

Proceeding Paper

Integrating Lean Six Sigma with Sensors and IoT Monitoring Technologies to Optimize Efficiency in Construction Projects [†]

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Abstract: The research focuses on improving construction project workflow efficiency using a hybrid scheme of Lean Six Sigma and monitoring sensors. Real-time data and automated monitoring improve project timeframes by detecting waste and eliminating inefficiencies. The study found that delays were primarily caused by long lead times, delayed order placements, and job rework. The sensor-enhanced EOQ model and CiteOps software reduced delays, highlighting the importance of continuous technology integration for long-term efficiency and sustainability in building projects.

Keywords: Lean Six Sigma; monitoring systems; IoT sensors; workflow efficiency; construction project management

1. Introduction

The success of construction projects is largely dependent on their efficient administration. Construction projects are prone to unforeseen events, wasteful and unnecessary expenditures, and overspending, which can raise the risk of project delays and errors that lower the quality of work completed (Van Den Bos, 2014). Construction companies seek to improve process efficiency by streamlining workflows and focusing resources on tasks that directly impact project success while reducing costs. This is achieved through the application of the lean six sigma approach. Lean Six Sigma (LSS) integrates Six Sigma and Lean concepts to reduce waste and enhance process quality. LSS can be used to find and fix inefficiencies in the construction industry, like delays, rework, and material waste. LSS uses an organized method called DMAIC (Define, Measure, Analyze, Improve, and Control) to accomplish these objectives (Al-Aomar R., 2012).

This study's main goal is to investigate, classify, and identify the different inefficiencies that exist in the construction sector while also developing an all-encompassing framework that is founded in lean six-sigma methodology and smart technology. The quality, cost, and schedule efficiency of lean construction methods are to be measured and contrasted using this framework (Abdelhamid, 2003). The integration of Lean Six Sigma with cutting-edge technical tools like monitoring sensors, IoT solutions, and soft robotics is essential to improving the workflow efficiency of construction projects. In the study under review, inefficiencies are found and eliminated to enhance project deadlines through the use of real-time data and automated monitoring (Rane et al., 2023). CiteOps software and IoT sensors were used in the study to improve real-time project parameter monitoring and enable dynamic alterations that greatly improved overall efficiency. By using these advances, the research identifies important inefficiencies in building operations and provides cutting-edge solutions to mitigate them.

The DMAIC framework finds wide application in construction optimization projects. It is often used to enhance precast manufacturing quality, identifying defects and their

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causes (Agenbag and Amoah, 2021). A Brazilian construction firm adopted the Lean Six Sigma to restructure its management system adopt Lean Six Sigma, reducing waste and variability (Bravo, 2020). The DMAIC was employed to improve groundwork quality, eliminating errors and inefficiencies (Nowotarski, 2019). The SME productivity and quality was enhanced by employing the DMAIC, yielding significant improvements (Soundararajan, 2020). The DMAIC was also applied to study and improve construction project performance (Maryam, 2010). These studies highlight DMAIC's effectiveness across various construction processes.

Real-time and automated monitoring of several construction processes is now possible because to advancements in sensor technology and the Internet of Things (IoT) (Bucchiarone et al., 2019). Construction waste management is made possible by real-time monitoring enabled by sensing and IoT, which improves environmental sustainability and lessens environmental impact. Sensors are positioned around construction sites to capture data in real-time, enabling continuous monitoring of many aspects such as labor productivity, machine performance, material availability, and environmental conditions (Bucchiarone et al., 2019). Through the use of CiteOps software, the perception sensors identify inefficiencies and notify project managers of problems including equipment failures, work-flow bottlenecks, and material delays.

In this perspective, the integration of IoT technologies with CiteOps software is especially noteworthy. As a command center, CiteOps gathers data from a range of IoT-enabled devices and provides project managers with this data in a format that they can use (Bucchiarone et al., 2019). This facilitates prompt decision-making, the capacity to predict project obstacles, and the adaptability to adjust workflows. Moreover, the program facilitates automated task execution, which enables the system to modify some procedures on its own without requiring human input. In conventional construction environments, inefficiencies like protracted lead times for material acquisition, postponed order placements, and job rework because of mistakes or misunderstanding are frequently blamed for project delays. These issues tend to compound, leading to major delays and increased project costs. Through the use of IoT sensors and real-time monitoring, the research found that such delays can be dramatically reduced (Bucchiarone et al., 2019).

