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Evaluating Laser Tracking for the Improvement of Quality Control Methods of Precast Concrete

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EVALUATING LASER TRACKING FOR THE IMPROVEMENT OF QUALITY CONTROL METHODS OF PRECAST CONCRETE

A Thesis

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Abstract

Current quality control (QC) methods of precast concrete are outdated and present challenges of human error and lengthy inspections. Current research into modernizing QC practices revolves around the implementation of laser scanners, with less focus on the possibility of using laser trackers. The aim of this study is to evaluate the implementation of laser trackers into the QC process of precast concrete by comparing time, accuracy, and cost to the traditional method of using a tape measure. The time studies and accuracy tests were performed in the pre- and post-pour of the precast concrete process at a precast concrete plant using both the traditional and laser tracker methods. The time study data for the traditional methods was provided by the plant while the laser tracker data was collected during a visit to the plant by the laser technology company FARO. Due to cancelled production on the visit for the laser tracker, data collection was limited to the first checks in the pre- and post-pour processes which prevented an accuracy analysis. As a result, the focus shifted to the time study data collected for the available checks. While the laser tracker demonstration was incomplete, estimates were able to be made for the updated process, and a full economic analysis was able to be completed. The main findings of the study indicate that using the laser tracker results in an 80% reduction of time for the pre-pour and 38% reduction of time in the post-pour in comparison to the traditional QC method. In addition, using the laser tracker results in an annual savings of $47,806.51 from labor costs. The laser tracker is able to save time by making the inspection process more efficient. In the post-pour process, multiple pieces were able to be measured at once rather than one at a time. Additionally using the laser tracker is quicker than measuring by

hand and removes potential human error by plotting a real time point. These savings in time resulted in lower labor costs in comparison to the traditional method. Overall, this study shows that the laser tracker is the quicker and cheaper method as the inspections are streamlined resulting in lower labor costs.

Introduction

Quality control (QC) is an essential part of any industry for ensuring products meet the expected standards. Having effective quality control methods in place allows for companies to save time, reduce costs, and produce quality products for customers. In the precast concrete industry effective QC methods are especially important as the mistakes can be costly and extremely time-consuming. While the materials and machinery in the precast concrete industry have evolved, the QC methods have not.

Precast concrete is a construction product that is produced in plants using molds which allow for a controlled environment. In these plants, concrete is poured into the molds and then left to cure for at least twelve hours. Once hardened the cast is removed from the molds and inspected. After being inspected to ensure these concrete casts are up to the customer standard, they are transported to storage (typically outdoors) to finish curing. Once fully cured the casts are then transported to the customer. Precast molds are commonly used in applications such as parking garages, foundations, bridges, and buildings. The reason that precast concrete is preferred over regular concrete construction is that it is versatile, efficient and made in a controlled environment. Versatility comes from being able to easily alter the size or shape of the concrete. It is efficient as it is produced in a controlled environment which allows for concrete production regardless of the weather. Additionally, it allows for higher quality structures to be built. Having concrete production in a factory setting allows for the implementation of QC methods.

The general methodology of performing QC checks in precast concrete can be broken into two different checks, the pre-pour, and post-pour check. The pre-pour check is comprised of three different quality inspections before the concrete is poured to ensure the foundation and different elements are of the correct dimensions. The post-pour check consists of two different checks in which the sides, top, and edges are checked in the first check, and then followed by a check of the bottom of the structure. There are additional checks such as slump, unit weight, etc. The biggest challenges with the current methods include factors such as human error and wasted time. This is in part because the current method involves quality inspectors manually taking measurements with a tape measure.

In general, the current quality control methods have remained relatively the same for the last twenty years. Hariyanto et al. (2005) performed a case study on quality control in precast tunnel segment manufacturing, which uses similar methods to a traditional precast concrete plant. They identified a need for QC improvements due to non-conformities. The methods in 2005 have very little difference to the ones of today. Implementing improvements into the QC process can help improve the accuracy and efficiency of the QC inspections which should in turn reduce the number of deficiencies. One way to accomplish this is by implementing laser scanning technology into the current QC process of measurement.

Laser scanning technology can potentially be utilized in the precast concrete industry for QC methods. Studies from Liu et al. (2018) and Aziz et al. (2016) showed an increase in accuracy for tolerances and were able to automate the measuring and audit process. However, limitations such as long upload time, and no real time measurements do not make it optimal for QC. An alternative that could potentially alleviate these limitations would be to introduce a laser tracker into the QC methods instead of a laser scanner. A laser tracker is able to perform real time measurements, and there are no scans that need to be uploaded. This has the potential to be a better alternative to both the laser scanner and traditional methods and will help address the issues with human error and wasted time.

The objective of this study is to evaluate the benefit of laser tracking technology in the QC methods of precast concrete. Studies from Kim et al. (2019), Liu et al. (2018), and Aziz et al. (2016) show the evaluation of laser scanning technology was used exclusively in the post-check. This study will look at implementing the technology in both the pre-pour and post-pour check process. It is important to implement it in the pre-check as finding the majority of deficiencies in the pre-check is cheaper and easier than later in the process. As a whole, studies into the implementation of laser trackers into QC practices have been widely understudied. Implementing laser tracking technology into the QC methods of precast concrete can potentially improve the accuracy and efficiency of the process, by eliminating wasted time and deficiencies due to human error.

Literature Review

Quality Control Methods

Developing QC Methods

Developing efficient and effective quality control (QC) methods is a top priority in any industry. This helps ensure a quality product is being produced which has the benefits of saving time and money, increasing customer satisfaction, and allowing for a standardized process. The basic process of developing effective QC methods is universal across all industries. This includes,

- Identifying the quality standards of the product
- Selecting a QC method
- Training employees and establishing procedures
- Conducting QC testing
- Analyzing the data

After the implementation of the quality methods, routine checks can be made on products to ensure what is being produced is up to standard.

Traditional QC Methods in Precast Concrete

The precast concrete industry is a unique industry that presents different methods and challenges in quality control in comparison to traditional concrete. In 1954 the Precast Concrete Institute (PCI) was formed which serves as the collective of precast concrete information and standards. The standards dictate the base requirements that the precast concrete form has to meet depending on the specifications required and intended use (American Society for Quality, 2024). Quality control is essential in precast concrete as the mistakes can be costly and extend the time it takes to produce a piece. For the last twenty years the methods have remained relatively the same leaving room for innovation in the quality methods (Hariyanto et al., 2005).

In precast concrete there are two different stages in which a QC inspector will perform a quality check. The first is the pre-pour check, which is before the concrete is poured, and the post-pour check, which is after the concrete is poured and the piece is cured. During the pre-pour check, the QC inspector takes measurements of the length, width, depth, squareness, and locations of elements (block outs, plates, etc.) using a tape measure. In addition to these measurements the QC inspector will also test the concrete being poured for the temperature, unit weight, and air content, and perform a flow test and a cylinder test. During the post-pour check, the sides, top, edges, and bottom are checked for length, width, depth, squareness, and locations of elements (block outs, plates, etc.) using a tape measure. It is essential to do this check in case something is missed or changed after the curing process before it goes to the customer. After the piece passes the check, it undergoes a visual check where it is then sent to the curing yard to finish curing until it is sent to the customer.

Current Issues in Traditional QC Methods in Precast Concrete

In the current precast concrete industry, higher quality precast elements are being created from innovations in materials and production technology, but there is a lack of research in innovating QC methods (Skrzypczak, 2023). Current issues that are apparent in the current QC methods are human error, and excessive amount of time to perform checks. Wonseok et al. (2023) demonstrated how much time can be saved from traditional quality control methods by adding an automated audit system. This system saved up to 47% in time compared to manual audits which equated to 17.5min. This highlights the need for innovation in the current QC methods for precast concrete.

Laser Scanning and Tracking

Laser scanning and laser tracking are two technologies that have potential to impact QC methods in precast concrete. Laser scanning takes a 3D scan of an object or environment that can be used in a program like CAD. This is useful for applications such as reverse engineering or capturing big environments. Laser tracking uses a laser beam to plot precise points on an object, which can be mapped in a plane and allow for precise measurements. This is useful for QC where measurements and dimensions are important. Implementing either technology could reduce the time taken to perform manual measurements and human error.

Laser Scanner Applications

The application of laser scanners can be used for both small- and large-scale applications, however it is best suited for large-scale applications such as buildings or bridges. This is due to not having to scan many pieces in a limited amount of time, as multiple scans can cause a significant increase in computer processing time. Dimensional accuracy and structural performance measures are highly reliable (95%) when using scanning technology for detecting and assessing spatial elements in large scale projects such as buildings and bridges (Liu et al., 2018). In this large-scale application, the scanner proved beneficial as the only goal at hand was accuracy. Another example of large-scale laser scanning application is in the construction of residential buildings. Polat and Ali

(2023) performed a case study on QC applications using building information modeling (BIM) laser scanning in a sample housing construction project. During the construction phase, the building was scanned to develop point clouds which could then be converted into a 3D model. This 3D model was then overlayed with the original 3D building model of the plans for the building. This allowed for analysis of any defects. After analyzing the model, 2.2% of the productions had defects.

In small scale applications such as taking repeated scans in a timely manner the laser scanner is very limited. In the precast industry, implementing laser scanning and tracking technology in QC methods has the potential to save time and costs by reducing human error. Aziz et al. (2016) performed a study using terrestrial laser scanning (Leica ScanStation C10) to enhance productivity by measuring objects. They scanned four different structures. The laser scanner results had a mean square error of 2.972mm while the traditional tape measure had 13.687mm. This difference of nearly 10mm displays the factor of human error. Although the accuracy was better, it took nearly two hours total to perform all four scans and acquire the data. The majority of this time was spent on data acquisition as it is extremely slow with uploading the scans, while recording the scans took seven minutes per piece. This study clearly illustrates a major limitation of laser scanners as the time to process data far exceeds the time to manually perform these checks.

There are some uses for laser scanners in small scale applications such as pipe fabrication. Pipe fabrication is a complex process in which a laser scanner might be the most appropriate tool to integrate QC methods. This would allow for easier measurements and alleviate some of the workload that is put on the QC inspectors (Safa et al., 2015).

Overall, in QC methods where time and workload in the number of scans is a factor, using a laser scanner may not be beneficial to use as the traditional methods take less time. However, in QC methods of large-scale applications such as construction, or building analysis where time is not a factor, the laser scanner is optimal as there is only one object being scanned which avoids the issue of having to upload multiple different scans.

Automation of QC Methods Using Laser Scanners

The main implication of laser scanning tech in QC methods is to automate or replace steps in the current processes. This usually involves using a laser scanner to measure dimensions of a structure and perform an analysis. Traditional methods can be time consuming and labor intensive that puts strain on the worker. Implementing automation can free up time to be utilized elsewhere. Overall, this should help to decrease deficiencies caused by human error, and potentially save time.

Precast Concrete

QC automation in precast concrete replaces the traditional method using a tape measure where measurements are taken in both the pre-pour checks and post-pour checks. Kim et al. (2016) implemented a new automated quality check technique for pre-cast structures using laser scanning and building information modeling (BIM). A dimensional quality assurance (DQA) technique was developed that entailed the steps of data acquisition, coordinate transformation, edge and corner extraction, dimension compensation for edge loss, dimension error calculation, and comparison with the required tolerance. This technology can achieve a measurement accuracy of 3 mm for dimension and position estimates. However, this study was limited by only being able to measure the top side of precast structures. The DQA process developed is a good visual to understand the process in which the laser scanners work. Ideally this is how the laser scanner should be implemented into QC of precast concrete. This automates the traditional process of using a tape measure to take measurements and perform audits.

