suitability of six-sigma in the construction sector. Additionally, the interviewees were requested to comment on the advantages and disadvantages of six-sigma compared to other TQM techniques. It should be noted here that the researchers did not attempt to formulate a construction-specific framework due to the limited number of participants who have had experience using the six-sigma methodology. However, the described DMAIC steps and learning experiences documented from this project should be useful for future researchers and practitioners attempting such a task.

Define

This six-sigma PIP was initiated to improve the construction of raised platform beams with the explicit aim of identifying particular activities that were causing defects. A defect in terms of this process relates to the late delivery of platform beams, i.e. in comparison to the construction programme. The main features of the platform construction include piles, pile caps, support columns, pre-cast T-beams and platform beams. Evidently, the construction of the platform beams was dependent on a number of other activities that subsequently had the potential to impede their progress. The business case for this PIP was built around the additional cost incurred to the project due to delays in the construction of the platform beams. The cost of poor quality (COPQ) associated with delays caused by the beams include the following: (1) the cost (above budget) of additional equipment and labour required to accelerate the construction (i.e. crash the project) to meet the programme; (2) the cost of maintaining equipment and labour on site beyond the planned completion to work off the deficit; (3) the impact of the above two factors on follow-on activities such as roof construction and fit-out; and (4) the £54k per day penalty for delay to opening the interim station.

A comparison between the scheduled and the actual beam construction performance is illustrated in Figure 2. At this early stage of the project only 32 of the 276 beams were completed; the figure illustrates that there was plenty of room for improvement for the remaining beams. A review of past performance revealed that the rate of beam production was 2.3 beams per week, whereas the target was 2.9 beams per week. If this performance continued, the construction of the beams for the interim station (146 beams) would overrun by 8 weeks (Figure 2). The average weekly cost (labour, equipment and materials) of the beams is £71k. An eight-week overrun of labour pay and equipment hire would cost an additional £0.57k. In addition, liquidated damages (LDs) of £54k per day are levied for the delayed opening of the station. If the delay to the beams directly impacted the opening of the station, the LDs would amount to £3.02M.

The goal of the PIP was to reduce the delays to the beam operation, reducing the forecast delay by four weeks, saving £284k (i.e. half of £0.57k) of labour and equipment costs. The team attempted to reduce the time taken to construct platform beams and improve the handover process by either increasing work efficiency or by reducing factors leading to delays. The primary metric was the gap in the beam performance (number planned to date versus number actual to date) measured on a weekly basis. The secondary metric was the gap in the cost performance (the difference in the planned and actual cost to date). This metric was monitored to highlight whether increased performance was due to excessive resources being deployed.

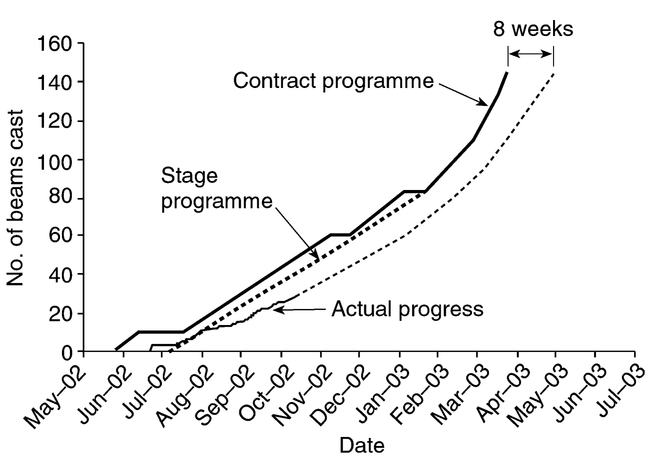

Figure 2 Beam performance gap analysis – east deck extension

Measure and analyze

In this phase of the beam construction process the team initially took a broad project-wide approach when searching for potential problem areas and associated measures in pre-beam activities. A cause-and-effect analysis (i.e. mapping the beam construction process and examining the impact of different scenarios and/or production rates on the process's efficiency) was carried out with the process owners to establish the more general causes (i.e. pre-beam activities) of delays to the beam construction process. The feedback from this exercise was that some preceding construction activities were causing delays to the beams. The exercise was expanded to include the managers of the other activities that precede the beam construction process. It became very clear from the cause-and-effect analysis that the success of the beams was heavily reliant on preceding activities such as site access, utilities and road diversions, demolition, piling, pile caps, and columns.

