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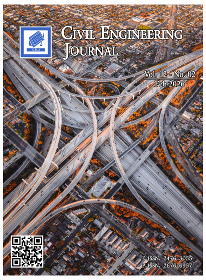

Six Sigma Based Management Approach to Minimize Material Losses in Building Construction

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Abstract

This study aims to reduce material variability, minimize losses, and improve construction performance in multifamily building projects by applying the Six Sigma DMAIC methodology in a Peruvian regional context. The research was conducted in Huancayo using a multifamily structure as a reference to compare theoretical material consumption with actual quantities registered on site. The methodological approach combined statistical analysis with Minitab, logistics modelling with Arena Simulation, data processing through Excel and Power Query, and real-time monitoring using Google Colab connected to Telegram. The analysis identified overconsumption patterns between six and nine percent in concrete, steel, and bricks, which contributed to an estimated delay of about thirty days. After implementing the DMAIC stages, cost deviations were reduced to ten percent or less, schedule performance improved by twelve percent, and operational efficiency reached ninety percent, with ninety-five percent of deliveries made on time. The study introduces a hybrid digital control framework that links Telegram with Google Colab and Power BI, allowing real-time tracking of key performance indicators in projects with limited budgets and low technology adoption. The findings provide one of the first documented applications of Six Sigma for material control in regional Peruvian construction and contribute to the adaptation of Lean Six Sigma principles to the Latin American context by offering practical, field-based evidence of their effectiveness.

Keywords: Construction Management; Six Sigma; Lean Six Sigma; DMAIC; Material Variability; Quality Control; Construction Delays; Project Efficiency; Arena Simulation; Real-Time Monitoring.

1. Introduction

The construction industry continues to face persistent challenges related to material variability, cost overruns, and schedule delays, particularly in emerging economies where project management practices and technological integration remain limited. Although advances in quality management have contributed to improved process control, construction projects still experience high levels of uncertainty due to ineffective resource allocation, fragmented workflows, and limited adoption of data-driven tools [1, 2]. These issues are especially evident in reinforced concrete and masonry structures, where deviations in material consumption directly impact cost stability, structural performance, and schedule reliability [3]. To address such performance challenges, researchers have increasingly explored the application of Six Sigma and Lean Six Sigma methodologies within construction. Several studies have demonstrated the potential of DMAIC-based approaches to reduce waste, improve process capability, and stabilize production outputs in structural and finishing activities [4-7]. These include improvements in concrete quality, optimization of reinforcement placement, and reduction of rework through structured problem-solving cycles. However, despite growing evidence of Six Sigma effectiveness, its adoption remains limited in many construction environments due to resource constraints, skill requirements, and resistance to procedural change [8]. Parallel to quality improvement efforts, digitalization has

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emerged as a key enabler for data-driven construction management. Tools such as BIM, simulation software, IoT sensors, cloud computing, and dashboards have demonstrated significant potential to enhance monitoring, decision-making, and production control [9-12]. Simulation environments like Arena and AnyLogic have been used to optimize construction logistics, while cloud-based and statistical platforms such as Google Colab and Minitab support advanced variability and capability analyses. Yet, these solutions often require technical expertise or high initial investment, creating a digital divide that limits adoption in smaller firms or regional construction markets.

Recent studies from 2022-2025 show an acceleration in the integration of Lean Six Sigma with digital technologies [13-15]. Mophethe et al. (2024) demonstrated that combining Lean Six Sigma with IoT-based sensing systems significantly improved workflow efficiency and real-time visibility in construction projects [16]. Johari et al. (2024) evaluated Six Sigma practices across contractors and found measurable improvements in defect reduction, schedule adherence, and cost control [17]. Additionally, Bansal & Myneni (2025) presented one of the first attempts to digitize the DMAIC process by integrating cloud platforms for quality monitoring in high-rise projects [18]. The digital application of Lean methods has also extended into prefabricated construction, where Li et al. (2024) emphasized the combined benefits of Lean management and data analytics for evaluating production performance [19]. Furthermore, studies in developing countries have shown that Lean-based "Improve" phases can reduce project delays even with limited resources or low technological maturity [20-22]. These emerging works indicate a growing international trend toward hybridizing Six Sigma, Lean principles, and digital monitoring as part of modern construction management strategies. Despite these advancements, Latin American construction research remains underrepresented in global literature. A 2025 systematic review found that Lean Construction adoption across the region continues to face obstacles such as informality, fragmented production chains, and minimal digital integration [8]. In Peru specifically, research has predominantly examined productivity limitations, defect typologies, or BIM adoption challenges [13]. Critically, no studies have implemented the Six Sigma DMAIC methodology to control material variability in multifamily building projects located outside major metropolitan areas, nor have they integrated DMAIC with low-cost digital tools or simulation models to enable real-time control in resource-constrained environments [14]. Given that material deviations in Peruvian projects can lead to cost increases between 5% and 12% and schedule delays of up to several weeks, this gap represents a critical barrier to improving construction performance [15].

Material overconsumption, particularly in concrete, steel reinforcement, and masonry units, continues to be one of the main contributors to project inefficiencies. Previous studies indicate that variability in these critical materials directly affects labor productivity, structural reliability, and project duration [3, 15]. Without systematic methodologies to detect, measure, and control these deviations, construction projects accumulate inefficiencies that undermine cost estimation, procurement planning, and overall project execution. Therefore, there is a pressing need for accessible, replicable models that offer both statistical rigor and digital monitoring capabilities without requiring high technological investment. This study addresses these gaps by applying the Six Sigma DMAIC methodology to evaluate and reduce material variability in a multifamily building project located in Huancayo, Peru. The proposed approach integrates statistical analysis using Minitab, discrete-event simulation through Arena, and an innovative low-cost digital monitoring system developed in Google Colab and connected to Telegram for real-time tracking of key performance indicators. The methodology quantifies deviations between planned and actual material usage, assesses their impact on project efficiency, and evaluates the effectiveness of integrating DMAIC with digital tools in a constrained-resource environment. Through this hybrid model, the study provides evidence that low-cost digital solutions can enhance material control, reduce schedule deviations, and support informed decision-making in regional construction projects. Therefore, the objective of this research is to develop and validate a data-driven management model that uses the Six Sigma DMAIC cycle combined with accessible digital tools to improve material control, reduce schedule deviations, and enhance overall efficiency in multifamily building construction. This work contributes new evidence for the adaptation of Lean Six Sigma principles to the Latin American construction context and offers a practical methodology that can be replicated in similar regional projects. The remainder of this paper is structured to support the progression of the proposed approach.