Another use for automation in precast QC methods is using laser scanning to detect surface imperfections such as billings. Kim et al. (2014) proposed a basis for analyzing dimensional and surface quality assessment in precast concrete using BIM and 3D Laser Scanning. The study was able to achieve an average error of 2.5mm for dimension estimation and 86.9% accuracy in detecting spalling defects with thickness changes over 3 mm. However, the study was limited due to confinement to rectangular shaped precast concrete with uniform thickness. Based off the study the utilization for surface imperfections worked, but in order to have industry application more research needs to be done using precast concrete molds in a variety of shapes and sizes.

Kim et al. (2015) performed a study in which a terrestrial laser scanner was used to perform measurements such as length, width, and squareness to ensure precast concrete panels meet specifications. This utilized cloud point data to create a model of the panels. Scans were taken at different angles to determine the optimal setup. This study was able to demonstrate the effectiveness of the technique at measuring the dimension, position, and squareness estimates within a 6 mm tolerance with 45 degrees being the best at 100% success rate.

These studies provide insight into the potential implementation of laser scanners to automate QC practices. In each study laser scanners were used to automate the measuring and audit process in the post-pour stage. These studies showed how much better the accuracy of the scanner was in comparison to the traditional process, but also how much more time it needed.

Implications

The studies done on the scanning of QC methods in both precast concrete and pipe fabrication give a good base understanding of where progress currently is and how this technology can be implemented. Most implementation occurred in the post-pour check process for precast concrete, and not the pre-pour. This study will utilize both. In general, there is a lack of research in the pre-pour quality control area. The automation of the QC methods using laser scanning technology seems best suited for applications such as pipe fabrication or precast concrete panels. The issues that arise from the laser scanner are alleviated using the laser tracker as the 3D model is not necessary.

Laser Tracker

Both the laser tracker and laser scanners can achieve the same end goal of dimension analysis in QC methods, but their approach and the way they are utilized vastly differ. Laser trackers are used in basic dimension analysis such as measuring height, width, or squareness for real time measurements. These are used as a replacement of the traditional tape measure. Laser scanners are used to scan an object to create a 3D model. No dimensional analysis occurs during the scan. It is only after the scan is uploaded to software like CAD that the dimensions can be found. Laser scanners function as a replacement to QC process steps such as measuring while laser trackers act as a tool.

Laser trackers excel in QC processes where real time measurements such as length, width, and depth are needed. Laser trackers work by shooting a laser beam to plot exact points in a plane of an object which are plotted in real time on a computer. Using these plotted points the laser tracker can quickly determine the flatness of an object's surface (Yang & Zou, 2022).

Implementing laser tracking into QC methods for precast concrete will be utilized more as a tool than complete automation. The system will take the measurements, but the user has to interpret the data appropriately. In the QC process this will replace the traditional role of a tape measure. This will reduce human error from mistakes that might be made in measurement or getting confused with a previous structure that was measured. The laser tracker system also produces automatic audits to determine if the measurements are following the tolerance set by the quality control inspector. Ideally laser trackers can be used for both the pre-pour and post-pour checks in comparison to the laser scanner only being used in the post-pour. This is due to the complexity of the pre-pour cast that the scanner would have trouble scanning. The post-pour check involves more uniform pieces that enables to scanner to receive better. One limitation of previous studies was the shape of the post-pour casts which is not as complex as the pre-cast molds.

As a whole the current research on laser trackers and the implications for quality control is sparse. This research can provide insight on the possible applications of the laser tracker and raise awareness for a technology that could potentially assist the precast concrete industry.

Evaluation

Looking at both the laser scanner and laser tracker, the laser tracker appears to be the most viable option in QC applications. More specifically this would be for applications involving basic measurements for large objects. Some examples of industries that could utilize this technology would be the precast concrete, shipbuilding, and aerospace industries. In the precast industry the objects would include pieces of concrete or bed forms. These pieces are large objects in which basic measurements are required in the inspection process. In shipbuilding the laser tracker could be used to measure the size of panels being welded into the ship or location of the propeller. The panels and rotor are large objects where a tape measure is not conventional. In the aerospace industry the laser tracker could be used to check the diameter of a jet engine or length of a wing. Similarly to the other industries, these are large scale objects where the laser tracker can optimize the measuring process. The laser tracker excels in these applications due to providing real time measurements, excelling in simple dimension analysis, and no extra added time from uploading scans. In previous studies for the laser scanner, time was a common issue. In particular, the upload time of the scans was nearly two hours for four scans while scanning the pieces took seven minutes a piece (Aziz et al., 2016). In contrast, the laser tracker provides real time measurements. The laser scanner excels in QC applications for large projects such as houses or buildings. These types of projects do not try to save time or require a rapid upload of scans in a short amount of time. The laser tracker excels in measurement applications in QC. Additionally, each study that was done for the laser scanner was performed in the post-pour check whereas this study examined both the pre- and post-pours.

Methods

Objectives

The objective of this study is to evaluate laser tracking technology for the improvement of quality control (QC) methods of precast concrete. The current challenges of traditional methods include errors in accuracy due to human error, and long measurement times. This study assessed whether the integration of laser tracking technology into current precast concrete QC methods lead to a decrease in time and increase in accuracy compared to traditional methods. Current studies in innovating precast QC methods involve laser scanning technology and have limited QC application due to lack of real time measurement, excess upload time, and need to perform measurements on the back end. These limitations are addressed by the laser tracker and shift the focus from implementing laser scanners to laser trackers for the QC methods in precast concrete.

Setting

This study was performed in collaboration with Tindall who is a precast concrete manufacturer that has six plants throughout the United States. This study occurred at their plant in Moss Point, Mississippi. At this plant, the type of precast structures commonly produced include walls, beams, columns, and pieces used in buildings. In this study, I have observed the current quality control practices performed by the QC inspectors. This has allowed for an identification of where to implement the laser tracker in the current process. I was able to observe processes using laser tracking and scanning technology in a demonstration at the plant and perform a comparative analysis.

Current QC and Non-Conformance Tracking

To better understand the QC process at the Tindall plant, I shadowed two different QC inspectors on the pre and post pour check shifts respectively. This allowed for the creation of two process diagrams (Figure 1 and Figure 2) that depict the steps of the QC process for both the pre-pour and post-pour check.

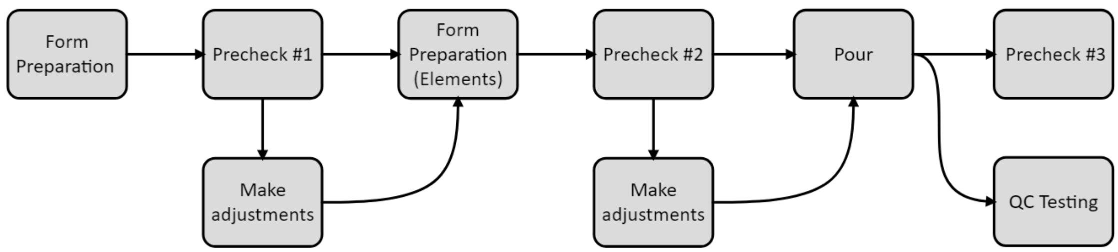

Figure 1. Current QC Process Pre-Check

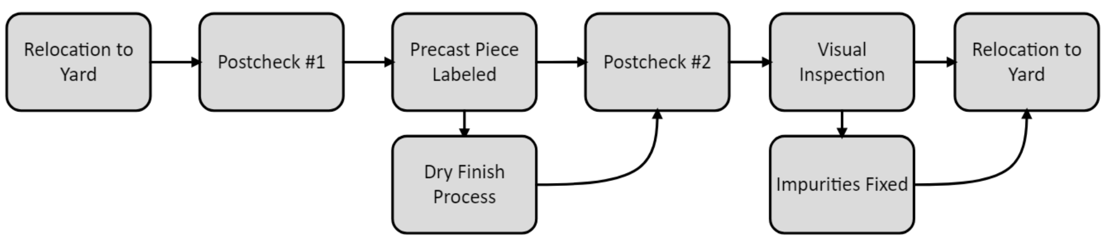

Figure 2. Current QC Process Post-Check

Where each check is being made in the process, the QC inspectors are looking for non-conformities. The QC inspectors use a tape measure in conjunction with a tablet that has the piece dimensions to ensure the measurements meet specified tolerances. The QC inspectors check dimensions such as length, width, depth, squareness, and element location. If a non-conformity is identified, the QC inspector will perform an audit using software on their tablets. This audit tracks the pieces and stores information in a database.

Available Technology

Overview

FARO is a company that specializes in 3D scanning and measurement products and will provide the scanning/tracking technology in this study. To determine what technology was most applicable in this study, a sales representative from Faro visited Tindall to give a demonstration of different technologies. The two products demonstrated included the Freestyle 2 Laser Scanner and Vantage Laser Tracker. The Freestyle 2 is a laser scanner that takes 3D scans of the precast pieces, while the Vantage laser tracker provides simple measurements. This visit allowed FARO to see what applications the technology would be used for and Tindall to obtain a better understanding of the technology and potential implications. The Vantage laser tracker offered by FARO was the best choice for this study as it excels in basic measurements (length, width, and squareness) in the QC process.

Freestyle 2 Laser Scanner

The Freestyle 2 is a handheld device that allows the user to take 3D scans of objects. Freestyle 2 consists of three main components, the handheld device, a smartphone or tablet and a CPU. The handheld device has three cameras to perform the scans using point cloud data. The smartphone or tablet provides a visual for the user and feedback on scan performance. The CPU is where the scans are stored after they are taken as Freestyle 2 cannot perform live uploads. Scans that are taken must be uploaded from the CPU to a computer using a USB. The scans are accessed using 3D software such as CAD.

Figure 3. Freestyle 2 Scanning

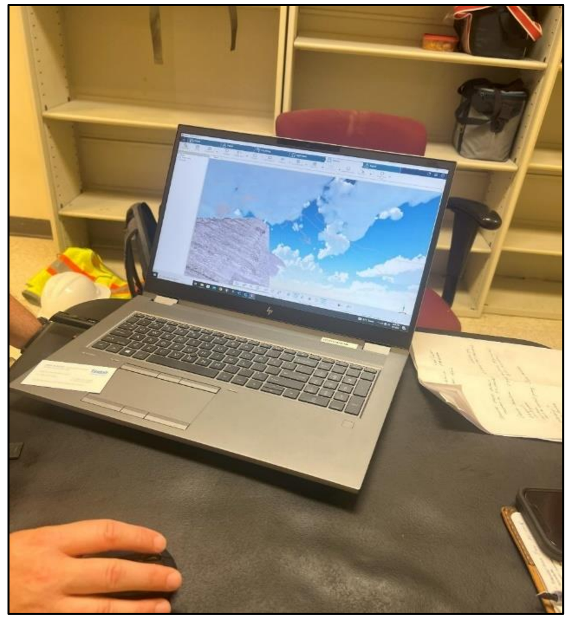

Figure 4. Scan in CAD

The process steps include:

1. Setting up the Freestyle 2 (assembling device)
2. Performing scan of piece
3. Uploading scan to a computer
4. Analyzing scan in 3D software

The Freestyle 2 is highly mobile and produces quick and accurate scans, however the time required to upload and analyze these scans for dimensions can be long. In the precast QC methods, many pieces are inspected at each stage which would require multiple scans resulting in even longer upload times. This would allow for longer inspection time than traditional methods. This is a limitation often seen in previous studies and would not be optimal for precast QC implementation.