The beam construction process necessitated a heavy reliance on multiple interconnected activities. The coordination of these activities and the interface between them played a considerable part in the eventual success of the on-time delivery of the beams. Discussions with members of the team in an informal workshop revealed several instances where poor coordination had caused significant delays/cost overruns to the beams or preceding processes. Many of these issues were attributed to the lack of a formal handover between three project teams: (1) utilities; (2) demolition and piling; and (3) deck team (pile caps, columns and beams). This was due to the fact that the teams were working independently and were not considering the needs of their customers. This individualistic culture evolved from the way in which the teams were measured. Progress charts were produced on a weekly basis and issued to the project participants and the head office. However, these charts served as individual team motivators rather than common goal drivers. For example, the piling team were recognized for placing concrete in the ground, not for delivering a satisfactory pile to the pile cap team, once the testing had been successful. It all comes back to the fundamentals of goal theory and motivating everyone collectively to a common goal. The PIP team realized that they needed to motivate workers to take ownership of what they do, through emphasizing the importance and contribution of their task to the overall success of the project. The departmentalization of the project, in effect, led to counterproductive fragmentation in the overall scheme of the project. Only after the process improvement team had participated in several weekly progress meetings did they realize the need for a coordinated programme so that progress and productivity projections would be discussed in terms of the whole project. The main outcome of this review was the creation of a second separate PIP (i.e. PIP2). The main focus of PIP2 was to guarantee the effective coordination of the activities associated with the construction of the beams and their interface with the piling and pile cap teams. Together these activities were considered as a significant contributor to the delay of the platform beam construction.

The findings of the second PIP suggested the creation of a coordinated plan linking piles, pile caps, columns and beams. This schedule would link all the major activities, showing which columns were needed for each pair of beams, which pile caps were needed for the columns and which piles were needed to support the pile caps. This scheduling method allowed construction durations to be known; thus target dates for piles, caps and columns could be listed. The main advantage of this method was that the impact of last-minute changes or drops in performance by one team could be assessed by others (process owners).

A technique used to help gather data to further measure the construction process was the constructability workshop. The attendees included designers, site agents, construction managers, foreman and architects as well as the members of the process improvement team. The aim of these sessions was to review the construction process and to gain an insight on any problems occurring in the process. The PIP team's next task was to sit down with the appropriate lead departments to have these issues rectified and most importantly communicated back to the site operatives so that improvements could be made.

Following a further review of the effects of the problems identified during the constructability workshop, it was decided to collect data on the duration of beam construction. The team's objective was to establish a theoretical performance for the construction of a single platform beam (beams were poured in 15m lengths). The start, end time and date were recorded by the beam field engineer on a data collection sheet. This information was then entered into a workbook so that performance could be measured and monitored to identify what processes were causing delays.

Production schedules (i.e. mapping the beam construction process) for the platform beams for the next 12 pours were created. The schedule illustrated how the equipment progressed on three overlapping fronts using three sets of falsework (including tables), yet only one set of formwork. An assessment of the equipment requirements for the remainder of the east deck was carried out. This analysis illustrated that at current resource levels (three sets of falsework legs and a single set of steel formwork) the programme targets could not possibly be met. Additionally, the entire construction programme was at risk should damage occur to this critical equipment. If these current levels of equipment were maintained it was estimated that a two-month delay would occur. Following this estimate an analysis was made of the appropriate levels of equipment (formwork and falsework) needed to meet the contract programme. The analysis used the latest revision of the construction programme (following the completion of PIP2) to show how the amount of formwork and falsework used would affect theoretical production rates. Figure 3 details the relationship between equipment levels and theoretical production rates. This figure illustrates that an additional set of falsework (tables) and an additional set of formwork were required to reduce the revised programme by four weeks. This analysis also demonstrated that there was diminishing return from the procurement of further additional equipment.