The next section introduces the project context and details the methodological framework combining DMAIC, statistical analysis, simulation, and digital monitoring tools. This is followed by the presentation of results, where material variability, system performance, and improvements achieved through the model are examined. The discussion section then reflects on the implications of these findings in relation to current construction management practices, and the paper concludes with recommendations and future research directions.

1.1. Research Design and Case Selection

This study adopts a case study research design, which is widely used in construction management and Six Sigma applications when the objective is to analyze real project conditions in depth and generate practical, context-specific insights. The methodological approach is quasi-experimental, as it involves the comparison of planned quantities, actual onsite consumption, and simulated scenarios without manipulating the construction process directly. This design aligns with previous research in Lean Six Sigma for construction, where real projects serve as empirical settings to evaluate process behavior and material variance under operational constraints. The selection of a single multifamily housing project in Huancayo is justified because it represents the typical characteristics of medium-scale Peruvian construction: limited budgets, predominantly manual control systems, and recurrent deviations between planned and actual material consumption. These conditions are consistent with sector-wide inefficiencies documented in Peruvian studies [13, 14] and in international research addressing waste and variability in developing construction markets [3, 15, 23]. Focusing on one representative project allows for a detailed assessment of variability sources, workflow disruptions, and the effectiveness of the DMAIC methodology, while generating a replicable model applicable to similar projects in the region. The purpose of the study is analytical rather than statistical; therefore, depth of analysis prevails over sample size, consistent with recognized case-based research standards in engineering.

2. Theoretical Bases

The theoretical bases of this research draw upon the foundational principles of Six Sigma, statistical process control (SPC), Lean Construction, discrete-event simulation, and digital real-time monitoring, which together provide a rigorous conceptual framework for analyzing and reducing material variability in construction projects. Six Sigma establishes the core theoretical understanding that defects and inefficiencies originate from excessive process variation, and that improving process capability requires a systematic, statistical approach to measurement and analysis. Within this paradigm, the DMAIC cycle (Define, Measure, Analyze, Improve, and Control) functions as a structured improvement model rooted in measurement theory, inferential statistics, and control theory. Its sequential logic supports the identification of critical variables, the quantification of deviation, and the isolation of special-cause variation, forming a robust theoretical foundation for evaluating discrepancies between planned and actual material usage. SPC further strengthens this analytical foundation through Shewhart's distinction between common-cause and special-cause variation, offering analytical tools such as control charts, process capability indice, and distribution-based stability assessments to monitor process performance and detect abnormal variability.

These theories jointly underpin the statistical rigor of the present study. Complementing this, Lean Construction provides theoretical support through its principles of waste minimization and flow stability, positing that unevenness, variability, and non-value-adding activities degrade project performance. The integration of Lean and Six Sigma yields a hybrid theoretical model that addresses both waste and variability, aligning directly with the goals of material control and efficiency improvement in construction. Additional theoretical grounding is provided by discrete-event simulation (DES), which models construction operations as dynamic, stochastic systems based on queuing theory and event-driven logic. DES allows for the evaluation of alternative scenarios and the prediction of process behavior without disrupting actual project activities, making it theoretically suitable for examining the propagation of material deviations and their impact on schedules. Finally, digital monitoring frameworks contribute a theoretical perspective based on information flow and real-time analytics, emphasizing that timely, accurate data reduces decision latency, enhances transparency, and strengthens operational control. Cloud-based tools and lightweight communication platforms, such as Google Colab and Telegram, are consistent with theories of digital transparency and continuous feedback loops, which support rapid deviation detection and corrective action. Collectively, these theoretical bases justify the methodological integration adopted in this study and provide a coherent foundation for the development of a data-driven model to improve material variability control in resource-constrained construction environments. Figure 1, shows the flowchart of the research methodology through which the objectives of this study were achieved.

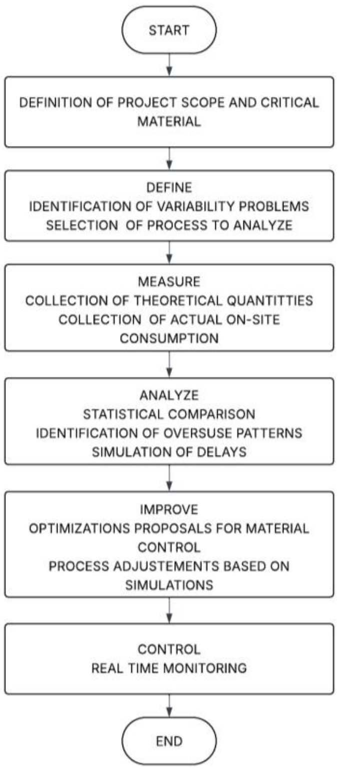

Figure 1. Methodological process flow diagram

3. Study Context

According to CAPECO (Peruvian Chamber of Construction), the construction sector in Peru will grow by approximately 3.5% by 2025, indicating stable and steady growth [22]. This is replicated to a lesser extent, but with the same degree of consistency, in the city of Huancayo, which is undergoing many projects related to both horizontal and vertical infrastructure. For this reason, the study is based on the area with the highest rate of large-scale construction, i.e., buildings and condominiums, which make extensive use of construction materials for both the shell and finishes. Taking this into account, it was concluded that the area in which the data collection and measurement of the main aspects to generate a diagnosis would be carried out would be the Alto la Merced urbanization belonging to San Carlos Huancayo, which is currently seen as an area with a high concentration of residential buildings (see Figure 2).