Vantage Laser Tracker

The Vantage laser tracker is a device that allows users to make real time measurements. The system is comprised of the tripod device, a reflective probe, a remote, and tracker software. The tripod device consists of a system that has two lasers and a camera built in. The Vantage laser tracker works by using the lasers and camera on the tripod to locate the reflective probe and plot points based on the distance of the probe and uses these points to make planes. Whenever the user wants to plot a point, the user must wait for the system to find the probe which will be signaled by the tracker lighting up green. Once the system is green the user will be able to press a button on the remote. This will plot the point in real time on the software. The user plots major points on each surface to map out each plane and get the shape of the object. The user can then use the probe to obtain real time measurements.

Figure 5. Vantage Laser Tracker

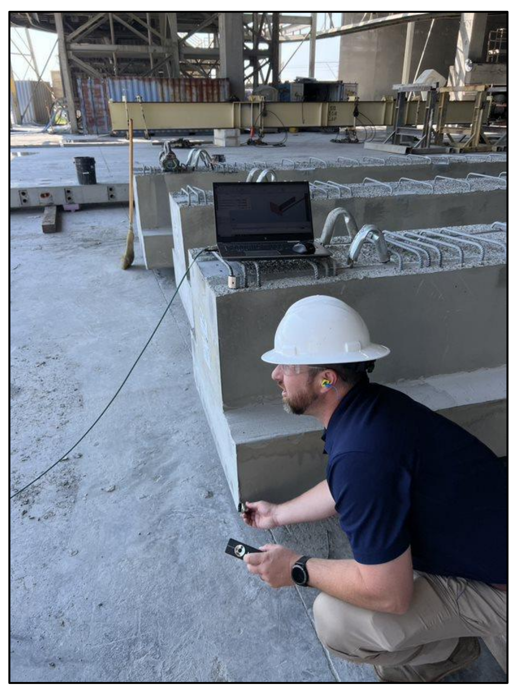

Figure 6. Using the Reflective Probe

The Vantage laser tracker software also comes with a template feature and automatic audit system. The template feature can help save time by pre-inserting expected dimensions and tolerances. Ideally this will be performed during downtime. These premade templates will be made based off the production schedule for the day and will be adjusted based on the real time measurements made. The audit system will then be able to determine out of tolerance measurements based off the tolerances set.

The process steps include:

1. Setting up the Vantage laser tracker
2. Calibrating the system
3. Loading the template for the piece
4. Plotting the points for each side of piece, moving the tracker when needed
5. Measuring and tracking element locations
6. Performing the audit

The Vantage laser tracker is an ideal tool for QC methods in precast concrete as it allows for accurate real time measurements. It addresses the limitations found with laser scanners as there is no upload time and no measurement calculations on the backend. It also addresses issues with the traditional method by removing potential for human error using a taper measure, and long inspection times. Additionally, the template and audit system will help save time. Table 1 provides a comparison of the two Faro products

Table 1. Comparative Analysis of Freestyle 2 and Vantage Laser Tracker

	Freestyle 2 Handheld Scanner	**Vantage Laser Tracker**
Cost	$40,000 for product $6,000 for software	$60,000 - $80,000 for product $9,500 - $12,000 for software ($1,950 optional annual updates) $4,000/year calibration
Time	Estimated 4 minutes per piece (45 minutes for current method) More time to make measurements on backend	Estimated 10 minutes per piece (45 minutes for current method) Real time measurements
Utlility	Perform 3D scan of objects to upload to CAD Perform measurements in CAD	Perform simple measurements Create a model using the points plotted
Life Span	TBD (New Product)	10 to 15 years

The decision on which product to implement was based off practicality. The main function of the vantage laser tracker fits the goal of the study as it excels with dimension analysis. The Freestyle 2, although cheaper, was not as practical. For the QC methods, 3D scans are not needed and the added time from uploading and analyzing the scans would add more time rather than optimize.

Procedures

To begin to evaluate the effectiveness of the laser tracker I identified where the tracker would be implemented in the current process.

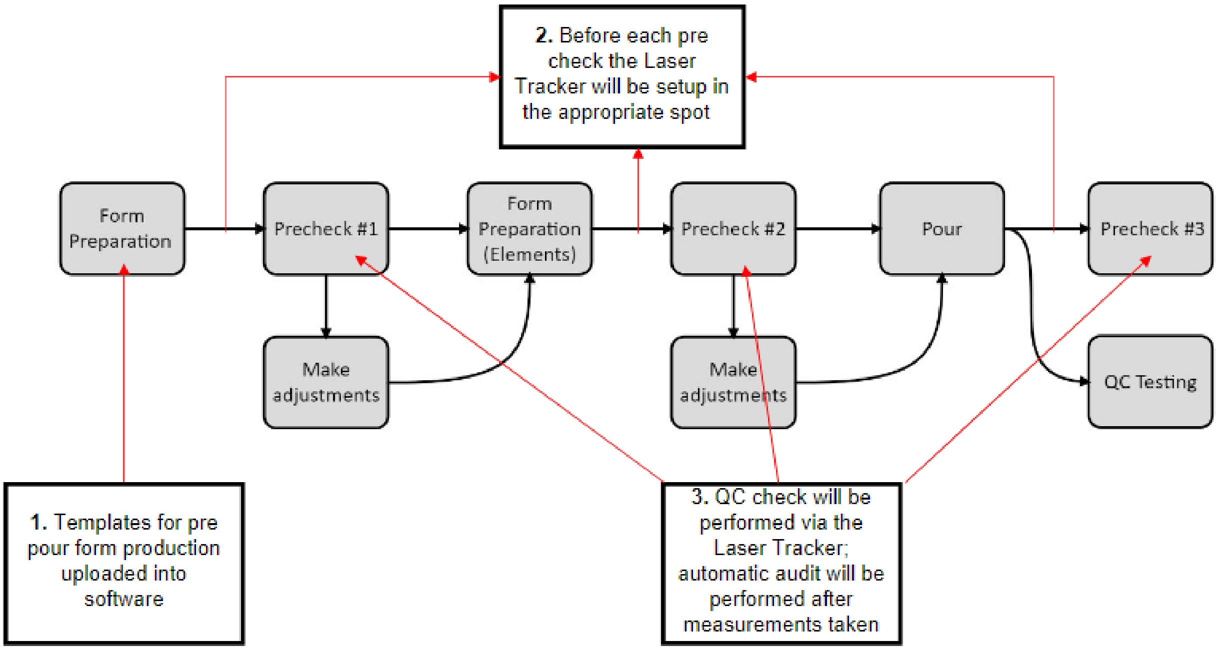

Figure 7. Pre-Pour Implementation

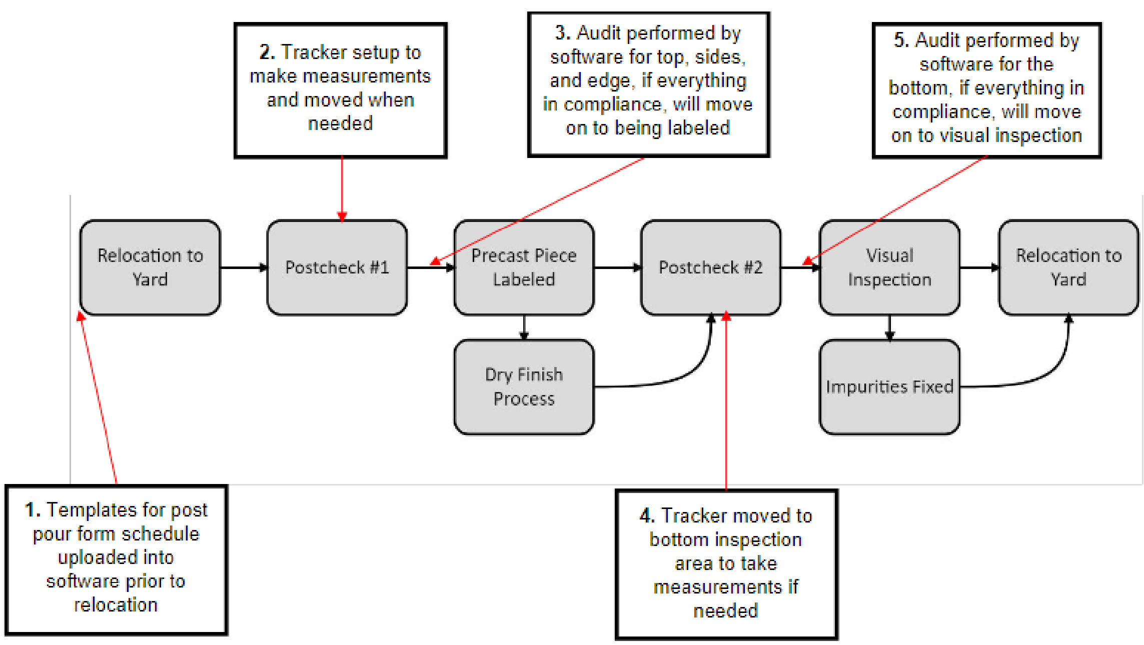

Figure 8. Post-Pour Implementation

Using the previous models from the current QC processes, I created process charts with the laser tracking implemented (Figures 7 and 8). This created a framework for the new process and performing the study. In the study, I performed a time study and intended to evaluate the accuracy of both the traditional and laser tracker processes.

Time Study

The first thing that was addressed was whether or not the laser tracker will save time. This was assessed by performing a time study on the traditional and laser tracker QC methods for both pre- and post-pour checks. A time study was then intended to be conducted using a stopwatch on my phone, the start times would vary depending on the process. This time study was intended to occur on two different observation periods. The first observation was a time study for the traditional QC methods. The traditional QC methods were performed by the normal Tindal QC inspectors on their respective shift (pre- or post-pour). Originally, I was to select two days to visit the Tindall plant. The first day I would arrive at 8:00 am for the pre-pour check and the next day, which would be the day after the first visit, I would arrive for the post-pour check at 3:00am. This would be to ensure that the pieces observed are the same for both the pre- and post-pour check.

For the pre-pour process, I conducted a time study for precheck #1, #2, and #3 (Figure 9) for each bed form available (Usually 4+ beds). Precheck #1 #2 and #3 were observed as each check includes the QC inspector performing measurement inspections.

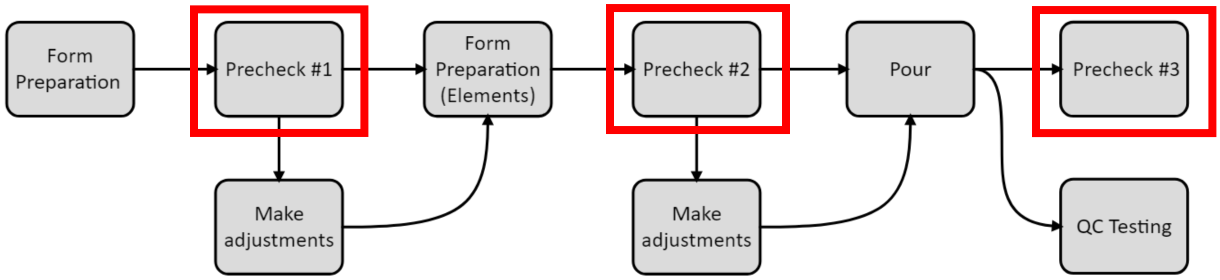

Figure 9. Pre-Pour Traditional Focus

In each check for the pre-pour, the time study began when the QC inspector made a move towards the form to begin measurement. In the event that the QC inspector was distracted with another task or talked to another employee the time this action was performed was excluded. The time was to be stopped when the audit was submitted for the form inspected.

For the post-pour check, I conducted the time study on each piece available, (Usually 5+ pieces) measuring the time it takes for each. I observed postcheck #1 and intended to observe #2 (Figure 10). Although measurements are not commonly taken in postcheck #2, time was still recorded during this inspection as it can affect the flow of the total inspection.

