An Analysis of Process v. Inspection Capabilities in Fabricated, Engineered-to-Order Construction Supply Chains

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ABSTRACT

Supplier Quality Surveillance (SQS) is an important process developed by Engineer-Procure-Construct (EPC) contractors to assure that products are delivered according to specifications and free of defects. In industrial projects, EPC contractors commonly design and oversee the fabrication of multiple products and large engineering components, which are classified in different levels of criticality according to the probability and consequences of failure and associated with these elements. The model discussed herein addresses the challenge of working towards zero rework in EPC projects. The authors use data obtained from an ongoing Construction Industry Institute (CII) project to build a simulation model that represents the different steps of the SQS process. Discrete event simulation is used to develop the model in the software EZstrobe. The model is developed to represent the dynamic nature of SQS, the interaction between different sub-processes (fabrication, release to site, and installation), and the impact the reliability of individual tasks has on the quality of final products delivered and installed at project sites. The results of the simulation are analyzed and a relationship is identified between the process capability (percentage of products delivered right the first time) and the inspection capability (percentage of non-conforming products identified and corrected).

INTRODUCTION

“You cannot inspect quality into a product.” Harold F. Dodge’s words, immortalized by W. Edwards Deming in his book “Out of the Crisis” (Deming 1986), have influenced production systems in many fields all over the world for decades. So much so that the word “inspection” has become synonymous with waste when designing any production system. With the construction industry becoming more and more influenced by Deming’s teachings the stigma with inspection has followed.
However even Deming agreed in his book that there are exceptions, circumstances in which inspection especially 100% inspection becomes an integral part of the production system.

This paper examines the supply chain for industrial construction projects from the perspective of supplier quality. A number of engineered-to-order (ETO) items are commonly produced for complex industrial projects. These items are typically procured to be delivered to the jobsite and installed into the growing facility as nearly standalone projects unto themselves. Because the consequences of poor quality in rework, schedule disruption, shipping, and so on can be very significant, Engineer-Procure-Construct (EPC) contractors deploy various efforts to ensure that the supplied ETO items meet the appropriate specifications. These practices include several inspections in multiple levels among other practices. In this paper, discrete even simulation is used to consider the effectiveness of these inspections throughout the supply chain, from the supplier’s shop to the site. The study presented is part of a broader project carried out by the Construction Industry Institute’s (CII) research team 308 (RT308) - Achieving Zero Rework through Effective Supplier Quality Practices.

BACKGROUND

As stated in the introduction when it comes to quality improvement in production systems inspection is often considered a waste of time and effort. Inspection in itself does not do anything to remove the cause of defects. Inspection is considered an added and avoidable cost in the production system; it is an acknowledgement that the system is not capable of conforming to the specification, and catching defects only leads to costly rework. According to Deming (1986, p.28) “Inspection to improve quality is too late, ineffective, costly.” Shingo (1989, p.14) argues that “inspection cannot prevent defects from occurring during processing”. Regular routine inspection does not address the causes of defects in the system; only by improving the process can quality be improved. However both Deming and Shingo agree that there are circumstances, certain condition under which defects are unavoidable and intolerable. Where zero defects are required in the product produced, 100% inspection becomes a necessity. Shingo (1989) gives the example of Mr. Tokizane, managing director at Matsushita, a television manufacturing company, who set in place a sampling inspection program. However “one day Mr. Tokizane made a profound observation. Each customer he realized, purchases only one television set out of the company’s total production of one million. If that one set were defective, the customer’s faith in the company is destroyed.” (Shingo 1989, p.16). Shingo gives this example in order to illustrate the importance of 100% inspection and its thoroughness. In a similar way defects of a major ETO component can have devastating consequences in cost, time and safety and such consequences can far exceed the cost of the purchase.

Construction is an industry deeply rooted in the inspection culture. A substantial portion of the work done has to be inspected by qualified inspectors to ensure quality before it is approved. With the advent of lean construction principles and the influences from lean manufacturing that include the stigma with inspection, lean construction literature tends to equate inspection with non-value adding activities
and tries to make inspection an intrinsic part of the production process through the use of mistake-proof devices or redesign of tasks and responsibilities. Ballard and Howell (1997) proposed to improve the in-process inspection by having craftsmen provide better feedback. Koskela (1993) presented inspection as a non-value adding flow activity and indicated that the primary focus of improvements in a production system should be the reduction or elimination of the flow activities rather than their improvement.

The impact of the various inspections found in a construction supply chain is explored in this paper via simulation. Simulation has been used to investigate inspection issues by others. To determine the appropriate inspection interval, Scarf (2007) uses a binary decision tree for determining the appropriate policy based on a maintenance decision model for an industrial system. Wang (2008) developed an optimization model in order to determine the intervals of inspection in a process that involves two different types of inspections and repairs. White et al. (2005) used a simulation software (Arena) in order to study a multi stage inspection process for determining an efficient system in which maximum inspections can be conducted. Yumbe and Hasegawa (2012) developed an algorithm to minimize the inspection cost based on the predicted inspection timing by calculating the optimal combination of two inspection schemes. Gardner et al. (1995) used SLAMSYSTEM in order to determine the cost for justification of quality improvement. This paper uses discrete event simulation in order to determine the probability of zero defects in multi stage inspection by simulating the outcomes of the inspection process under different scenarios.