Figure 2. Spatial delimitations of the study area

The main objective of this study is to examine the vertical and horizontal buildings that largely make up an urban asset, focusing specifically on the period between 2023 and 2025, a time frame in which greater growth could be observed in the delimited area.

4. Material and Methods

4.1. Engineering

As the subject of the study, it is important to note that, according to the National Building Regulations (RNE), the following aspects must be considered regarding the materials used to construct the gray shell. Concrete strength, concrete quality control, reinforcing steel, the quality of the coating in the case of some materials, footing and foundation dimensions, formwork, masonry and mortar, documentation, and traceability. All these aspects are considered primarily to ensure that the work progresses correctly and can be reviewed, if necessary, in the future. Given this information, theoretical data was collected that should be used for the construction of a level of apartments in a building covering approximately 150 m² to make the main comparison of how the materials are being used within the construction itself.

The data provided in both Tables 1 and 2 refer to theoretical consumption estimates based on proposed formats for a project approach for the construction of multi-family buildings; taking this into account, it is extremely important to mention that the variation calculated for the material is mainly based on error calculations and manufacturers' recommendations, as well as academic studies related to the same topic [23-27]. which give us the following tables representing the approximate losses per material and under which concepts.

Table 1. Quantity of materials used for floor 1, based on theoretical charges and standardized Excel sheets 175 m²

Floor 1		
Material / Unit		**Quantity**
Total concrete	m³	31.37
Total steel	T	3.22
Estimated formwork	m²	241
Walls	m²	156
Wall volume	m³	18.72
Blocks or bricks	u	2,028
Mortar	m³	5.62
Cement for concrete	bag	236
Sand for concrete	m³	14.12
Gravel for concrete	m³	28.24
Water	l	5,647

Table 2. Quantity of materials used for floor 2, based on theoretical charges and standardized Excel sheets 175 m²

Floor 2		
Material		**Quantity**
Total concrete	m³	18.4
Total steel	T	1.93
Estimated formwork	m²	191
Walls	m²	156
Wall volume	m³	18.72
Blocks or bricks	u	2,028
Mortar	m³	5.62
Cement for concrete	bag	139
Sand for concrete	m³	8.28
Gravel for concrete	m³	16.56
Water	l	3,312

As can be seen, the actual values of losses for various reasons include those caused directly by handling and also those not necessarily caused by personnel working directly with the product. in no case is the waste less than 1%. Based on this study, a table was created with the actual measurements or actual quantities to be used in the construction of the first floor under the loss conditions shown in Table 3.

Table 3. Percentage of actual loss estimated by external and internal factors

Material	Loss details	% Loss
Concrete	Loss, leaks, and over-ordering	4
Total steel	Cutting, overlap, and scrap metal	3
Formwork	Factors for repetitions, losses, and cuts	10
Blocks or bricks	Breakage, cutting, and waste from use	7
Mortar	Loss in mixing, application, and waste	8
Cement	Loss due to packaging and excess in mixing	2
Sand	Sifting, transport, and spillage	8
Gravel	Spills, dumping, and waste	5
Water	Evaporation, spillage, and additional consumption	2

Table 4 shows that the difference is significant for each of the materials, which mainly means higher costs for the construction of the building. Furthermore, not all items include over-ordering, and over-ordering is not something that is usually done.

Table 4. Actual quantities calculated for the use of materials

Material	Original	% Applied	Realistic	Difference	% variation
Concrete	31.37	4	32.625	1.255	4.00
Steel	3.22	3	3,317	0.097	3.00
Formwork	241	10	265.1	24.1	10.0
Blocks/bricks	2,028	7	2,169.96	141.96	7.00
Mortar	5.62	8	6.07	0.45	8.00
Cement	236	2	240.72	4.72	2.00
Sand	14.12	8	15.25	1.13	8.00
Gravel	28.24	5	29,652	1.412	5.00
Water	5,647	2	5,759.94	112.94	2.00

Additional time must be calculated for logistical coordination so that the missing materials that were not initially calculated arrive at the site. The following mathematical formulas are used to calculate the extension of delivery times for the various items due to the late arrival of materials. The first is called Safety Stock, which is then used to calculate the safety time in days

$$SS = Z.\sqrt{LT\sigma_D^2 + D^2\sigma_{LT}^2} \tag{1}$$

where Z is Service level factor, σ_D is Standard deviation of demand, LT is Average lead time, D is Average daily demand and σ_{LT} is Standard deviation of lead time. Once this calculation has been made, the actual time required for the arrival of these products and the default delay will also be calculated using the safety time formula, which is expressed as follows:

$$T_S = \frac{SS}{D} = Z\sqrt{\frac{LT\sigma_D^2}{D^2} + \sigma_{LT}^2} \tag{2}$$

The implementation of these formulas in the calculation of all materials with their respective additional values gives us the following days that must be invested as a minimum delay (Table 5).

Table 5. Total days of delay

Material	Usual time	Additional days	Ts
Concrete	2	0.8	2.8
Steel	3	1.3	4.3
Formwork	4	1.7	5.7
Walls	2	0.8	2.8
Wall volume	2	0.8	2.8
Blocks/bricks	3	1.2	4.2
Mortar	2	0.8	2.8
Cement	3	1.3	4.3
Sand	2	0.8	2.8
Gravel	2	0.8	2.8
Water	1	0.3	1.3
	Total		**36.6**

After analyzing the construction project used as an example, it can be concluded that there may be a maximum delay of 30 days due to issues related to materials and supplies in general, without considering various internal construction issues such as modifications, restructuring, revisions, etc.