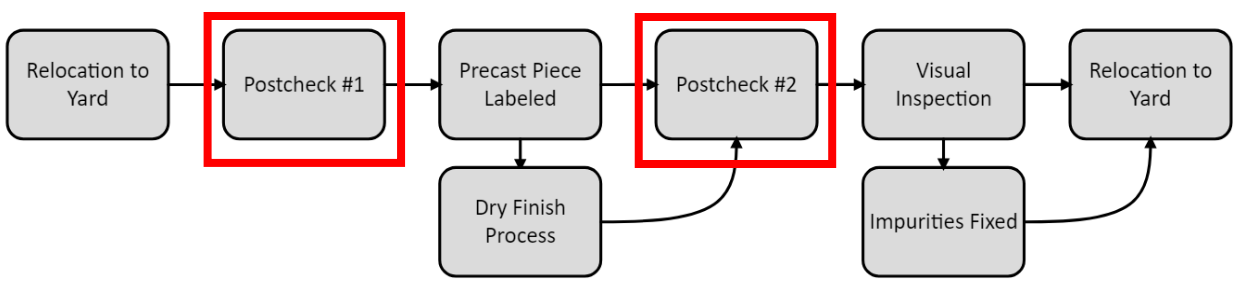

Figure 10. Post-Pour Traditional Focus

Postcheck #1 includes the measurements of the top, side, and edges of each piece in the yard. I started the timer whenever the QC inspector made a motion towards the piece he was to measure and intended to stop whenever the audit for the piece was submitted. In the event that the QC inspector was distracted with another task or talked to another employee the time of that action was excluded. I measured the time taken for each piece available in the post-pour process. Postcheck #2 was measured in the way as postcheck #1. The time started whenever the QC inspector began the motion towards the piece to begin the inspection and was intended to be stopped when the audit was completed.

The tracker time studies were intended to take place on a Friday after the traditional method time studies were completed and when a Faro representative was available to bring the laser tracker. Having this on Friday would allow for easier navigation with the laser tracker as there is no pre-pour production on Fridays. The pre-pour time study would still occur as there will be mock form beds set up to resemble those of the ones observed in the traditional method observations. This would help remove the variability of getting in the way of live production while the laser tracker is used. A FARO representative performed the laser tracker QC process as they are familiar with the product. This helped eliminate user errors due to unfamiliarity with a new product. To give the representatives a clear understanding of what is inspected, a QC inspector gave a demonstration and provided guidance through the process.

I intended to conduct the first-time study on the post-pour of casts from the previous day. I will ensure to pick a Friday on which the production is the same or similar to the observations from the traditional methods. This is usually the case as projects can last for around a month with similar or the same casts. The post-pour time study was to be observed in both postcheck #1 and #2.

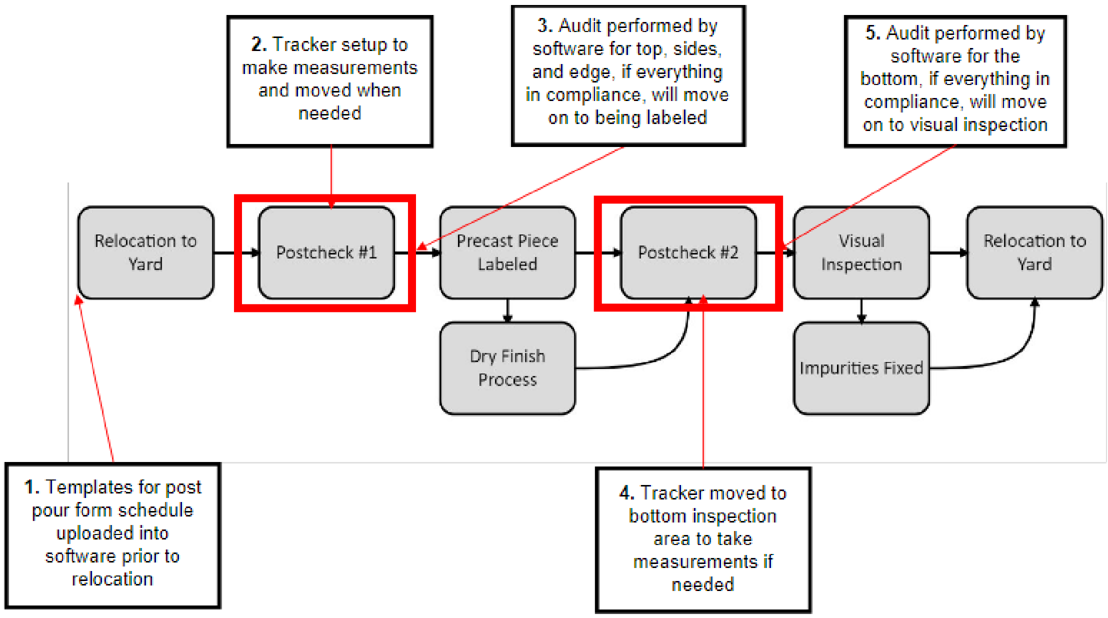

Figure 11. Post-Pour Tracker Focus

For each piece inspected, I began the time whenever the laser tracker began to be set up by the representative. For the first inspection, a calibration time was required for the vantage laser tracker. This time was tracked for the first inspection and factor it into the cycle time by dividing the number of uses of the scanner between calibration. The time was intended to be stopped when the audit is submitted for the piece inspected. I also tracked the setup time whenever the tracker was moved from video while originally it was to be used done by the lap feature on the stopwatch. This was to be repeated for each piece available on the floor and will apply to both postchecks. If there were no measurements to be taken by the QC inspector in precheck #2, the time will start on motion towards the piece.

Due to being on a Friday, the pre-pour was to be performed on mock beds. These form beds were to resemble the ones measured in the traditional process to minimize variability.

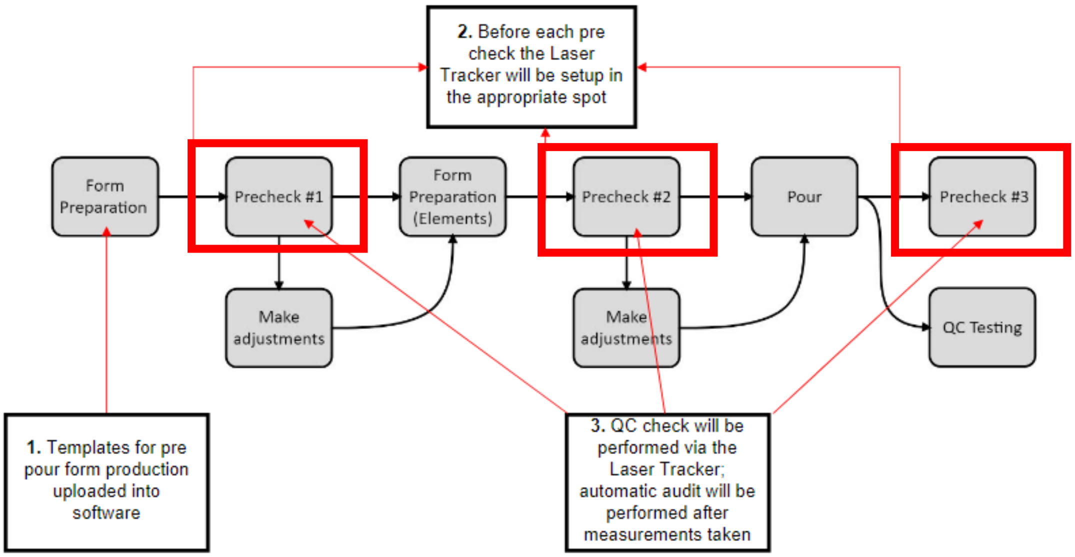

Figure 12. Pre-Pour Tracker Focus

For each form in each precheck, I began the time study when the representative began setting up the laser tracker. I stopped the time when the form was done, while originally it was supposed to be stopped when the audit is submitted. If the tracker was moved during the process, I recorded the setup time using the lap feature. Since there was supposed to be no production occurring, precheck #2 and #3 times may have differed due to no additional rebar being added or wet set plates. If this was the case and I was unable to replicate precheck #2 and #3 similar to the traditional methods, the time study for precheck #1 may be the only one used for both methods. Completing a time study allowed for a comparative analysis of the processes to see what process is most efficient and if the tracker actually saves time.

Accuracy

The next thing to address is whether the laser tracker is more accurate than the traditional process. By determining an accuracy rate based on the number of non-conformities found, I would have been able to assess the accuracy of each method. Kim et al. (2014), assessed accuracy by how close the measured value was to the true value. While being tolerant is essential, how much in tolerance is not important for this study. During the two different observation periods, I would take note of the non-conformities found for each piece and both processes. This would help to determine an accuracy rate based on the non-conformities found.

By doing two days in a row for the traditional methods I would be able to observe the non-conformities found in the same casts for the pre- and post-pour check. If there were non-conformities found in the post-pour check, I could assume that a non-conformity was missed, resulting in lower accuracy. Ideally all non-conformities should be caught in the pre-pour check. The total accuracy for each method would be determined by how many non-conformities were found in the post-check, which were missed in the pre-check. If there were zero conformities found in the pre-check for a cast, but one found in the post-check out of fifty measurements taken the accuracy rate would be 98%. If zero nonconformities were found, the accuracy rate would be 100%. For each check, if there were multiple non-conformances with one item, it would still be measured as one non-conformance. Each cast would be assessed between the two days. There are scenarios where a non-conformity could occur during the curing process in the bed and would be analyzed on a case-by-case basis.

Since the time study for the laser tracker method was to happen on Friday, the accuracy analysis would not be applicable as the post-pour check is the cast from the day before. One solution was to schedule an additional demonstration day using the laser tracker for the pre-pour check during production. I would not need a post-pour check as the accuracy will be determined from the number of non-conformities missed between the processes. Additionally, I could have proposed moving the first demonstration day to a production day. If these solutions were not viable, I could project the accuracy rate using the results for the number of errors found in the mock bed forms by the laser tracker, and double check these by traditional method.

Measuring accuracy would allow for a further evaluation of the laser tracker in comparison to the traditional method. If both result in 100% accuracy, it could have been due to a small sample size with further testing needed. Additionally, it would have emphasized time saved as a bigger factor in the evaluation.

Economic Analysis

The last thing to address was evaluating the cost of implementing the tracker. This was done by performing a cost analysis comparing the traditional and tracker methods as well as an ROI for the tracker.

To perform the cost analysis, I intended to meet with Tindall to obtain data to determine how much money is lost by the traditional process. This would include costs such as repairs, remakes, and labor costs per month. I would then determine the impact of implementing the tracker. I would use the time study data to assess how much money can be saved from labor costs based on the amount of time saved from the traditional method.

The accuracy data would be used to project how much money can be saved from repairs and remade products by comparing the accuracy results of the two methods. Using these calculated costs saved for time and accuracy, I could determine the potential money saved from the implementation of the laser tracker method. I would then calculate the ROI on the tracker by using the value of the projected amount saved to determine how long in months or years it would take to pay off the cost of the tracker.

Analysis

Since the laser tracker will not be utilized due to the cost, or timeline of the study, I planned to rely on the results of the demonstration and perform a projected or simulation implementation. The results of the demonstration would give valuable insight as it would be the only direct analysis. This would help identify future issues or changes that may have been needed to be made.