Improve

The previous phases drew the PIP team's attention to three areas relating to the construction of platform beams where improvements could be made and subsequent time/cost savings realized. These areas of improvements included: (1) pre-beam activities; (2) efficiency of beam construction based on the duration of construction; and (3) equipment levels (i.e. formwork). The first area of improvement related to the pre-beam activities. The process improvement team initially reviewed the pre-beam activities (i.e. ground works, piles and pile caps). The PIP team discovered that these activities required efficiency-related improvements. Subsequently, the team constructed a coordinated programme which allowed project teams to discuss productivity projections in terms of the whole project. This was achieved by formulating a schedule linking all the major activities supporting the beam construction. This outcome was achieved through a separate PIP working in parallel (i.e. PIP2); this PIP provided enhancements to the on-time delivery of beams by minimizing the impact of pre-beam activities. The second area of improvement targeted gaps in the construction process. During meetings, the PIP team stressed the importance of formal communication channels between department heads and foremen (including general site operatives) to ensure that when future problems were identified, they could be remedied efficiently and effectively. Finally, an analysis on the current levels of equipment used was conducted and it was recommended to purchase an additional set of falsework (tables) and formwork.

Control

Several members from the PIP team were responsible for ensuring that the schedule of action items (identified in constructability workshops) and associated action parties (departments) sustained the improvement(s) that had been achieved. Moreover, this select group were allocated the role of monitoring the performance of this process. Their role was to maintain close supervision and training of operatives to achieve further improvements. To sustain improvements, the PIP team monitored the construction of the beams with the charts developed in the measure and analysis phases of the improvement process. A review of these charts indicated that there had been noticeable improvements in most of the activities – specifically, less variability in activity durations. To illustrate this reduction in variability, Figure 4 details the total time to complete the beam construction. Theoretically, it was recommended that a 15m length of platform beam should be

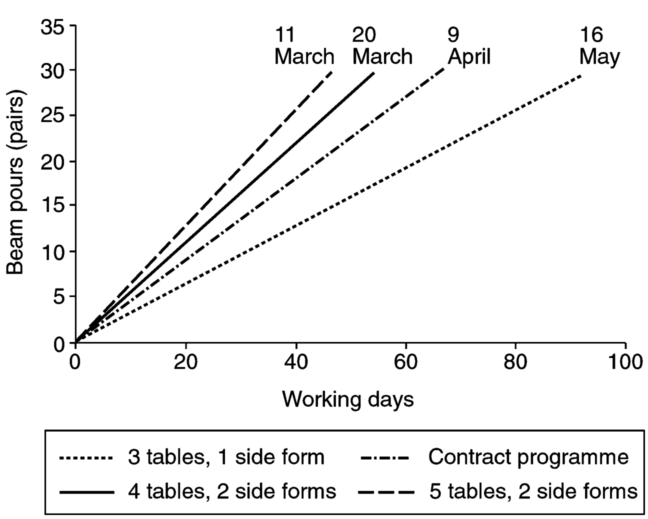

Figure 3 Comparison of equipment levels

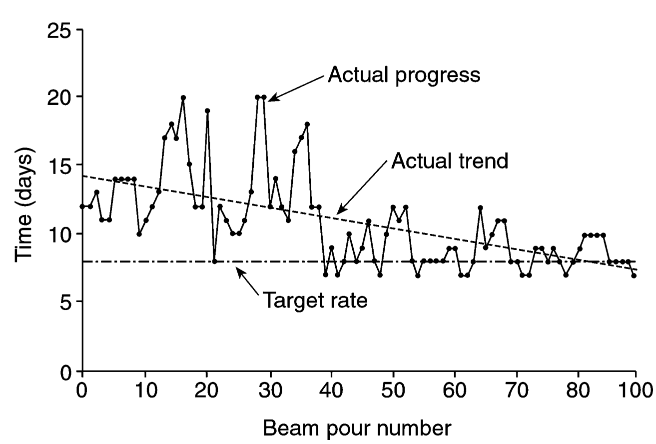

Figure 4 Control/monitoring chart for beam construction

completed in 8.5 days allowing for small abnormalities. Figure 4 highlights that the process is improving, and is continually being perfected. The control charts allowed the PIP team to identify problems with the potential to cause significant delays to timely project completion.

Summary

The primary outcome of the study was a number of contributions to the planning and management of the beam construction process. The PIP discovered that the major source of delays resulted from preceding activities and current equipment levels. Over the duration of the project, beam production performance has improved substantially (Figure 4). This has mainly resulted from the timely completion of service relocations. Moreover, an increase in efficiency resulted from the development of a coordinated construction programme that reduced the amount of piecemeal construction. The major findings and recommendations from this case study are as follows: (1) the most significant factor influencing the performance of beam construction is the availability of the site; (2) coordination of the construction activities through the use of monitoring and projection tools enabled the teams to work together, rather than independently; (3) continued collection of performance data (i.e. control phase) helped to highlight areas where future process improvements could be made; and (4) project teams should be measured in a different way, whereby they were rewarded for the handover of a defect-free structure to the next team.