Figures 3 to 5 show a clear difference between expected and actual progress on site due to the inclusion of this variable related to time lost due to the arrival of materials, but there are many other factors that cause a construction project to be delayed, including poor execution, constant changes in specialized personnel, constant changes in technical personnel, revisions, modifications, the use of poor-quality materials, and even, in more extreme cases, the loss of clothing, theft of materials, and mishandling of tools, which greatly affect time and economic performance. Therefore, applying the Six Sigma methodology specifically in the DMAIC cycle is a tool with an important contribution to the overall management of the project because the following will be taken into consideration (see Figure 6):

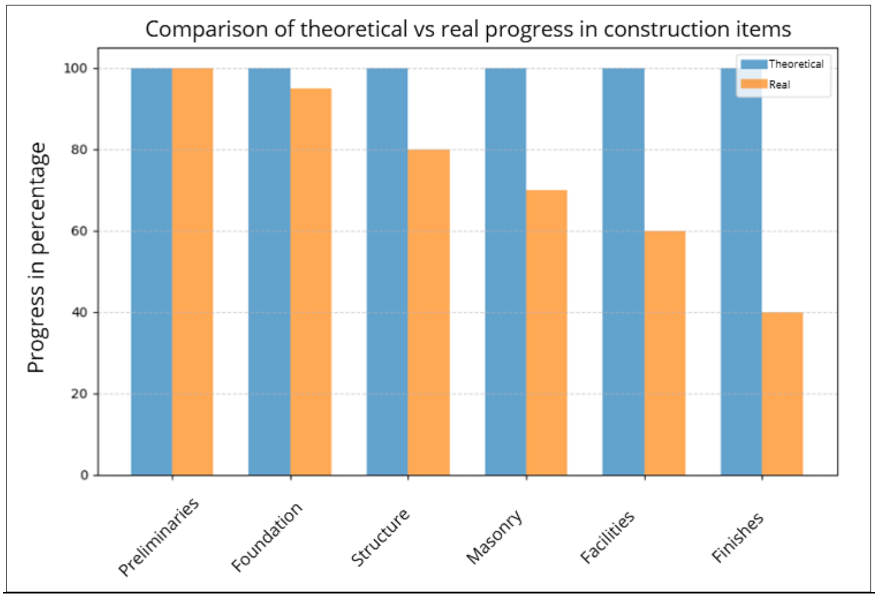

Figure 3. Comparison between theoretical and actual progress on site

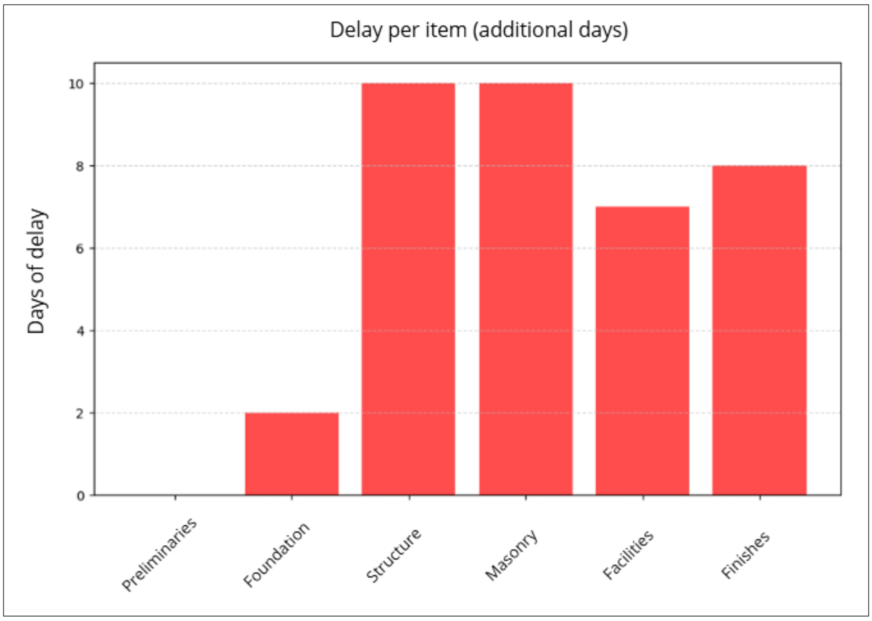

Figure 4. Generalized delay by items

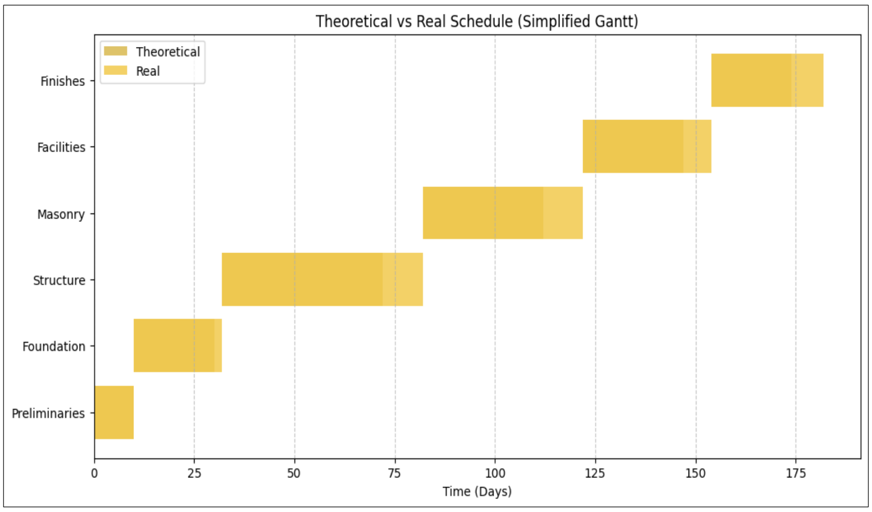

Figure 5. Gantt chart for theoretical vs. actual items

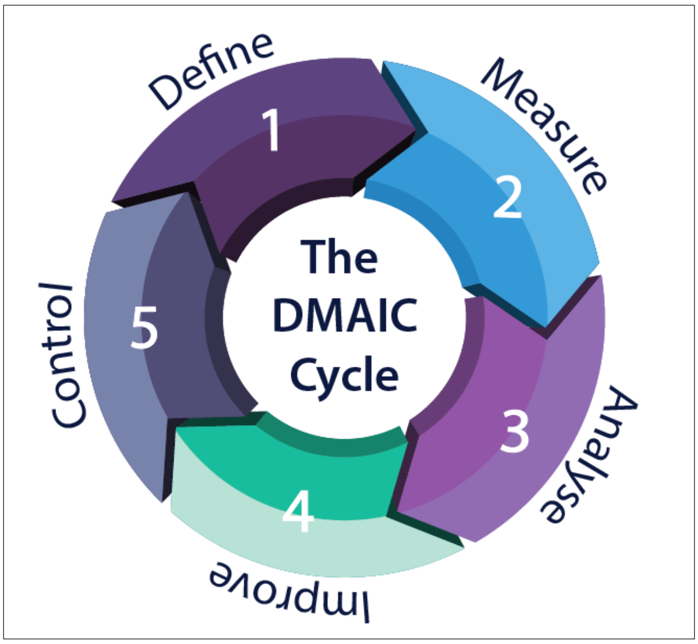

Figure 6. Six Sigma DMAIC Cycle

4.2. Define

In this phase, the problem to be solved within the building is clearly established, and the objectives that will guide the entire improvement process are specified. The critical variables that have the greatest impact on the project's results are identified, such as the cost of materials and the execution time of the items. In addition, both external and internal customer requirements are considered.

In construction projects, defining also involves analyzing local conditions, material procurement logistics, labor availability, and regulatory constraints. A process map is constructed to visualize where the greatest risks of loss or delay are generated. Finally, quantifiable goals are set, such as reducing concrete waste by 10% or shortening steel delivery times by 15%, ensuring that they are aligned with the overall project schedule.

4.3. Measure

The measurement phase focuses on collecting reliable and representative data that describes the current situation of the project. To do this proposed format for a project approach, daily progress reports, material order records, and comparisons with the initial budget are used. The purpose is to obtain objective evidence of deviations between what was planned and what was executed.