Assuming the sample size was large enough, I was to perform a projection for the analysis. I would use the data obtained from the study as the basis for my projection model to evaluate the laser tracker. The two hypotheses included the null hypothesis H_0: there was no significant difference between the traditional method and laser tracker method, and H_1: There was a significant difference between the traditional method and laser tracker method. Using these two hypotheses I was able to conduct a t test in R studio ($\alpha = 0.05$) for the data collected from the time study. I would have conducted a test on the accuracy measurements for both methods as well to determine if they are significant.

If the sample size was not large enough for a projection, I would conduct a simulation. This simulation would entail the results of implementing the laser tracker into the current QC methods. For the simulation, I would use the historical non-conformity data from Tindall. Using historical data, I could determine the non-conformities that could be attributed to errors from the traditional method by analyzing the items and types. From the projected improvements of accuracy and time saved by using the laser tracker from the study, I could use the simulation software in R studio to incorporate the improvements into the historical data for the traditional methods. The results would depict a simulated model of implementing the laser tracker from the time study, and accuracy measurements and apply it on a larger scale.

Given the results from either the projection or simulation I would perform an evaluation of the laser scanning method to the traditional method. To evaluate the time and accuracy, I would determine if there were any significant differences and use the data from the direct study. The t test will determine if there was a significant difference between the times and accuracies for both methods, which would show which method was more effective. From the direct study I would be able to assess how much time was saved or how much more accurate one method is than the other. This data would provide a clearer visual than the statistical analysis. I would evaluate the costs by comparing the traditional method to the laser tracker method. If the laser tracker proved to reduce the costs of the traditional methods, I would then complete and ROI to determine how long it would take to pay off. I would then decide if it is worth the investment based off the time to pay off and amount of savings. The t test would then determine if there was a significant difference between the time taken for both methods.

Revised Procedures

Due to unforeseen circumstances, which included the cancellation of production on the visit to the precast concrete plant for the laser tracker observations, data collection was limited. As a result, limited time study data was collected, and no usable accuracy data. This caused the procedures to be altered to adapt to the situation. Although the data collected was limited, the available time study data and economics analysis still provides insight into the evaluation of the laser tracker method. Additionally, some details in the procedures were changed due to there being better alternatives.

Revised Time Study

The first step in the evaluation process was to collect time study data. While the original plan was to perform a time study on the traditional laser tracker QC methods for both pre-and post-pour checks, observations were only recorded for the laser tracker QC methods. The traditional methods time study data was provided by Tindall for the same pieces observed during the laser tracker demonstration. The time studies were conducted by video recording the process on my phone. The data from the traditional QC methods was obtained from normal QC inspectors performing inspections on their respective shift (pre- or post-pour). The data from the laser tracker QC methods was obtained from a FARO representative performing the inspection as they were most familiar with the technology in comparison to a Tindall QC inspector.

For the laser tracker data collection, I arrived at the Tindall plant at 5:00am on July 24th. Due to this being a Wednesday, the first stage of production was occurring. The first-time study that conducted was on the post-pour process. In the post-pour process for the laser tracker method I conducted a time study for postcheck #1 (Figure 13) only.

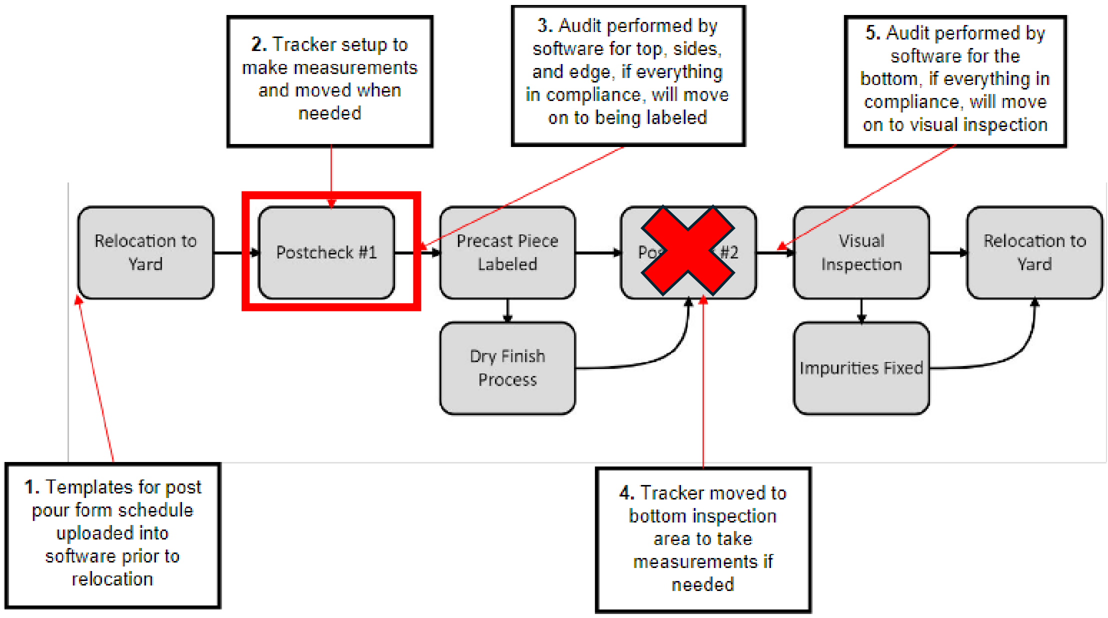

Figure 13. Revised Post-Pour Laser Tracker Time Study Checks

In the postcheck #1, the time study was conducted on 4 pieces due to time constraints. For each piece in the traditional check, the time began whenever the laser tracker was set up by the representative. This was important for factoring in setup time between pieces. In addition, an initial setup time for the first inspection was recorded as the laser tracker has to be set up and undergo calibration. This calibration time only occurs for the first initial setup time as it only needs to be calibrated once a day. The time for the inspection on each piece ended when the representative finished the last measurement on the current piece and was ready to move on to the next. Using the time study data from the videos two different times for each piece was able to be recorded. This included the process time and cycle time. The process time is the time it took each specific piece to be inspected from the start point of when the representative makes the first move towards measurement of the piece, to when the last measurement of the piece occurs. The cycle times included the setup time between pieces. The starting point for these times occurred whenever the representative began a motion to move the tracker to the next setup position. If the tracker did not need to be moved, then the time would begin when the inspection started similar to the process time. The same ending point was used as the process time which included whenever the representative checked off the conformity for the last measurement on the piece they were inspecting. These times were used in both the pre- and post-pour processes for the laser tracker. During the video/time analysis, in the event that the representative was distracted with another task or talking to another employee I excluded this time. Prior to the post-pour inspection, the FARO representative was given a demonstration and a walkthrough on what to measure.

After conducting the time study data collection for the laser tracker post-pour analysis, the pre-pour time study was conducted. This was conducted after the post-pour analysis due to on-going production in precheck #1 (Figure 14). While production ended up being cancelled, this only affected precheck #2 and #3, as #1 (Figure 14) was still planned to occur.

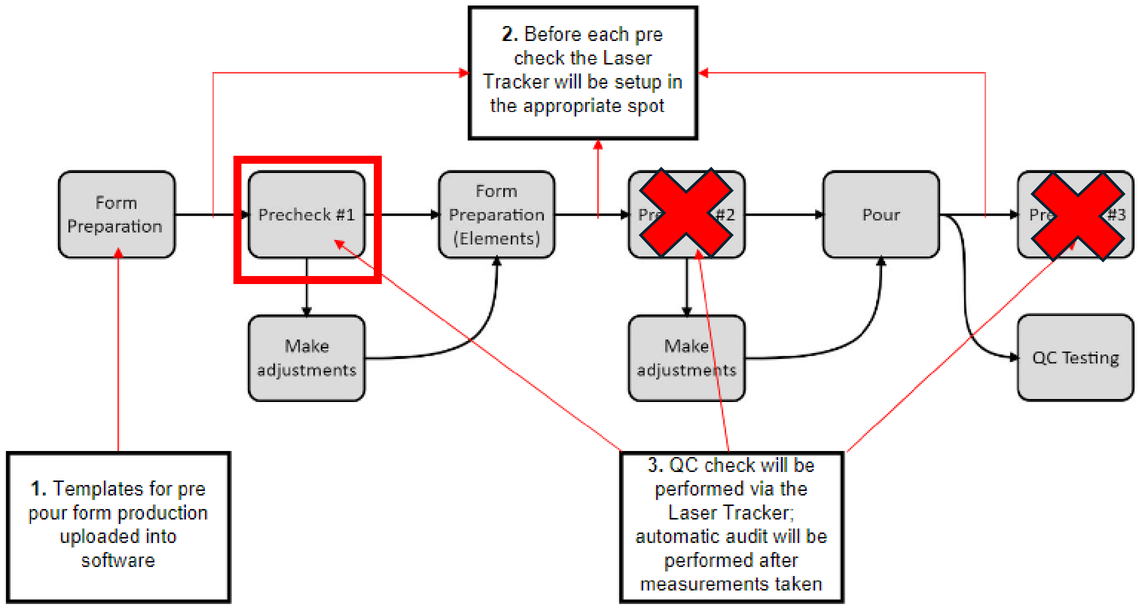

Figure 14. Revised Pre-Pour Laser Tracker Time Study Checks

Similarly to the post-pour analysis, videos of the inspections on 4 pieces/forms in the pre-pour process were taken to perform the time studies. Only 4 pieces were inspected due to time limitations. In a normal production day, 9 pieces on average are inspected in both the pre-and post-pour processes according to Tindall. From the videos that were taken the process and cycle times were determined for the pre-pour process for the laser tracker method. The start and stop points were the same from the post-pour as these were dependent on the time metric and not the process itself. Due to calibration already being performed in the post-pour check, this was not included in the initial setup time for the pre-pour time study. Prior to the pre-pour inspection, the FARO representative was given a demonstration and a walkthrough on what to measure.

The time studies for the traditional methods were originally planned to be performed in person as the laser tracker method was. However, Tindall stated that the visit was unnecessary, and they would send the times for the same pieces measured in the laser tracker inspection since those were already done that day. Figures 9 and 10 show the pre- and post-pour processes as well as the various checks. The data obtained from Tindall contained time study data for prechecks #1, #2, and #3, as well as postchecks #1 and #2. Additionally, it was noted that there is no initial setup time, and the setup time between pieces is about 20 seconds on average. Using this information the complete process and cycle times were found for each check in each process.

Revised Economic Analysis

In addition to the time study, a cost analysis was performed in order to evaluate the implementation of the laser tracker. This was done by comparing the difference in labor costs of the two methods as well as performing an ROI for the tracker. The first step for a complete cost analysis was to utilize the time study in each check of the pre- and post-pour processes. While the traditional methods had complete data for time study, the laser tracker method only had data for precheck and postcheck #1 (Figure 10). To obtain the missing times, the percentage difference in average time for precheck #1 (Figure 9) between the traditional and laser tracker methods was used to estimate the remaining times for prechecks #2 and #3. In addition, the average percentage difference in time to perform postcheck #1 between the traditional and laser tracker methods was used to find the estimated time for postcheck #2 (Figure 10). Utilizing these estimated times allowed for a more comprehensive economic analysis. To find the labor costs associated with each method, the time study data was used to determine how many hours a day that a QC inspector and a laborer would spend on each method. A laborer was included in this analysis as the laborer occasionally assists in the process and fixes any non-conformities found in the pieces in both the pre- and post-pour process. Using the US Bureau of Labor Statistics the hourly pay rate for QC inspectors and laborers were identified. This allowed for the daily labor costs of each method to be determined. From the daily labor costs, the annual labor costs for each method were determined, allowing for a cost evaluation between the two methods. Using the cost difference found, in addition to the quoted tracker price provided by FARO, an ROI was calculated as well as the amount of time it would take to pay off the laser tracker.