2. Methodology

In order to maximize railway fence construction project performance, the research integrates cutting-edge technology including IoT sensors and CiteOps software for real-time monitoring and problem detection. It also uses the DMAIC Lean Six Sigma framework. This framework integrates techniques for gathering and analyzing data in order to pinpoint inefficiencies, evaluate their consequences, and suggest solutions.

Phases for data gathering and analysis make up the research design. IoT sensors are integrated onto the building site to track workflows, equipment, and material movements. These sensors provide feedback data to CiteOps software, which detects inefficiencies like material delays, workflow bottlenecks, and equipment problems and instantly alerts project managers.

Time studies are used to calculate the difference between planned and actual activity. The gathered data is validated using descriptive statistics, which also help to determine distribution curves, dispersion, and central tendency. The data is analyzed using the DMAIC framework where the first stage of the framework consists of defining and identifying the cause of the problem, in this case, project inefficiencies. The value stream map is designed using Microsoft Visio, it is used to identify non-value-adding activities which could potentially result in project inefficiencies. The second stage of the DMAIC framework is the analyze phase, in this phase, the previously identified activities are analysed and quantified to determine their impact on project inefficiencies and they are ranked accordingly. To efficiently analyse these activities, a control chart is used to quantify these inefficiencies. Factor analysis is then used with data recovered from IoT sensors to determine the impact of these inefficiencies and rank the most significant causes of

inefficiencies. The Economic Order Quantity (EOQ) model is used in the “Improve” phase of the DMAIC framework to forecast the optimum quantity and timing of material orders in order to maximize construction inventory management. For real-time performance tracking, data from sensors and manual inputs are gathered into a centralized database and presented using Microsoft PowerBI. Software for scheduling and planning increases output and worker accountability, while IoT-based data helps with decision-making.

The data gathered during this time is presented in the tables and figures below. It is validated using statistical methods. Tables 1 and 2 below show the mean, median, standard deviation, mode, variance as well as the range for all the project delay factors identified.

Table 1. Description statistics for data validation.

	Lead Time	Ordering Time	Job Completion
Mean	112.2	6.33	97.33
Median	70.5	3	80
Standard Deviation	105	7.06	70
Mode	327	0	0
Variance	11015	50	4874.27
Range	318	16	193
Confidence Interval	75-150	3.8-8.9	42-153.2
Skewness	1.099	0.66	0.622

The data presented in Table 1 above shows the measures of central tendency such as the mean, median and the mode for lead time, delays in ordering time as well as the number of days it takes to complete assigned tasks. The mean signifies the average value of each of the factors presented in the tables. This is the balance point of the dataset, the typical value and behaviour of the dataset.

The median is the middle value of the dataset for each of the factors presented in Table 1. This is the point where the dataset is divided into two parts, half of the values lie below these values and the other half lie above this value. This is important for skewed distributions. The mode shows the most common value in the dataset, this is also presented in Table 1. It is used to describe the most typical observation.

Table 2. Description statistics for data validation.

	Inspection Delays	Training Days	Delays due to Weather	Limited Equipment Availability
Mean	25.25	8.4	2.37	1.6
Median	27	2	1.5	1
Standard Deviation	4.69	14.89	2.13	1.26
Mode	27	1	1	1
Variance	22	221.8	4.55	1.6
Range	12.5	34	6	3
Confidence Interval	21.5-29	-26.1	0.89-3.85	0.82-2.38
Skewness	-1.443	1.33	1.363	1.42

Factors such as inspection delays, training days, delays due to changes in weather as well as limited equipment availability are shown in Table 2 above. Table 2 shows the measures of central tendency for these factors. These measures are used to determine the data skewness which is presented in the figures below. It may be expected for the lead time delays, days spent on training, delays due to changes in weather, and delayed ordering time to be positively skewed and inspection delays negatively skewed.