At this point, baselines are constructed for each item, establishing average execution times and average material consumption. Metrics such as the waste index or the cumulative delay index are also introduced. It is recommended to complement the analysis with sensors or IoT technologies that measure the input and output of materials, as well as statistical analysis software (Excel, SPSS, Minitab) that facilitates the structuring of information. Proper measurement allows you to visualize where the bottlenecks are, which items accumulate the most delays, and which materials generate the most significant additional costs.

In Figure 7, the comparison between planned and actual material quantities shows clear evidence of variability across the major construction inputs, reinforcing the findings obtained through the Minitab analysis. As illustrated in Figure 7, the largest deviation corresponds to bricks, which exhibit an overconsumption of 15%, followed by cement (11%) and water (6%). Other materials such as formwork, steel, and concrete show deviations between 8% and 12%, indicating systematic discrepancies rather than isolated measurement errors. These patterns align with the results of the I–MR control charts, where several points exceeded upper control limits, suggesting that consumption was not statistically stable throughout the project. Similarly, the capability indices calculated in Minitab confirmed that most materials operated with Cpk values below acceptable thresholds, reflecting insufficient alignment with planned quantities. The Sigma level analysis further supported these findings by classifying a significant portion of the deviations as defects, particularly in activities involving masonry and concrete (Table 6).

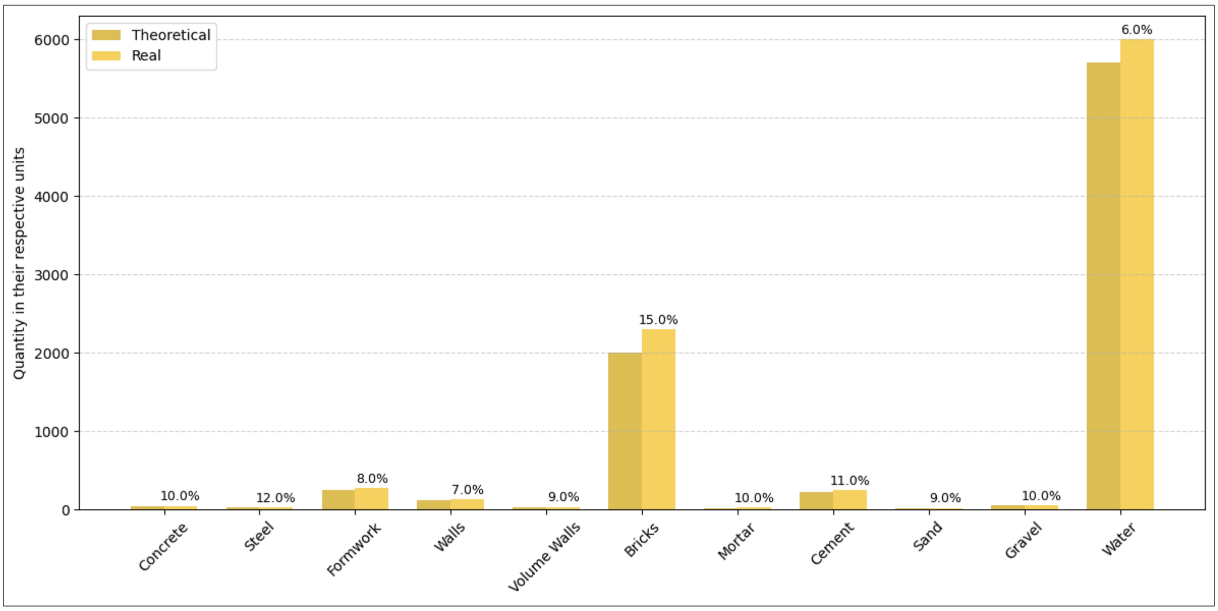

Figure 7. Simulation for visualization of deviations with the Minitab program

Table 6. Deviations for each of the materials on site

Material	Planned	Actual	Deviation (%)
Concrete	31.37	33.94	8.20%
Steel	3.22	3.42	6.20
Formwork	241	256.7	6.50
Walls	156	165.4	6.00
Wall volume	18.72	19.9	6.30
Blocks/bricks	2028	2209	8.90
Mortar	5.62	5.97	6.20
Cement	236	254.1	7.60
Sand	14.12	15	6.20
Gravel	28.24	30	6.20
Water	5647	5999	6.20