Revised Analysis

Due to the timeline and costs, the laser tracker will not be utilized. While not enough data was collected to perform a projected or simulated model, enough was collected to perform the analysis and evaluation of the two methods. Using the time study data collected for the first checks in the pre- and post-pour for both methods a t test in R studio ($\alpha = 0.05$) was conducted. For this statistical analysis, the two hypotheses included the null hypothesis H_0: there is no significant difference between the traditional method and laser tracker method, and H_1: There is a significant difference between the traditional method and laser tracker method. This t test was able to determine whether there was a significant difference between the two methods and which was the considered the better method. In addition to the test, a basic statistical analysis in the comparison of means and standard deviations between the time study data was conducted between the two methods. This allowed for a more basic comparison of data.

Along with time study being an important part of the evaluation process, the economic analysis played a vital role. Comparing the costs of the two methods provided a clear understanding of the impact between the two methods. Using the difference in cost of the two methods, an ROI was performed to determine how long it would take to pay off the tracker. Although the accuracy data was missing, using the time study analysis in combination with the economic analysis provided essential insight into the evaluation process.

Results

Time Study

Pre-Pour

For the time study of the pre-pour process, only the times from precheck #1 (Figure 14) will be used for the evaluation due to data availability. For the process time, the time began when the Tindall QC inspector/FARO representative made the first move towards a piece to begin measurement. This was the same starting point for both methods. The time ended whenever the last conformity was checked off which occurred after the last measurement was made for that specific piece. The QC inspector/FARO representative are aware of when the last measurement is made as there is a specific method in measuring the pieces. In general, the main measurements of length, width, and depth of the whole piece are recorded first. After this, element locations are inspected where the inspector moves down the piece left to right or right to left depending on preference until all checks are completed. In addition, the QC inspectors carry a tablet in which each check is listed and checked off as they are inspected. In the traditional methods, the end point occurred when the Tindall QC inspector checked off the last conformity on his tablet which occurs after the last measurement with his tape measure is made. For the laser tracker, after the last point was plotted with the laser tracker and the conformity was checked off from the FARO representative's laptop the time was ended. The point in which the conformity of the last piece was checked was considered the ending point. While the laser tracker does off an automated audit system, it was not utilized for this study. Instead in the QC inspectors tablet with the checkoff sheet was utilized in tandem with the measurement readings from the laptop plotting the laser tracker points. In addition, prior to the time study, the FARO representative was given a demonstration and practice run on how to perform these inspections. In turn the FARO representative was aware when the measurements were over due to familiarity with the methodology and assistance from the QC inspector.

Table 2. Pre-Pour Traditional QC Methods Process Times (Mins)

Pieces	Pre-Pour 1	Pre-Pour 2	Pre-Pour 3
Process Time for Piece 1	14.27	9.87	19.05
Process Time for Piece 2	15.61	9.52	21.52
Process Time for Piece 3	11.89	12.25	30.27
Process Time for Piece 4	14.64	12.7	17.19
Average	14.10	11.09	22.01
SD	1.58	1.62	5.79

Table 3. Pre-Pour Laser Tracker QC Methods Process Times (Mins)

Pieces	Pre-Pour 1	Pre-Pour 2	Pre-Pour 3
Process Time for Piece 1	3.48	N/A	N/A
Process Time for Piece 2	3.48	N/A	N/A
Process Time for Piece 3	2.08	N/A	N/A
Process Time for Piece 4	2.08	N/A	N/A
Average	2.78	N/A	N/A
SD	0.81	N/A	N/A

In Tables 2 and 3 the process time taken to perform measurements on each piece is listed in minutes. These times are the amount of time it takes to perform the measurements without setup time considered. The setup times were recorded and will be included in the "normal" time analysis. Pre-pours 1, 2, and 3 refer to different checks in the pre-pour process as seen in Figure 9. Pieces 1, 2, 3, and 4 refer to the bed forms that are measured during the inspections in the pre-pour process.

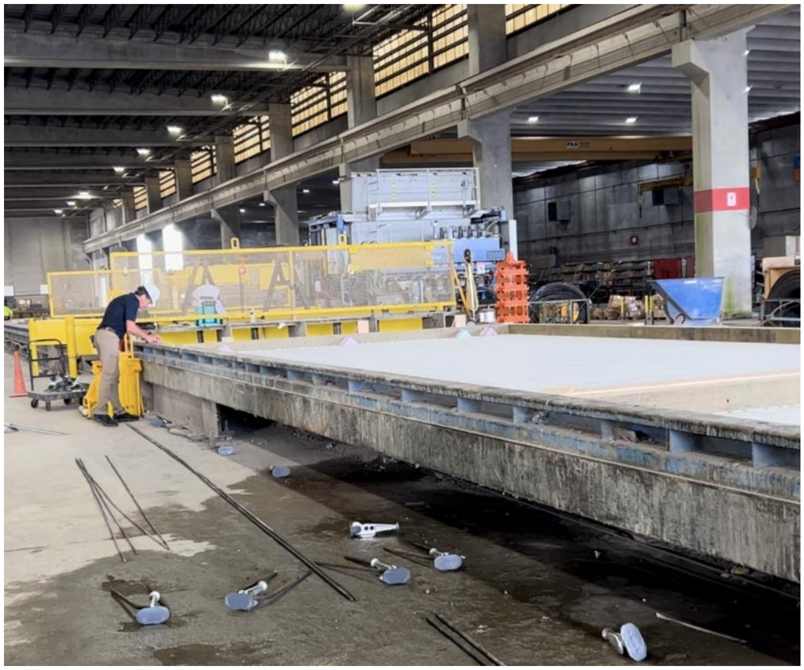

Figure 15. Pre-Pour Pieces

In Figure 15 one of the "pieces" from the pre-pour 1 is shown where the basic measurements of length, width, depth, and skewness are being measured. One thing to note is that the times for pieces 1 and 2, and 3 and 4, are the same due to both being measured at the same time. For example, pieces 1 and 2 were inspected in the same check which took 7.96 minutes, but the time was split between the two pieces to enable an easier analysis. This was the best method for measuring the pieces and overall led to a huge reduction in time. The average time to perform an inspection using the traditional methods was 14.10 minutes (14 minutes and 6 seconds) with a standard deviation of 1.58 while the average time for the laser tracker was 2.78 minutes (2 minutes and 49 seconds) with a standard deviation of 0.81. This shows an 80% reduction in time when using the laser tracker in comparison to the traditional method of using a tape measure. Additionally, the difference in standard deviation shows the laser tracker method provides more consistent times while the traditional method times are more volatile. For the analysis a one-sided t-test was performed to compare the times which resulted in a p-value of $5.49e^{-05}$. Since $5.49e^{-05} < 0.05$, there is a significant difference between the times indicating the laser tracker is the better option due to the amount of time saved in comparison to the traditional method.

Table 4. Pre-Pour Check 1 Cycle Times for Each Method

Times (Mins)	Traditional Method	Laser Tracker
Initial Setup Time	0	8.33
Process Time for Piece 1	14.27	3.48
Setup Time	0.33	N/A
Process Time for Piece 2	15.61	3.48
Setup Time	0.33	0.5
Process Time for Piece 3	11.89	2.08
Setup Time	0.33	N/A
Process Time for Piece 4	14.64	2.08
Average Setup Time Between Inspections	0.33	0.50
Cycle Time per Piece	14.43	5.36
*N/A is due to there being no setup time as piece 1 and 2 were measured in the same inspection		

Table 4 shows the cycle time of both methods where initial setup time and setup time between measurements are being accounted for. This gives an in-depth look at the process as a whole to ensure that it will be carried out normally. The initial setup time for the laser tracker took approximately 8.33 minutes (8 minutes and 20 seconds) while there was no setup time for the traditional method. This included moving the tracker from the post-pour process of the floor as the post-process is measured before the pre-pour process each day and setting up the software. The setup time between pieces for the traditional methods included switching blueprints on their tablets while the laser tracker setup time included moving the tracker to the appropriate position. The average times for the traditional method and laser tracker method were 14.43 (14 minutes and 26 seconds) and 5.36 minutes (5 minutes and 22 seconds) respectively. This shows a 63%-time reduction in the cycle time with setups included.

Post-Pour

As seen in the pre-pour results, the post-pour study results will only show a comparison of the first check due to data availability (Figure 13). The full results for the traditional QC check time study will still be shown. Similarly to the pre-pour the times for the traditional and laser tracker methods began when the Tindall QC inspector/FARO representative made the first move towards a piece to begin measurement. This was the same starting point for both methods. For the traditional method the time ended whenever the QC inspector performed the last measurement with his tape measure and checked off the conformity on his laptop. The QC inspectors carry a tablet in which each check is listed and checked off as they are inspected. Using the tablet, the QC inspector is aware of when the inspection is finished. In addition, each QC inspector follows a specific methodology in checking off different dimensions and elements of the pieces. For the laser tracker, the time ended when the last point was plotted with the laser tracker and the conformity was checked. This was considered the ending point. The FARO representative was aware of the ending point as he was provided with a demonstration of what to measure and allowed a practice run. Additionally, the QC inspector's tablet with the checkoff sheet was utilized in tandem with the measurement readings from the FARO laptop that was plotting the laser tracker points.

Table 5. Post-Pour Traditional QC Methods Process Times (Mins)

Pieces	Post-Pour 1	Post-Pour 2
Process Time for Piece 1	10.19	5.15
Process Time for Piece 2	8.1	4.64
Process Time for Piece 3	9.07	6.45
Process Time for Piece 4	9.59	5.3
Average	9.24	5.39
SD	0.89	0.76

Table 6. Pre-Pour Laser Tracker QC Methods Process Times (Mins)

Pieces	Post-Pour 1	Post-Pour 2
Process Time for Piece 1	6.93	N/A
Process Time for Piece 2	5.17	N/A
Process Time for Piece 3	5.65	N/A
Process Time for Piece 4	5.33	N/A
Average	5.77	N/A
SD	0.80	N/A

Tables 5 and 6 show the time or time taken to perform the designated QC check for each piece during the post-pour. In these tables, post-pours 1 and 2 refer to the different checks that the QC inspector performs during the post-pour process which can be seen in Figure 10. Pieces 1, 2, 3, and 4 refer to the finished pieces that are measured during the inspections in the post-pour process.

Figure 16. Post-Pour Pieces

In Figure 16, pieces from the laser tracker post-pour check 1 are being measured. The main measurements in this process include length, width, depth, and element locations. The average time to perform a check for the traditional method was 9.24 minutes (9 minutes and 14 seconds) with a standard deviation of 0.89 and the laser tracker was 5.77 minutes (5 minutes and 46 seconds) with a standard deviation of 0.80. This shows a 38% reduction in the time that it takes to perform a QC inspection with the laser tracker method in comparison to the traditional method. Additionally, the standard deviations of the two methods are similar with a small difference of 0.09 which indicates that the laser tracker method is slightly more consistent in time to complete each piece. Using a one-sided t-test, the difference in times between the methods proved to be significant as the p value 0.0005896 < 0.05, indicating that the laser tracker is the better method as it takes significantly less time than the traditional method to perform an inspection.