Figures 1–3 presents the skewness of lead time, delay in job completion, delays in order placement and equipment availability. All these figures indicate that the data for

these factors is positively skewed. In this case, it is expected for the mean to be greater than the median and the mode. There may be a few outliers pushing the mean higher than the median. The skewness of the data indicates that the distribution is not symmetrical, and the bulk of the data is concentrated towards the lower end, with a few exceptionally high values on the right side.

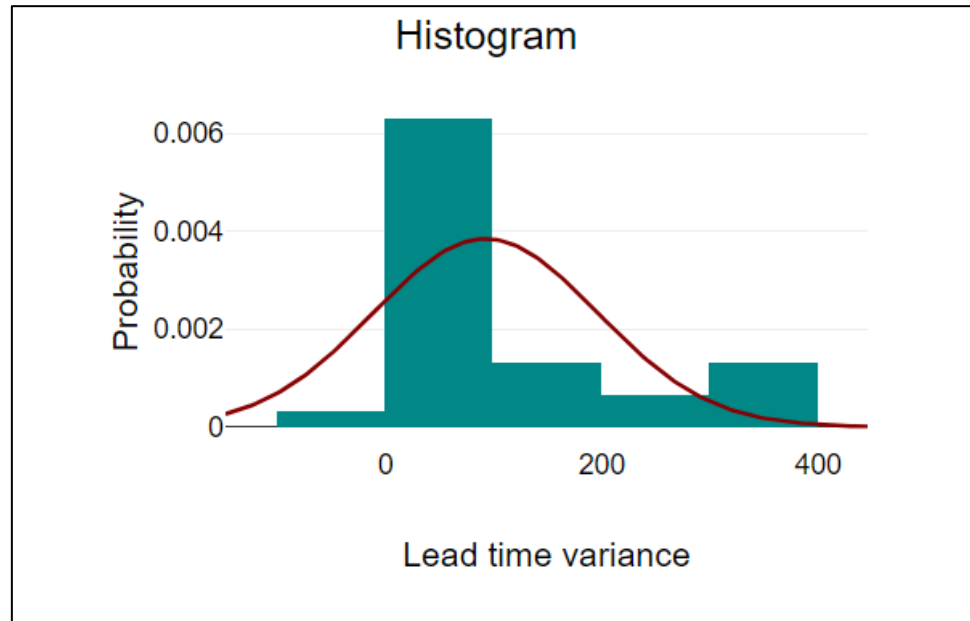


Figure 1. Histogram showing positive skewness for lead time variance.

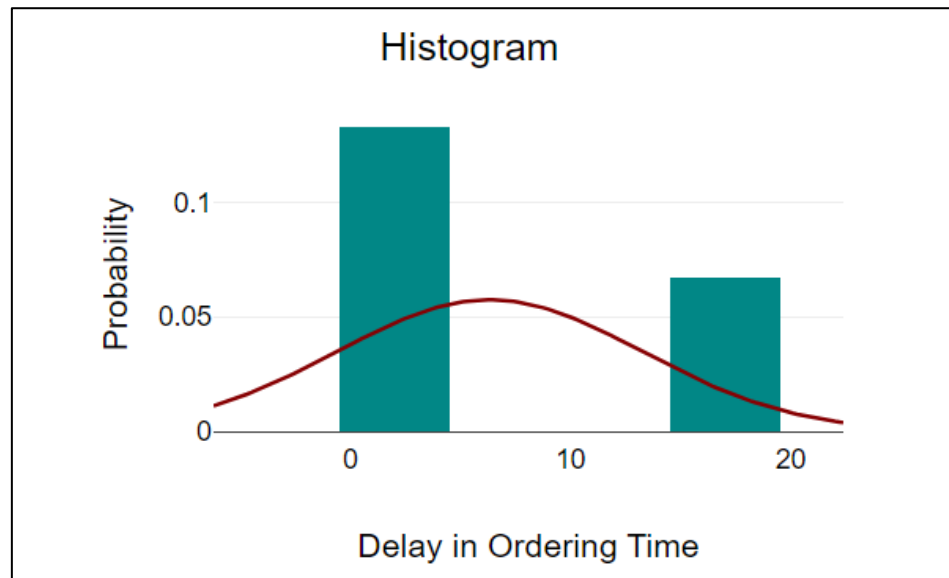


Figure 2. Histogram showing positive skewness for delays in ordering time.