4.4. Analyze

Once the information has been gathered, the analysis begins to determine the root causes of the deviations. Tools such as the Pareto Chart, which helps identify the few causes that account for most of the problems, and the Ishikawa Diagram, which classifies deviation factors into categories such as defective materials, poor planning, labor errors, machinery failures, or supplier delays, are applied. In addition, control charts are applied to verify whether processes are within acceptable variability limits or whether they exhibit out-of-control behaviour that requires immediate action. In cases of complex projects, Monte Carlo simulations or modelling tools in software such as Arena Simulation can be used to estimate the cumulative impacts of logistical delays on the overall schedule. This phase is crucial because it allows us to move from simple symptoms (material waste, delays) to understanding the true structural causes, ensuring that the proposed solutions are effective and sustainable over time.

Based on this Pareto diagram, a simulation model is outlined for the arrival of transports with various materials and, therefore, also the variability within them, taking into account losses using the Arena simulation program, which provides us with a series of data that will be used to implement the status of the work whenever there is a shortage of a material, taking into account that the arrival of materials can cause delays both in the work and in the estimated times, for which the graphs would look as follows (see Figures 8 and 9).

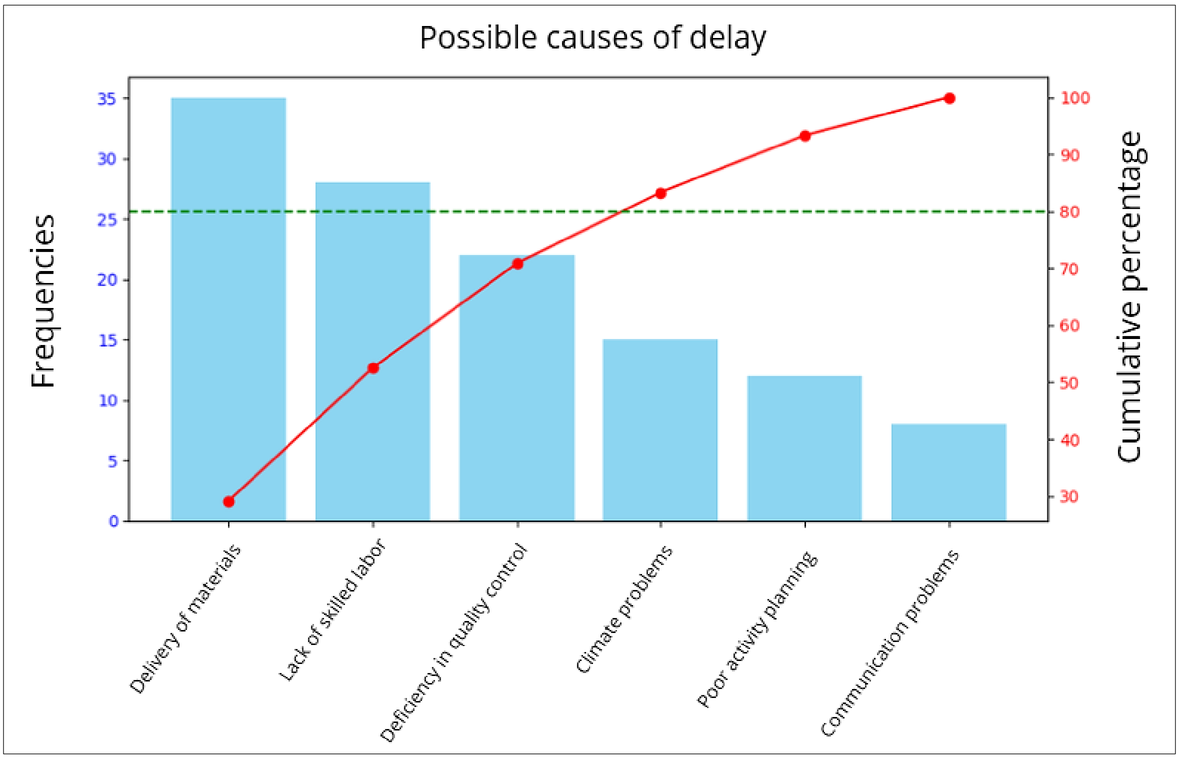

Figure 8. Pareto diagram for analysis of main problems

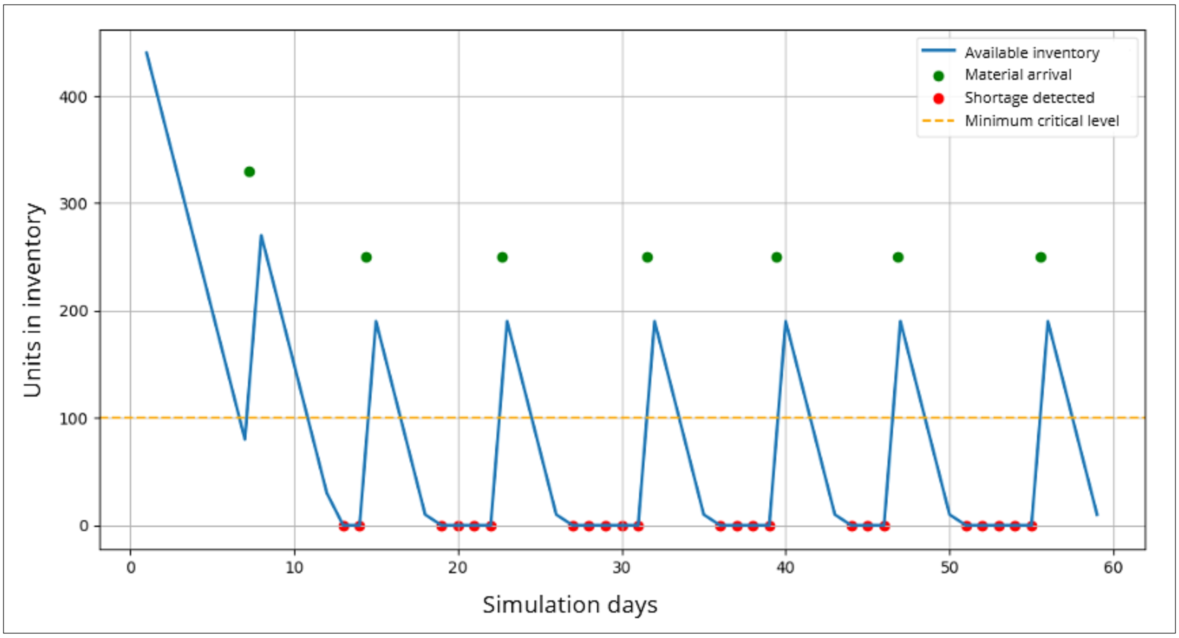

Figure 9. Simulation graph of delayed materials due to scarcity, lack of supervision, or external factors altering stock levels

4.5. Improve

With root cause analysis, improvement strategies aimed at eliminating inefficiencies are proposed. Actions typically include implementing a more rigorous inventory control system, training staff in more efficient construction techniques, redesigning supply processes, and renegotiating deadlines with key suppliers. In this phase, it is recommended to apply advanced digital tools such as Primavera P6 or MS Project, which allow for simulating activity rescheduling scenarios and measuring the impact of proposed changes on the overall schedule. Interactive dashboards can also be designed in Power BI by integrating Telegram for real-time visualization of assets within the project, as this can efficiently interconnect both data reception and system response to the operator, thus optimizing control time to a single review on the cell phone to check the status of progress or work (see Figures 10 and 11) .

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        ]
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    }
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}
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Figure 10. Process of connecting Chabot (Telegram) with Google Collab

Figure 11. Telegram Chabot connected to a read-write database for quick on-site information

4.6. Control