Table 7. Post-Pour Check 1 Cycle Time

Times (Mins)	Traditional Method	Laser Tracker
Initial Setup Time	0	13.02
Process Time for Piece 1	10.19	6.93
Setup Time	0.33	0.50
Process Time for Piece 2	8.10	5.17
Setup Time	0.33	0.67
Process Time for Piece 3	9.07	5.65
Setup Time	0.33	1.03
Process Time for Piece 4	9.59	5.33
Average Setup Time Between Inspections	0.33	0.73
Cycle Time per Piece	9.57	9.76

While Tables 5 and 6 showed the process times, Table 7 shows the cycle time. The cycle time considers setup times that the process times do not consider. This allows for a look into how the process would be performed naturally. For the initial setup time, a time of 13.02 minutes (13 minutes and 1 second) was observed for the laser tracker. This time includes setting up the laser tracker, booting it up, and calibration. This setup time is longer in comparison to the setup time in the pre-pour check as the post-pour check is the first QC check of the day which requires the daily calibration to be performed. In addition to this, an extra 0.75 minutes (45 seconds) was added to the setup time as the laser tracker used was brand new which requires extra bootup time. The bootup time took a total of 2.5 minutes and the setup/calibration accounted for 9.85 minutes. Additionally, an extra 0.67 minutes (40 seconds) was added to the initial setup time to account for setup time for piece 1. In total the setup time for the laser tracker took 13.02 minutes while the traditional methods have no initial setup time. Each method also involves setting up time between measuring pieces. For the traditional methods, a setup time of 0.33 minutes is needed per piece to set up the tablet being used with the correct blueprint. The laser tracker method included an average setup time between pieces of 0.73 minutes which included moving the tracker to a better position depending on the piece. The average times for the traditional and laser tracker methods were 9.57 minutes (9 minutes and 34 seconds) and 9.76 minutes (9 minutes and 46 seconds). With these 4 pieces there is little difference between the cycle times.

Economic Analysis

In the economic analysis, the two methods were evaluated using the labor costs to determine the better method and a ROI was performed. In order to obtain the labor costs, the average cycle times were used. The cycle times were used instead of the process times due as the cycle times provide a more accurate analysis as the setup times are included. While using the cycle times can add variability due to ununiform setup times, it still provides a more accurate insight into the cost analysis by more accurately portraying the real methods. Additionally, they could lead to a misleading cost analysis due to uncontrollable factors. While the times for the pre-pour check 2, and 3, and post-pour check 2 were not collected due to canceled production, these times were estimated to get a more accurate cost analysis.

Table 8. Average Pre-Pour Cycle Times for Traditional and Laser Tracker Method (Mins)

Methods	Pre-Pour 1	Pre-Pour 2	Pre-Pour 3
Traditional Method	14.43	11.42	22.34
Laser Tracker	4.20	3.31*	6.48*
* indciates that the time was estimated, not observed			

Table 9. Average Post-Pour Cycle Times for Traditional and Laser Tracker Method (Mins)

Pieces	Post-Pour 1	Post-Pour 2
Traditional Method	9.57	5.72
Laser Tracker	8.09	4.83*
* indciates that the time was estimated, not observed		

Tables 8 and 9 display the average cycle times for each check in both processes for the traditional and laser tracker methods. The pre-pour 2 and 3, and post-pour 2 for the laser tracker method have a * as these values were not recorded and are estimated. The estimations were found using the percent decrease in cycle time between the traditional and laser tracker methods in the first checks for the pre- and post-pour. Since all the traditional method data was recorded, the percentage difference could be used to estimate the time saved for the remaining steps. In the pre-pour process the percentage difference between the traditional and laser tracker method was 71%, which was used to find times of 3.31 and 4.83 minutes for the laser tracker method in checks 2 and 3. In the post-pour process there was a 15% difference which was used to find the time of 4.83 minutes for the laser tracker in post-pour 2 from the traditional time.

After obtaining the estimated times, a more accurate cost analysis and ROI could be performed as this provided data for each check in both processes for the traditional and laser tracker methods. The cost analysis was divided into the pre-pour and post-pour analysis to compare the two different methods.

Table 10. Pre-Pour Cost Analysis of Traditional and Laser Tracker Methods

	Traditional Method	Laser Tracker
Hours Per Day	7.23	2.10
QC Inspector Hourly Cost	$22.04	$22.04
Laborer Hourly Cost	$19.90	$19.90
QC Inspector Daily Cost	$159.35	$46.28
Laborer Daily Cost	$143.88	$41.79
Total Daily Cost	$303.23	$88.07
Yearly Cost	$63,071.84	$18,318.56
Difference	$44,753.28	

Table 10 shows the pre-pour cost analysis between the traditional and laser tracker methods using the cycle times. To find the hours per day, the average times to measure each piece for each method from Table 8 were added together and multiplied by 9. These times were multiplied by 9 as this is the average amount of pieces inspected in a normal shift at Tindall. This was confirmed by asking a Tindall representative. Only 4 pieces were measured in the time study due to time constraints and availability. Using the US Bureau of Labor Statistics (2024a) *Occupational Employment and Wage Statistics* the hourly wage for production workers was found to be $19.90 which is the pay used for laborers in this study. Bureau of Labor Statistics (2024b) *Occupational Outlook Handbook* provided the hourly pay for QC inspectors at $22.04. Laborers are included in the labor costs due to having to fix any non-conformities and assist in inspections at the Tindall plant. Using the hours per day and hourly pay a total daily cost for labor and yearly cost could be found. To find out the yearly cost, the daily cost was multiplied by 208, which is the number of days worked in a year for the pre-pour as they only operate 4 days a week. It was found that the yearly cost for the traditional methods was $63,071.84 while the laser tracker method cost was

$18,318.56. This results in savings of $44,753.28 in labor costs when using the laser tracker method.

Table 11. Post-Pour Cost Analysis of Traditional and Laser Tracker Methods

	Traditional Method	Laser Tracker
Hours Per Day	2.29	1.94
QC Inspector Hourly Cost	$22.04	$22.04
Laborer Hourly Cost	$19.90	$19.90
QC Inspector Daily Cost	$50.47	$42.76
Laborer Daily Cost	$45.57	$38.61
Total Daily Cost	$96.04	$81.36
Yearly Cost	$19,976.86	$16,923.63
Difference	$3,053.23	

Similarly to Table 10, Table 11 shows the post-pour cost analysis. The yearly cost for the traditional method was $19,976.89 while the laser tracker was $16,923.63. This results in savings of $3,053.23 in labor costs when using the laser tracker method instead of the traditional method. Combing the savings from both the pre- and post-pour methods results in total savings of $47,806.51. The big opportunity for savings is the implementation of the pre-pour methods.

Table 12. Cost Savings of the Laser Tracker Implementation

Total Cost Difference	$47,806.51
Tracker Quote Price	$109,464.70
ROI	43.67
Pay Off Time (Years)	2.29

Table 12 shows the ROI for the implementation of the laser tracker into the QC methods. The total cost difference or amount saved using the laser tracker came out to $47,806.51. FARO quoted the laser tracker at $109,464.70. The breakdown of the quoted price can be seen below in Table 13. Using this cost difference, the tracker quote price of $109,464.70

an ROI of 43.67 is found with a payoff time of 2.29 years (1 year and 340 days). According to FARO, the lifespan of a Vantage Laser Tracker is 10-15 years. Using the median life span of 12.5 years and subtracting the 2.29 years of pay-off time gives a result of nearly 10.2 years of savings. If $47,806.51is saved annually for 10.2 years, the laser tracker would save a total of $487,626.42 not considering increases in wage after the tracker's investment is paid off. One thing to note is that with the quoted price provided by FARO the laser tracker is only under warranty for 3 years (Table 13). This means that if the tracker breaks or needs repairs FARO will cover the costs for the first 3 years. With the plan in the quote, a loan device is not offered for free, but one can be rented. Additionally, after three years if there is an issue with the tracker FARO will still fix it, but for a charge depending on the fix.

Table 13: Laser Tracker Quoted Price Break Down

Item	Quantity	Cost
Tracker Vantage E	1	$64,404.00
Cables	1	$170.00
Reflector Piece	2	$3,366.00
Target Tooling Kit	1	$3,897.00
Stand and Softcase	1	$3,600.00
Stand Extension	1	$495.00
Remote	1	$330.00
Notebook Laptop	1	$3,231.00
3 year warranty	1	$8,586.00
Single User Hard Lock	1	$220.00
CAM2 Probing Software	1	$8,505.00
Tracker TR Cam2 Upgrade	1	$5,751.00
Taxes	N/A	$6,785.01
Shipping Cost	N/A	$124.69
Total Cost	$109,464.70	

Additionally, another annual cost to factor in are software updates. Under the current quoted price, whenever the purchase is made that software version is purchased as well.

This can be seen under the CAM2 Probing Software in Table 13. With the purchases from the quoted price, the first year of updates and maintenance is covered while every year after it will cost an estimated $1,950 annually. While these annual updates are highly encouraged, they are completely optional. The laser tracker will continue to operate even without the most up to date software. The quoted price includes all the options available, meaning that this is the “high end” version of a deal. The essential pieces of the quoted price would include the Tracker Vantage E which is the tracker, the reflector pieces, stand and soft case, remote, and probing software. This total with the essential pieces would equate to $80,205. In regard to training, in the quote price training would be included in the Tracker TR Cam2 Upgrade which includes site training for up to 4 people over consecutive days (number of days not specified) to ensure proper transfer of knowledge.

Discussion

The purpose of this study was to evaluate laser tracking technology for the integration of QC methods in precast concrete. This evaluation compared the laser tracker method to traditional methods by using time studies, accuracy measures, and an economic analysis. The purpose was to determine whether laser tracking can alleviate issues associated with the traditional methods including human errors in accuracy and long measurement time. This study addresses a new area of research as previous studies include the implementation of laser scanners rather than laser trackers. In addition, laser scanners address the associated limitation with laser trackers of excess time required to perform inspections.

Although data collection was limited, the study still presents key findings that can be expanded upon in the future. The first key finding was the time saved using the laser tracker methods in comparison to the traditional methods in both pre- and post-pour which was an 80% reduction and a 38% reduction respectively. Additionally, a 63%-time reduction was found in the cycle time of using the laser tracker method in comparison to the traditional method. This shows that using the laser tracker can significantly save time in comparison to the traditional method and is the better choice. Another key finding is the labor cost difference between the two methods in a year. Using both the observed and estimated cycle using the laser tracker instead of the traditional method would save $47,806.51 annually. This alone would pay off the tracker cost in a little over 2 years.

The results for the time study were broken into the pre- and post-pour which allowed for a comparison of the different methods at each stage. Due to the cancellation of production during the visit for the laser tracker, only a time study for the first pre- and post-pour check was able to be conducted, while data for each check in the traditional methods was obtained. This allowed for only a comparison of the first check between the traditional and laser tracker methods. The average time significantly decreased by nearly 8 min, or 80%, for the process times during the first check in the pre-pour from the traditional methods to the laser tracker QC methods. One factor that can be attributed to the huge time difference is the way in which the pieces were measured in the laser tracker time study. Using the laser tracker allowed for multiple pieces to be measured at the same time as it was the most efficient method in contrast to the traditional method where pieces have to be measured one at a time. This huge difference could also be because of the specific pieces or forms measured in the pre-pour check 1 that allowed for this. Different forms could allow for more efficient or slower times for the laser tracker, which indicates the need for further testing. Looking at the pre-pour cycle times for check 1, which included the fixed times of initial setup times and setup time between pieces, the average time for the traditional method is 14.43 minutes per piece. This time included non-initial setup time and an average setup time between pieces of 0.33 minutes. In comparison, for the laser tracker cycle time, the average time was 5.36 minutes which resulted in a 63% reduction of time. One important thing to note is that on a normal day of production at Tindall, the QC inspectors will inspect 9 pieces on average. This means that the gap between the process times will continue to increase as the fixed times of the setup is diluted. Four pieces were used in the time study for this study due to time limitations. Overall, these findings suggest that the laser tracker can greatly reduce the time taken to perform QC checks in the pre-pour method and is the better alternative. With the pre-pour inspections currently taking the most time per piece the laser tracker implementation could significantly reduce the time taken. Although these results are promising, this comparison was only done for 4 pieces in one check, further research is needed.