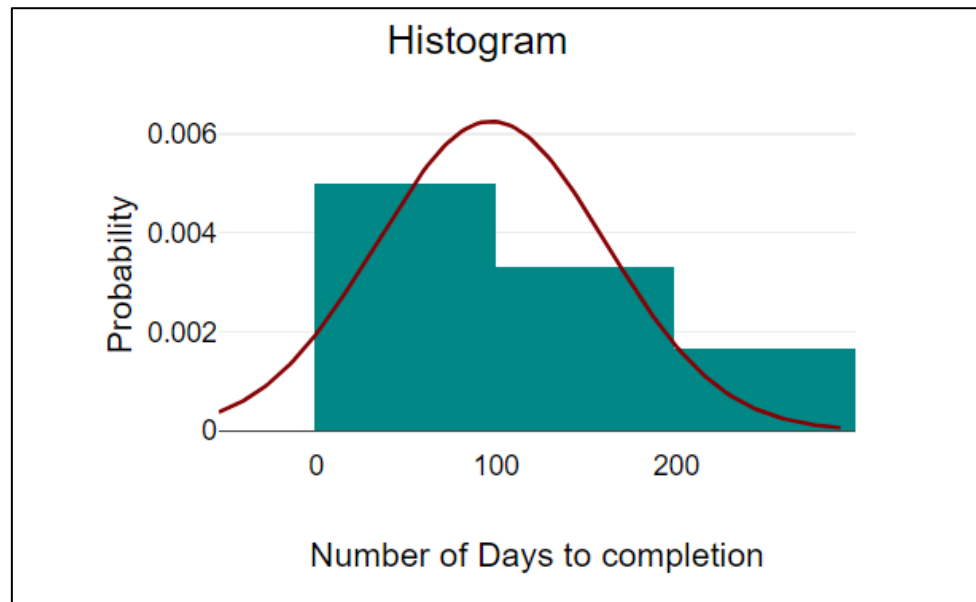


Figure 3. Histogram showing positive skewness for number of days to complete jobs.

Figure 4 presents the factor that consists of negatively skewed data. This skewness indicates that the distribution is also not symmetrical, and the bulk of the data is concentrated towards the higher end, with a few exceptionally low values on the left side. The skewness of the data may signify data randomness. Data typically follows a normal distribution, but imperfections in the data collection can introduce randomness. A skewness close to zero indicates a normal distribution with less outliers and variation. Factors like lead time, inspection frequency, and weather conditions can introduce randomness in the data set. This data-set’s skewness and few outliers ensure data validity.

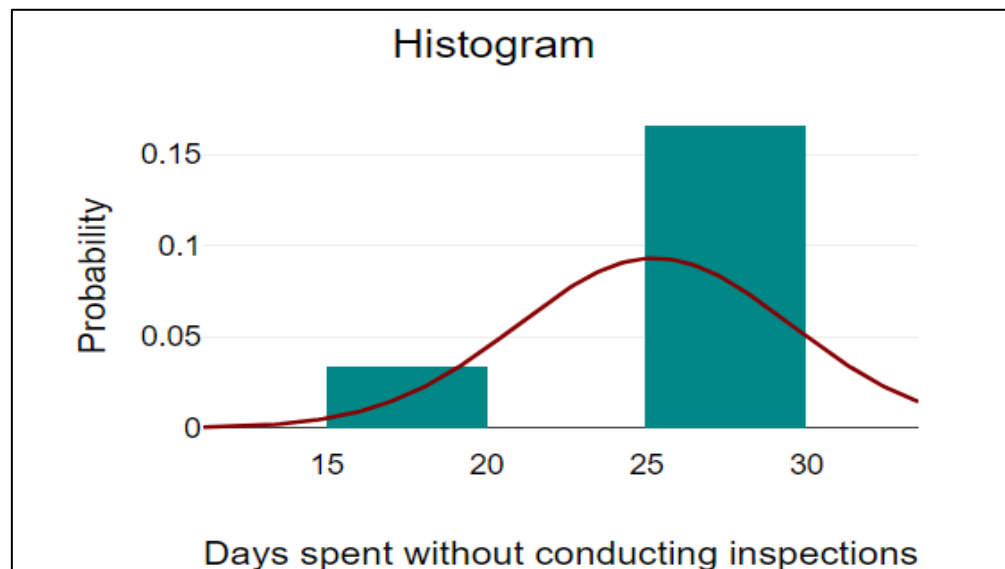


Figure 4. Histogram showing negative data skewness for days spent without conducting inspections.