PROCESS MAP

The goal of this paper is to model the supplier quality inspection process for ETO items in EPC projects. Construction projects are planned to use labor, equipment and materials in the most economically effective and safe way to get the desired results. In many situations the requirements of a construction project are standard. However in certain cases and especially in EPC projects, certain items are ETO. One-off items that are designed and manufactured for a particular project, ETO items are very specific and usually an integral part of the project. Therefore any non-conformances to the specifications are intolerable and must be corrected. The correction of a non-conformance may require the replacement or repair of components, engineering rework to design a work around, or acceptance of the deficiency by the client. Each case represents a cost incurred; furthermore, this cost will be higher the later the non-conformance is discovered within this process. For the purposes of this investigation, we will consider only from the supplier’s execution of the work through mechanical completion.

In order to eliminate, identify and/or correct non-conformances, contractors deploy several supplier quality practices. These practices include a series of inspections that could be conducted at a number of points in the process, ranging from the suppliers manufacturing facility to the site. Alves et al. (2013) presents a detailed description and map of the supplier quality (SQ) process for EPC projects used as a reference for this paper. Alves et al.’s SQ map is the result of the mapping effort carried out by members of CII’s RT 308.
The inspection process starts at the supplier’s facility with an in-process inspection. This consists of observation and inspection carried out during the fabrication process, usually with personnel present in the supplier present in the supplier’s facility observing and documenting the work as it is underway. The next stage of inspection comes at the release of the item, from the shop. Any non-conformance detected at this point is addressed and the item, if free of non-conformances, is marked as ready for shipment to site. At the site a receipt inspection is conducted as the item has been moved from the supplier’s facility to the site, and may have been damaged or the in-process and release inspections could have missed a non-conformance. This inspection is also referred to as an overage, shortage and damage (OS&D) inspection. After successfully completing the receipt inspection, the item is marked as ready for installation. During installation or during an inspection at mechanical completion, additional non-conformances could be noted. Any non-conformances that still remain are considered as “Latent Defects” for the purposes of this study; these non-conformances remain undetected and may or may not affect the project in the long term. This project limited its investigation to mechanical completion. Further research is needed to consider additional portions of the life cycle.

**DEVELOPMENT OF THE MODEL**

The model went through several stages of development, beginning with development of a process map with the aid of subject matter experts (SMEs) from the industry (Alves et al. 2013). The portion of the process map dealing with the in-process and gate (release, receipt and mechanical completion) inspections was then instantiated in the discrete event simulation. This development process was conducted in stages to allow for testing against a simple model developed in a spreadsheet to make sure the model was operating as expected.

The simulation model was developed in EZStrobe, a simplified version of Stroboscope that also operates with a graphical user interface in MS Visio™. EZstrobe is a general purpose simulation system designed by Martinez (2001). In the program models are represented using Activity Cycle Diagrams (ACDs), which consist of circles and squares linked together to form a network. The rectangles represent activities, the circles represent queues, and the links between them represent the flow of resources Martinez (2001).

**BASIC MODEL**

Figure 1 shows the EZstrobe model used for this analysis. The model tracks the purchase of an ETO item (or items) through the fabrication process, including the four inspection cycles identified (in-process of fabrication, release, receipt at site, and mechanical completion). The purchase is conceived of as including 100 dimensions of conformance that must be checked.
For example, Figure 2 shows a skid, with a list of 100 dimensions that must be checked for conformance. Some fraction will be fabricated in conformance, and the remainder might not conform. Each of the 100 dimensions modeled thus represents 1% of the total number of dimensions that must be checked, should they be different than 100.

The model shown in Figure 1 represents the fabrication process itself only via a process capability, $P_{fab}$, which represents the probability that fabrication will be completed in conformance with the specification. In other words, the probability that non-conformances will exist against any of the 100 dimensions would be given by $1 - P_{fab}$. Non-conforming dimensions are placed on the upper “track” on Figure 1 (next to the solid black arrow).
Once the items are fabricated, they are then subjected to the four consecutive inspection cycles. In each inspection, a probability \( P_{\text{insp}} \) exists that a given non-conformance will be identified and corrected. In the model, in contrast to the real process, non-conforming items produced during fabrication are known at the beginning, and so only those need be subjected to inspections at each step. Thus, in this model there is no chance of a “false negative”.

The model (Figure 1) starts at 1 with the queue “Start” which represents the order for the item or items (and their 100 dimensions of conformance). At 2 the components are split into two paths by a fork which represents the probability that the components will be fabricated correctly; or in other words the process capability. This probability is given by \( nP_{\text{fab}} \). The grey arrows show the path of the correctly made components and the black arrows show the path of the non-conforming components. The conforming components go through the in-process inspection, the final inspection (sometimes called a release from shop inspection), the receipt inspection and the mechanical completion inspection at 3, 4, 5, and 6, respectively, pass them, and become available in the queue marked ‘MC’ at the end representing conforming mechanical completion. Thus, this model simplifies reality by assuming that conforming components cannot become non-conforming (as, for example, might result from damage or a specification change).