Evaluation

To evaluate the effectiveness of the six-sigma method, a small number of interviews (N=6) were conducted with some key project participants. These interviews sought to ascertain respondents' perceptions as to the success factors, barriers and suitability of the six-sigma method for improving the performance of construction processes. Moreover, the interviewees were requested to compare the six-sigma approach to other TQM techniques. Most of the interviewees identified management commitment, appropriate organizational infrastructure and linking six-sigma to business strategies as the critical success factors for achieving effective six-sigma implementation. Surprisingly, the interviewees identified the selection of an appropriate PIP as the most significant barrier. Other barriers identified included resistance from workers, implementing required changes and a lack of understanding of the six-sigma approach. Clearly, there are also other barriers to overcome to ensure the success of six-sigma. The ability of the organization to proactively acknowledge further barriers will increase their likelihood of delivering sustainable improvements to construction processes. The interviewees were questioned as to whether they believed six-sigma was a suitable method for improving quality and efficiency in the construction industry. All the respondents agreed that six-sigma was well suited to the industry provided that the PIP could be clearly defined as a series of processes and that senior management introduced the method in a supportive manner. One interviewee commented: 'this technique is well structured and lends itself to many processes within construction'. Interestingly, the interviewees perceived that six-sigma mainly improved efficiency but not quality. They thought that the main improvements were in the areas of coordination, process planning and cost allocation. However, these comments only demonstrate that many construction professionals have a common misconception about the concept of 'quality' and its relationship to the whole procurement process. This misconception is best described by one of the respondents who commented that 'improved efficiency=less panic=better product'. The interviewees were asked whether they thought that six-sigma should be applied to future construction projects. They predominately indicated that as long as six-sigma was applied by an experienced management team it had potential to refine processes and ultimately enhance the bottom line.

Lastly, the interviewees were requested to compare the six-sigma approach to other TQM approaches they had adopted previously. Most of the interviewees found that six-sigma was more statistically oriented and better structured for overcoming construction problems. They generally considered that six-sigma was best applied for well-defined problems and for process diagnostic solutions. None of the interviewees confirmed that one approach was better than another. Their overall consensus was that the six-sigma method was better for getting to the heart of an isolated or a complex process problem quickly and efficiently. TQM on the other hand, was considered to be better for system-wide organizational improvement and deployment.

Conclusion

The structured yet flexible six-sigma framework provides a solid procedure for the gathering of information on the sequence of construction processes, enabling process and quality improvements. Misconceptions of six-sigma method stem from its origins as a manufacturing approach; however, six-sigma also has the potential to improve processes in construction. The main advantage of six-sigma is that it uses its people to reach a practical solution – it doesn't just attempt to revolutionize construction procedures with mechanized process improvements.

Despite the large number of studies having addressed the concept of quality in construction, there is limited research into the use of six-sigma as a strategy for process improvement in construction. In an attempt to address this gap in the research, this article has presented a review of six-sigma and its subsequent application in an industry case study. The case study described the outcomes of a six-sigma PIP conducted for the construction of concrete longitudinal beams in the St Pancras raised railway station in London. The outcome of the six-sigma PIP was the improved productivity of beam construction, enhanced interaction between project teams and reduced project delays.

The literature and associated case study detailed herein provides essential implications for both researchers and practitioners. Firstly, it provides a solid foundation for academics to enhance the six-sigma process improvement methodology for the benefit of future construction and engineering projects. Secondly, practitioners interested in improving their own project productivity can utilize the explanations, outcomes and learning experiences detailed in the above-mentioned case study to enhance their productivity, reduce delays and maximize profitability on projects.

Due to the limited application of six-sigma in the construction industry, this research principally sought to document its implementation in an industry-based case study and examine the benefits derived. Future research should quantitatively compare the benefits derived from a six-sigma approach to other popular CPI techniques and tools. Moreover, academics and practitioners should attempt to formulate industry-specific guidelines for six-sigma implementation, not only for the larger enterprises but also the small and medium ones. Furthermore, researchers should attempt to evaluate the impact of partnering on the six-sigma approach and develop means for six-sigma to be fully integrated into the entire construction supply chain.

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