3. Results

The first phase of the DMAIC approach concentrates Defining the problem and diagnosing inefficiencies. At four crucial project stages—the design phase, excavation and clearing, foundation formation, and fence construction—waste is identified using a value stream map, or VSM. Project managers are notified of inefficiencies including equipment

failures, workflow obstructions, and material delays when IoT sensors coupled with CiteOps software monitor equipment, workflows, and material movements in real-time. Due to erroneous measurements and equipment malfunctions, the design and excavation phases saw the most delays.

Figure 5 presents the value stream map (VSM) showing each stage of the construction project and identifying factors that could potentially introduce inefficiencies. A project redesign and a drawn-out approvals process resulted in major delays throughout the design phase. Bottlenecks in communication may have been identified sooner by IoT devices. Frequent machine breakdowns were found during the excavation phase, but delays were prolonged by unscheduled maintenance and shortages of parts. Erroneous methods caused delays in the foundation-forming phase, necessitating rework. There were also reports of other delays, such as protracted material lead times and problems with project fund release. IoT sensors are being used to monitor any weather-related delays in the continuing fence building. When combined with IoT data, the VSM in Figure 5 offers a thorough understanding of the project, empowering project managers to spot inefficiencies early on and take appropriate action to improve decision-making and cut down on delays.

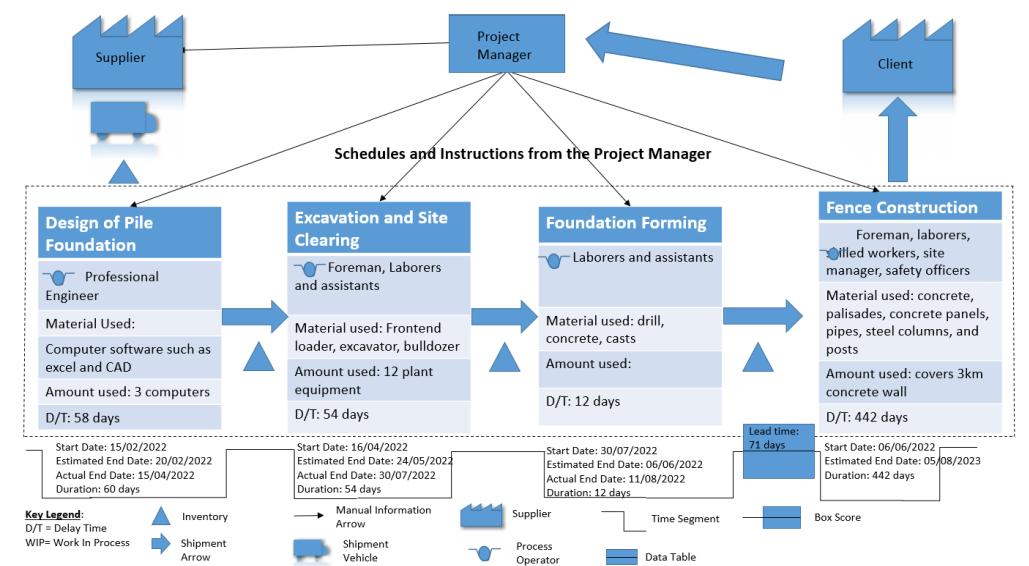


Figure 5. Value stream map showing non-value adding activities in the construction project.

The project involved collecting real-time data from IoT sensors to monitor equipment, material movements, and workflows. The data shown in Table 3 illustrates the number of delays per project activity. These sensors provide detailed insights into inefficiencies, such as equipment breakdowns or material shortages, and help identify, measure and understand the extent of the problem.

Table 3. Delay days shown for each project activity.