The defective components go through the same inspections, however they have a chance after each inspection that the defect is caught, the non-conformance is corrected, and the component is sent to the conforming path. This possibility is represented by the forks at 3, 4, 5 and 6. The probabilities \( nP_i \), \( nP_r \), \( nP_f \) and \( nP_{mc} \) represent the chance to catch and fix the non-conformance at the in-process inspection, the final (release) inspection, the receipt inspection and the mechanical completion inspection, respectively. The defective components that are not caught after the mechanical completion inspection are sent to the queue marked Latent. Thus, in the model it is possible to know how many non-conformances existed but were not identified and corrected by the time of mechanical completion. Mechanical completion was chosen as the end point for this model because other data collection efforts for the work of RT 308 were limited to this point in the ETO product life cycle. In practice, additional opportunities to identify non-conformances exist.

The model assumes that all components that are made correctly originally are in conformance with all requirements and no latent defects are present. Another assumption is that whatever the non-conformance in a component is, once it is caught at any stage, the non-conformance is corrected removed and there is no chance that defect remains.

**ANALYSIS OF THE BASIC MODEL**

An analysis was conducted using the model. The objective was to track the chances of having perfect execution of the manufacturing and inspection process, meaning what is the chance that if a procured component were fabricated, inspected and installed, there would be no non-conforming elements left at the mechanical completion stage. This represents the probability that, even if non-conformances existed after fabrication, they have all been corrected by the mechanical completion stage. For performing the analysis two variables are considered, the process
capability, which represents the chance that the component will be made correctly $P_{fab}$ and the chance for an inspection to catch and correct a defect, $P_{insp}$. For simplicity it is assumed for now that all inspections in a run of the model have the same chance of success. So that if for a certain run $P_{insp}$ is 50% for, say, the in-process inspections, then all inspections across all four stages have a 50% chance of catching and correcting a defect. In practice these probabilities could be different across those stages.

A range of values for the variables were used in the model at an increment of 10% starting from 10 up to 99 for both $P_{fab}$ and $P_{insp}$ so that there are a hundred possible combinations of the $P_{fab}$ and $P_{insp}$ (Table 1). An X in the table represents a pair of $P_{fab}$ and $P_{insp}$ for which a set of 1000 runs was completed. Crandall (1977) suggested that 1000 iterations were sufficient to develop the range of potential outcomes, so 1000 iterations were used for each $P_{fab}$ - $P_{insp}$ combination.

Table 1: Summary of simulations conducted showing range of process and inspection capabilities used

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The results are summarized in Figure 3. Contours of the probability of perfect execution are shown, with $P_{fab}$ along the horizontal axis and $P_{insp}$ on the vertical axis. Because 1000 iterations were used, note that 0 represents <1/1000 and 1 represents >999/1000.
The results of the simulation (Figure 3) show that there are several scenarios in which a high chance of “zero errors” can be achieved. It is also interesting to note that the curves developed in Figure 3 suggest that investing in $P_{\text{insp}}$ has a greater impact on the chance of having no latent non-conformances as compared with investing in $P_{\text{fab}}$, at least until $P_{\text{fab}}$ is quite large. The contours are relatively flat across a wide range of $P_{\text{fab}}$, and experience significant changes with $P_{\text{insp}}$ at relatively high values of $P_{\text{fab}}>0.8$. This outcome suggests that the best solution for improving overall function can be heavily dependent on the current state of process and inspection capability. When process capability ($P_{\text{fab}}$) is low, for example, a vertical move upward by improving inspection capability ($P_{\text{insp}}$) might be easier than a dramatic improvement in process capability, and the opposite is true when the process capability is high.

**SUMMARY AND FUTURE RESEARCH**

In this paper we used discreet event simulation software EZStrobe to simulate the results of a multistage inspection process of ETO items, such as occurs for EPC projects. A model of the supplier quality processes in the fabrication effort was developed to represent a multistage process that includes in-process inspection, final release inspection, receipt inspection and mechanical completion inspection. The model simulates a range of different probabilities of both catching a non-conformance
during the inspection process and fabricating the component in conformance during initial manufacture.

The model needs to be further developed to assess costs associated with the different stages of inspection and with a correction effort at the different points in the project cycle. Costs for correcting non-conformances generally increase as the item moves further along the path, so that a non-conformance that is not detected until the mechanical completion inspection can be far costlier to correct than one identified during the fabrication process. Further, ongoing data collection efforts will be used to assess realistic values for the variables $P_{\text{fab}}$ and $P_{\text{insp}}$ for different classes of ETO items. The impact of simplifying assumptions (continuity of $P_{\text{insp}}$, lack of consideration of in-process damage or change, for example) must also be assessed.

ACKNOWLEDGEMENTS

The authors acknowledge the generous support of these research efforts from the Construction Industry Institute on RT 308 – Achieving Zero Rework through Effective Supplier Quality Practices. The opinions expressed here are those of the authors and not necessarily of CII.

REFERENCES