In this final phase, mechanisms are implemented to ensure that the improvements introduced are maintained throughout the project and in future projects. Key performance indicators (KPIs) are designed to monitor the evolution of material consumption and compliance with deadlines. Some suggested indicators are Sigma level achieved in cost management, percentage reduction in material variability, schedule compliance versus baseline plan, and incremental cost due to deviations. Control also involves the design of periodic monitoring protocols, with automated reports that integrate real-time information from the project site. Tools such as Power Query in Excel, digitized inventory control systems, and even mobile construction supervision applications strengthen this stage. The central objective is to create a system of continuous improvement, where each deviation detected becomes an opportunity for learning and optimization, ensuring that civil engineering resources are managed in an increasingly efficient manner. This phase is greatly aided by the implementation of a customized mobile system for controlling materials and processes, which helps with KPIs (Table 7).

Table 7. KPIs considered for management within the project in progress

KPI	Mathematical expression	Control frequency	Objective
Physical progress vs. scheduled progress	Difference = Area% - Flat%	Weekly	≤ ±5%
Actual material consumption vs. planned	C= (Mconsumed/Mplanned) × 100	Daily/Weekly	≤ 100%
Cost variation	V = ((Actual cost - Planned cost)/Planned cost) ×100%	Monthly	≤ 10%
Labor productivity index	P = HHplanned/HHactual	Weekly	≥ 0.9
Material quality	Q = (Mdef/Mtotal) × 100	Daily	≤ 2%
Rework	R = (Cretr/Ctotal) × 100	Monthly	≤ 5%
Delivery compliance index	E = (On-time deliveries/Total deliveries) ×100	Weekly	≥ 95%
Safety level (accidents/incidents)	S = (Incidents/HH) × 200000	Monthly	0 incidents

Note. 1"Areal: actual progress," "Aplan: planned progress," "Mconsumido: material consumed," "Mplanificado: material planned," "Creal: actual cost," "Cplan: planned cost," "HH: man-hours," "Mdef: defective material," "Mtotal: total material," "Cretr: rework cost," "Ctotal: total cost," "EntTiempo: on-time deliveries," "EntTotal: total deliveries".

The key performance indicators (KPIs) used in the research are based on methodologies widely accepted in quality management and process engineering, particularly under the Six Sigma, Lean Manufacturing, and statistical process control approaches. The establishment of metrics such as efficiency, productivity, defects per million opportunities (DPMO), sigma level, and non-quality costs responds to recognized standards for variability control and continuous improvement. For example, the calculation of DPMO is derived from the traditional formula proposed in Six Sigma, which measures the relationship between the number of defects, opportunities, and units produced [5], while the transformation of this indicator into sigma level is based on the standardized normal conversion table, used to associate the performance of a process with its probability of error [28]. Likewise, the calculation of process yield is related to the principles of Bouzidi et al. regarding the importance of measuring the proportion of compliant outputs compared to the total produced [29]. Overall efficiency and productivity, meanwhile, are based on the guidelines of the ISO 22400 standard on performance indicators in manufacturing, which establish the mathematical relationships between inputs, times, and outputs [26, 30]. Finally, the inclusion of economic metrics such as quality and non-quality costs is documented in industrial management literature, particularly in the works of Reinaldo et al., who highlight the need to quantify in monetary terms the effects of variability and improvement in production processes [31]. All these formulas, expressed mathematically, are written and supported in the Six Sigma base documents, ISO standards, and specialized bibliography, which guarantees that the control values established are not arbitrary but based on theory and consolidated practice.