Delay Description	Delay Days
Awaiting for permits and occupation	35
Induction	14
Lead time for construction material	21
Project funds by client	25
Redesigning of the wall and Engineer's approval	58
Pouring of concrete for foundation reworked	12
Weather conditions	7
Casting of concrete panels	32
Inspection of project progress	2
Political interference	3
Employee go-slow	3
Equipment breakdown	5

Control charts, shown in Figure 6, are used to visualize and analyze the delay data, plotting delay days, type of delay, mean, lower, and upper control limits. These charts help detect issues and find solutions for delays, tracking process variability to determine if a process is out of statistical control. IoT sensors continuously feed data into the CiteOps software to create these charts, capturing variations in real-time, such as sudden equipment failures. The control variation (CV) is calculated using the formula:

$$CV = \frac{\sigma}{\bar{x}} \times 100 \tag{1}$$

Which is the standard deviation (σ) divided by the average delay days (\bar{x}) multiplied by 100. This percentage gives an indication of how variable the process is. The control variation for this procedure, with an average of 18 and a standard deviation of 17, is 95%, which is much too high. The permissible deviation should ideally not go above 40%. Lean Six Sigma approaches will be used to lower the high variation and the frequency of delays, with the help of IoT sensors continuing to deliver real-time insights and enabling quicker process adjustments. Factor analysis was used in the "Analyze" phase of the DMAIC framework. The purpose of this is to identify and pinpoint the reasons behind the delays encountered in this particular project. It also involves determining the inefficiencies that have the biggest impact on the project.

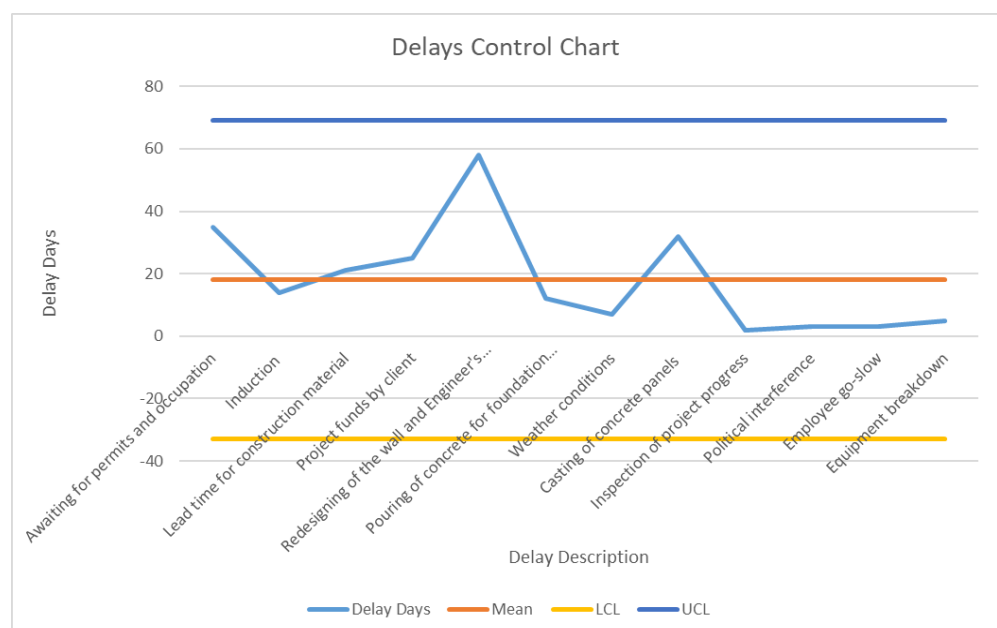


Figure 6. Project delays quantified by means on control charts.

The eigenvalues shown in Table 4 are important in figuring out how many elements need to be looked at in more detail. A factor is deemed irrelevant if its eigenvalue is less than one, and it is eliminated from additional analysis because it does not significantly contribute to the overall percentage variance. Finding and analyzing the elements that have the biggest effects on the variance is the main goal. Using the following formula, the percentage of variance was determined:

$$\frac{\text{Eigenvalue of factor}}{\sum \text{Eigenvalues}} * 100 \tag{2}$$

A factor is deemed irrelevant if its eigenvalue is less than one, and it is eliminated from additional analysis because it does not significantly contribute to the overall percentage variance. Finding and analyzing the variables that have the most effects on the variance is the main goal. It is clear from the data in Table 4 that factors 1, 2, and 3 account for the majority of the variation in total. Therefore, there will be much greater control over the entire process by lowering the variability related to these components. The project’s planning procedure will consequently see a notable improvement.