For the post-pour time study, times for the traditional QC methods were found for both the first and second checks while the laser tracker methods only included a time study for the first check. While having the second check time would be helpful, the laser tracker would not commonly be utilized in this check as the bottom check is mainly for deformities rather than measurements. For the first check in the post-pour, the average process time showed a 38% reduction in time taken to perform the checks when using the laser tracker method. While not as large of a difference as the pre-pour, the difference is still statistically significant and shows the laser tracker as the more efficient method. One thing to note is that the first piece measured by the tracker is higher than the others. This can be attributed to the FARO representative going at a slower pace to get comfortable with the QC inspection and ensuring that each piece is measured. There may be an even greater difference in time due to the learning curve. If the FARO representative had the same experience as the QC inspector, the times could be even lower. Looking at the cycle times, the average time of the two methods are 9.57 minutes for the traditional method and 9.81 minutes for the laser tracker. On the surface level, these times appear to signify the traditional method as the better method however, this is not the case as the times are not meaningfully different. This difference can be explained by the large initial setup time. Since the post-pour QC inspection is the first to occur during the day, the laser tracker must be set up, booted up, and calibrated before use. This contributed to 12.35 minutes of initial setup time while the traditional methods did not have a setup time. In addition, the average setup time between pieces for the traditional time was 0.33 minutes while it was 0.95 minutes for the laser tracker. This led to a quicker cycle time for the traditional method in contrast to the laser tracker. Only measuring 4 pieces in this study made the traditional method appear as the best method in regard to cycle time which is misleading. In a normal day 9 pieces on average are inspected which would result in the gap between the average and total times growing as the setup time becomes less of a factor in the data. This in turn would cause the laser tracker to have shorter cycle time. Another factor that could have potentially influenced the times is the variability in the setup time between pieces in the traditional methods. As the inspectors get more familiar with the setup the optimal location for the laser tracker could be identified which can measure more pieces without the need of constant movement. While the results indicate that the laser tracker can save time, more research is needed.

While there are no previous studies utilizing laser trackers for the QC methods of precast concrete, there are research studies utilizing laser scanners. While laser trackers are used as a tool similarly to the tape measure, a laser scanner works on its own by scanning a piece or building by itself. A big limitation with the application of laser scanners is the time required to produce measurements from scans. While this is useful in large scale operations such as buildings or large rooms, in a small-scale application such as a QC tool the laser tracker proves to be better. This can be seen in the study by Aziz et al. (2016) where it took nearly 2 hours for 4 scans to be completed. This is important as this provides new research in the area of improvement for QC processes where this research provides alleviation for a major limitation from previous research.

Due to the cancelled production, accuracy data was not collected. To perform the accuracy measurements, it was essential to be able to use the laser tracker on each pre-pour check. This would allow for non-conformities to be tested for by the tracker and results could be found from the number of non-conformities found in the post-check. The accuracy comparison is critical to the evaluation of the two methods as non-conformities are a big issue in which the laser tracker could be a possible solution. If the laser tracker was able to reduce non-conformities in addition to reducing time the payoff would be tremendous. Liu et al. (2018) and Kim et al. (2014) were able to measure at a higher accuracy in tolerance using laser scanners rather than traditional methods. While these studies used automated scans instead of a tool like the laser tracker it is possible that the laser tracker could improve accuracy in comparison to the traditional methods. The laser tracker could also address issues of human error such as mixing up measurements or not being accurate with the tape measure. While the accuracy measurements were not able to be performed in this study, future studies should carry this out for a fuller evaluation.

With limited data, an economic analysis was still able to be performed. This economic analysis was performed by finding the yearly labor costs associated with each method and comparing the two. While there was only complete time study data for the traditional methods, the percentage difference between the two methods in the first checks for the pre- and post-pour could be used to obtain estimated time values for the missing times in the laser tracker time study. This allowed for a more accurate and comprehensive estimation of the cost analysis and ROI. The cost analysis was done by finding the hour per day that the QC inspectors and Laborers spend per day on the inspections and the hourly pay associated with each role. The pay rate was found from the US Bureau of Labor Statistics which was a median pay of $22.04 for QC inspectors and $19.90 for laborers. One thing to note is that the hourly pay could be different as these rates were for QC inspectors as a whole and general laborers in the manufacturing industry. In the pre-pour process, a total yearly labor cost was found using each check for both pre- and post-pour processes. The yearly cost was $63,071.84 for the traditional method, and $18,318.56 for the laser tracker method. This results in savings of $44,753.28 in labor costs for a year if the laser tracker is used instead of the current traditional methods. In the post-pour process the yearly cost was $19,976.89 for the traditional method and $11,949.60 for the laser tracker method. This resulted in a savings of $7,155.20 in labor costs in a year if the laser tracker is used in the post-pour process. In both processes the cost analysis showed that using the laser tracker method saves in labor costs which indicates the laser tracker is the better method. In total, the laser tracker could save $47,806.51 a year in labor costs. This is a significant amount of money and shows the extent to which the traditional methods lack efficiency in comparison to the laser tracker. In the ROI, the total cost difference of $47,806.51 in addition to the FARO quote price of the laser tracker of $109,464.70. This resulted in an ROI of 43.67 and a payoff time of a little over 2 years. FARO stated that the lifespan of the Vantage Laser Tracker is 10 to 15 years. Using the median life span of 12.5 years, after the tracker is paid off this gives nearly 10.5 years of use before a new one is needed. This means 10.5 years of saving $47,806.51 which would result in saving nearly $600,000 over this time span. This shows the total potential in savings and impact that implementing the laser tracker could have.

While this economic analysis only considers labor costs, there could be additional savings from preventing non-conformities. If the accuracy study was able to be performed the results would have been factored into the economic analysis. The first step in doing this would be to first determine which non-conformities can be attributed to the QC inspector/process itself as some are out of the control of the inspector. Non-conformities can occur during the curing or smoothing process in which the pre-pour prechecks have already been completed. The next step would be testing, which would be performed in the pre-pour process. In theory, if there are non-conformities found in the post-pour, it can be assumed that a non-conformity was missed in the pre-pour. In turn, this would result in lower accuracy unless this non-conformity was identified to be caused outside of the control of the inspector. Ideally all non-conformities should be caught in the pre-pour check. The accuracy rate of the traditional QC method would be determined from the historical non-conformity data from Tindall, while the laser tracker method would perform the accuracy test in the pre-pour process. The accuracy test would include using the laser tracker for the inspections in the pre-pour process and finding the number of non-conformities out of possibilities. For example, if the utilizing the laser tracker enabled the operator to correctly identify 485/500 elements or measurements within tolerance while missing 15 non-conformities this would result in a 97% accuracy rate. Using the difference in accuracy percentage from the test, a cost saved value could be calculated. To find the cost saved value, an average daily cost would first be found and associated with the current non-conformity rate caused by the traditional method. Using the daily cost value of non-conformities, daily savings of using the laser scanner could be calculated by using the percentage difference. This daily cost could then be estimated into an annual savings and be included in the cost analysis. If the laser tracker showed no improvement or proved to be worse, the cost analysis of the non-conformities would still be included as this is still valuable to the evaluation. The difference in percents and daily number of non-conformities found that can be attributed to the traditional method. The accuracy rate of the tracker the current accuracy rate Using these accuracy rates, the average number of daily non-conformities, and associating an average cost   Another limitation of the economic analysis was the estimated times used. The times for the laser tracker method in checks 2, and 3, in the pre-pour and check 2 in the post-pour were estimates based off the collected percentage difference in the first checks in between the two methods in both processes. While it provided a good base to perform an economic analysis and ROI it cannot be assumed that the time differences will follow the same trend as they did in the first checks. This further highlights the need for further research and additional studies as this only serves as a rough estimate.

While the data provided shows promising insights into the evaluation of the laser tracker QC methods, there are limitations that need to be addressed. This will allow for proper interpretation of the results. As stated previously, due to cancelled production data collection was impeded resulting in time study data for only the first checks in both processes for the laser tracker. This limited the data analysis to a comparison of the first checks only and not the entire process. This inhibited accuracy as well, as there were not enough data points to perform an analysis. Outside of the missing data, another limitation is the small sample size. Due to the availability of FARO and Tindall only 4 pieces were analyzed whereas during their shift QC inspectors will perform inspections on 9 pieces in each check on average. Additionally due to the small sample size, only a small variety of pieces were able to be inspected. There could be other pieces that are more complex which may lead to an increase in the time taken to inspect the piece for either method. Another limitation to be noted is the familiarity of the inspectors with each method during their respective methods. While the FARO representative observed a demonstration before performing the inspection with the laser tracker, there was still some unfamiliarity and hesitation with what to measure. This could cause variability in the recorded times in comparison to the Tindall QC inspector who performs the same checks every day.

While there are limitations in the study, the data collected, and analysis performed provides valuable insight into the benefits of implementing laser trackers in the QC process. With all of the current research of implementing laser scanning technology in precast concrete QC methods consists of implementing laser scanners, this study presents new insight into the implementation of laser trackers. This provides a window into a new area of research and opportunities for new and further research to be carried out. With the opportunity for future research, the current research should be expanded upon, and the limitations of this study should be addressed to allow for a full analysis.

Conclusion

This study aimed to evaluate the implementation of laser tracking technology into the QC methods of precast concrete in comparison to the traditional method of using a tape measure as a baseline. The evaluation consisted of comparing time studies, accuracy measures, and an economic analysis. While data collection was limited due to unforeseen circumstances, enough data was obtained to indicate that implementing the laser tracker into the QC methods can significantly improve the current traditional methods.

The main findings of this study include valuable time study and cost analysis data. The time studies performed showed an 80%-time reduction to perform an inspection in the pre-pour check 1- and 38%-time reduction in the post-pour check 1 when using the laser tracker in the QC methods. These times proved to be significantly different, indicating the laser tracker as the better method. The cost analysis showed an estimated savings of $47,806.51 in annual labor costs from just the pre- and post-pour processes. This indicates more can be saved when analyzing the rest of the checks and further emphasizes the need for further research for more insight. While the accuracy analysis was intended to be a big part of the evaluation, it could not be performed due to the canceled production. However, previous studies indicate that a reduction in non-conformities is likely, further pushing the need for future research. In addition to future research addressing the shortcomings of the data collected, larger sample sizes that mimic a typical day of inspection and a variety of pieces should be analyzed.

Current research of laser scanning technology provides insight into the implementation of laser scanners rather than laser trackers, which this study provides. A limitation of laser scanners in the QC process includes the excess time taken to perform an inspection. Laser trackers help optimize the time taken to perform inspections and directly address the main limitation of laser scanners. It also provides a new area of research as the majority of current research involves laser scanners rather than laser trackers. Although limited in data, this study provides an evaluation and valuable insight into the application of laser scanning technology in QC for precast concrete that can be used as a foundation for future studies.

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Vita

Blake A. Barbay grew up in Sunshine, Louisiana and graduated from Louisiana State University (LSU) with a Bachelor of Science in Industrial Engineering in December of 2022. Left with the feeling of wanting to learn more, he decided to stay at LSU and pursue his master's degree in industrial engineering the following semester.

During his graduate studies, Blake was an operations intern at JBS in Greeley, CO where he focused on waste minimization and process improvement. In addition to being an intern, he also served as a teaching and research assistant for the department of mechanical and industrial engineering in his time as a graduate student. In his research assistantship, he was able to contribute research on laser scanning technology for the improvement of quality control methods of precast concrete. He plans to receive his masters in December of 2024.