Table 4. Eigenvalues for each project activity.

Component	Factor name	Eigenvalues	% of variance	Accumulated %
1	Material lead time	2.93	48.86	48.86
2	Delay in ordering time	1.66	27.64	76.5
3	Reworking jobs description	1.27	21.25	97.75
4	Equipment availability	0.1	1.63	99.39
5	Days spent without conducting inspections	0.04	0.61	100
6	Number of days of rain	0	0	100

The analysis phase aims to improve the identified factors, revealing that lead time for materials significantly impacts project delays and is significantly influenced by order placement duration. In the “Improve” phase of the DMAIC framework, the EOQ model is used to calculate optimal time and quantity for placing orders using differential equations. This model specifically assumes that items do not deteriorate over time. Notations used for the model are as follows:

- Q* Optimal quantity of inventory
- D Demand of the inventory (How much is being used during construction)
- t Material storage time before use

- p Purchase price for the item
- V Quantity after the effects of demand or deterioration or both

The company had specified a budget for material of R30 000 000 out of the total project cost of R52 000 000. Using the following information, the EOQ model is applied using equation 3 and 4 below:

$$Q_j^* = \frac{4 \cdot V^2 \cdot D_j}{\sqrt{p_j \left(\sum_{j=1}^n D_j p_j \right)^2}} \tag{3}$$

$$T = \frac{\sqrt{\frac{4 \cdot V^2 \cdot D_j}{p_j \left(\sum_{j=1}^n D_j p_j \right)^2} + Dt}}{D} \tag{4}$$

The values represented in Table 5 were determined using these formulae for frequently used inventory.

Table 5. Recommended optimum order quantity and order time.

Material	Quantity Used (Units)	Reordering Days	Purchase Price (R)	Optimum order quantity (Units)	Optimum order time (days)
Panels	86	33	850	261	36
Cement	230	30	80	5529	54
Palicades	158	141	950	163	142
Columns	58	32	1500	136	34
Rods	100	93	500	537	98

By utilising T and Q*, individuals are able to ascertain the optimal timing for ordering additional materials. This strategic approach facilitates improved project planning and effectively reduces the delay period for the delivery of construction materials, thereby preventing any interruptions in the project’s progress.

The following phase in the DMAIC framework is the control phase where the improved processes are monitored in real-time and controlled. When combined with IoT sensors, CiteOps software significantly improves job management inside the company. To cut down on misunderstandings, workers are linked via a mobile app that delivers real-time notifications regarding the duties they have been allocated as shown in Figure 7. Employees mark tasks in the app when they are finished, and each shift has a workplan. IoT sensors also keep an eye on the status of the workflow and the equipment, automatically sending data into the system to give updates on task completion and equipment conditions. The job schedule shows managers and supervisors how activities are completed visually and includes sensor input. The schedule can be viewed remotely. Tasks that aren’t finished are indicated, and sensors identify delays or malfunctions in the machinery, allowing workers to explain their work and management to take immediate action. This system provides precise workflow status data, which facilitates early problem diagnosis, accountability, and productivity gains. The organization guarantees productivity and timely work completion through the use of sensor data and remote task monitoring.

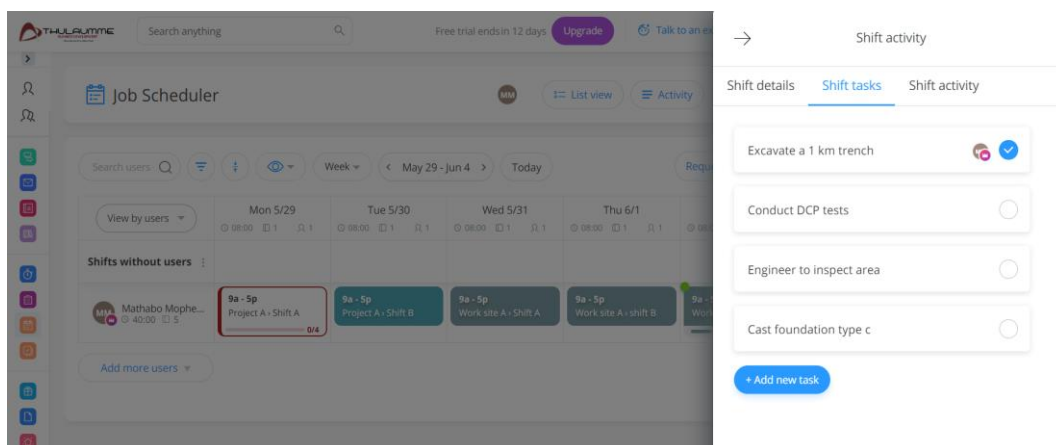


Figure 7. CiteOps job scheduler.

Figure 8 is an essential monitoring tool for managing equipment use and maintenance at the project site when combined with IoT sensors and CiteOps software. IoT sensors automatically monitor the state of the equipment and send real-time data to the platform, allowing for the early detection of problems that need maintenance or repairs. This system keeps track of the condition of critical spare parts and creates a thorough timetable to guarantee prompt maintenance, lowering the chance of malfunctions. IoT sensors allow a proactive strategy that maximizes equipment efficiency and reduces downtime. Authorized staff may monitor the status of the equipment and the progress of maintenance in real-time from remote locations, which helps them respond quickly to crises or urgent repairs. The importance of routine inspections is highlighted by the sensors, which monitor wear and tear and send data into Figure 8 for proactive maintenance and documentation. In summary, the incorporation of sensors with Figure 8 facilitates efficient equipment management, lowers malfunctions, and boosts operational effectiveness via automated tracking and real-time monitoring, guaranteeing better equipment longevity.

EQUIPMENT MAINTENANCE SCHEDULE

MACHINE NAME	CONDITION	LOCATION	ASSIGNED TO	LAST MAINTENANCE DATE	Planned MAINTENANCE FREQUENCY in Days	NEXT MAINTENANCE DATE	NOTES
Pump 101	Acceptable but needs attention	On site	Kasango Tau	19/05/2022	30	19/06/2022	Impeller in beginning phase of wear. We will keep monitoring the equipment but it is working well at the moment.
Generator	Good	On site	Isaac Masete	23/05/2022	7	23/06/2022	Replaced bearing. Working well.
Breaker	Good	On site	Thabo Tswai	23/05/2022	30	23/06/2022	Working well.
Frontend Loader	Good	Workshop	Thabo Mononyane	14/05/2022	7	14/06/2022	Working well.
Poker and Drive Unit	Unacceptable and must be inspected frequently	On site	Lethabo Klaai	14/05/2022	7	14/06/2022	End shank needs replacing.
Light Driven Vehicles (LDV)	Acceptable but needs attention	Workshop	Thapelo Mashile	14/07/2022	7	14/08/2022	V-belt worn out.
Trench Compactor	Good	On site	Thabo Mononyane	17/05/2022	30	17/06/2022	Working well
Piling Rigs	Good	On site	Thabo Tswai	19/05/2022	7	19/06/2022	Working well

Figure 8. CiteOps equipment maintenance schedule.

4. Conclusions

CiteOps software has been used to improve employee management in a construction project, enhancing communication and coordination among team members. The software allows on-site supervisors to assign tasks and track progress in real-time, preventing delays or inefficiencies. It also tracks employee productivity, providing insights into bottlenecks and areas needing additional training. Regular meetings foster accountability and teamwork, leading to improved overall performance. To address inefficiencies, a modified Lean Six Sigma DMAIC framework was implemented, highlighting factors like material availability, equipment delays, and insufficient inspections. An Economic Order Quantity model was created to optimize material orders and minimize delays. IoT sensors are used to remotely track progress, ensuring timely interventions and reducing over-inspections. This integrated method lowers delays, boosts project oversight, and increases overall building process efficiency by fusing real-time IoT sensor data with DMAIC.

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