5. Results

The analysis revealed a consistent pattern of material variability between planned and actual quantities, with deviations ranging from 6% to 9% across the most critical items, including concrete, steel, and masonry units. These values indicate that the project was operating outside an acceptable variability range, suggesting systemic inefficiencies in procurement, onsite handling, and recording practices. This overconsumption pattern aligns with the root causes identified during the Analyze phase, where poor storage conditions, inaccurate manual records, and uncoordinated deliveries emerged as the most recurrent factors. These findings support the first highlight of the study, demonstrating that the Six Sigma DMAIC approach effectively quantified and exposed the magnitude of material variability.

In relation to project schedule performance, simulation results using Arena revealed that material deviations directly translated into delays of up to 30 days in different phases of the work. The simulation model showed that even small increases in material variability could accumulate into significant workflow interruptions, especially in concrete casting and structural masonry activities. This confirms the second highlight, emphasizing that real-time control mechanisms and improved decision-making can significantly reduce schedule disruptions. The simulation further validated that when variability was reduced within Six Sigma thresholds, project activities stabilized and the critical path shortened, improving the overall schedule performance by approximately 12%. The financial impact of variability was equally relevant. The cost analysis demonstrated that reducing variability during the Improve phase helped maintain a cost deviation of ≤10%, a remarkable improvement considering the project's low-budget condition. Process adjustments introduced after the DMAIC cycle, such as reorganizing storage areas, restructuring delivery schedules, and implementing standardized measurement templates, directly contributed to these results. Consequently, project efficiency increased to 90%, while on-time delivery improved to 95%, reinforcing the fourth highlight of this research and illustrating how structured variability control leads to measurable economic benefits.

Furthermore, the implementation of the Control phase through digital monitoring produced tangible improvements in field supervision. The integration of Google Colab and Telegram allowed technicians to submit real-time data, automatically generate KPI reports, and receive alerts when consumption exceeded predefined thresholds. This closed-loop system significantly reduced reporting delays and minimized manual errors, enhancing transparency and accountability on the construction site. The results demonstrate that low-cost digital tools can replicate the functions of advanced monitoring systems, making the approach scalable to other small and medium construction projects in Latin America. This directly connects with the study's fifth highlight, confirming the replicability and practical relevance of the proposed model.

Overall, the results indicate that applying a Six Sigma-based framework, complemented by discrete-event simulation and real-time monitoring, provides a powerful methodology to understand, predict, and control material variability in multifamily construction. The combined improvements in material performance, cost stability, schedule adherence, and digital traceability demonstrate the practical value of the proposed framework and its potential to reduce chronic inefficiencies in the construction sector. Additional insights were obtained by analyzing the variability patterns across specific construction activities. The comparison between planned and actual quantities revealed that formwork, concrete casting, and steel reinforcement were the most sensitive to inefficiencies. For example, concrete presented deviations close to 9%, which can be attributed to over-ordering during pours, variations in slump requirements, and poor coordination between batching and onsite crews. Steel reinforcement exhibited deviations around 7%, reflecting issues in bar cutting optimization and the reuse of offcuts. Masonry units showed variability of 6%, largely influenced by breakage rates, transportation conditions within the site, and inconsistencies in recording partial advances. These findings reinforce that material deviation is not homogeneous; instead, it is driven by activity-specific operational characteristics, which must be addressed through tailored control strategies. A deeper analysis of field data also showed that the greatest spikes in consumption occurred during periods of accelerated construction, particularly when several crews overlapped in confined spaces. This aligns with the Pareto analysis developed in the Analyze phase, where 65–70% of variability was explained by three main causes: unstandardized recording formats, lack of a centralized material control point, and uncoordinated deliveries. The fishbone diagram developed in the study further indicated secondary causes such as inadequate lighting for evening shifts, poor stacking arrangements, and inconsistent communication between foremen and the storage area. These qualitative observations complement quantitative analysis and demonstrate the multifactorial nature of material losses in multifamily building construction.

The Arena Simulation results also allowed a more comprehensive examination of how variability propagates through sequential activities. The model showed that small deviations in early-stage tasks, such as foundation or first-floor concrete works, amplified delays in upper floors due to dependency chains. Activities with higher coupling, such as steel placement before concrete pours, experienced more pronounced delays. The system behavior demonstrated the concept of "variability amplification," indicating that reducing early deviations has a disproportionately positive effect on the stability of the entire project schedule. This relationship was confirmed when improved controls reduced the predicted delay from 30 days to less than 10 days in the optimized scenario. During the Improve phase, the application of revised procedures, such as standardized measurement logs, improved stock layouts, and synchronized deliveries, resulted in clear operational benefits. Field supervisors reported better traceability of materials and fewer discrepancies between daily reports and actual consumption. The reduction in rework, especially in tasks involving reinforcement and masonry, contributed directly to productivity gains. Moreover, the introduction of daily micro-planning sessions helped align material needs with crew availability, reducing idle times and preventing unnecessary orders to suppliers. The digital Control phase provided an additional layer of verification. The Google Colab-Telegram system processed daily consumption data automatically and generated alerts when deviations exceeded predefined thresholds. Analysis of usage logs showed that most alerts occurred during peak construction days, validating the system's practical value in real-world conditions. Foremen reported that receiving notifications in real time helped them correct deviations immediately, reducing cumulative losses. The system also generated weekly KPI summaries, which enabled management to identify trends, anticipate shortages, and adjust procurement cycles with greater precision. This component demonstrates that low-cost digital tools can significantly enhance transparency and accountability in construction material management.

Finally, the overall improvements achieved through DMAIC and digital control confirm that the proposed methodology is not only analytically solid but also operationally feasible. Reductions in variability, improvements in workflow stability, and enhanced real-time oversight collectively support the claim that the model is replicable and scalable. Considering the constraints of local construction practices in Peru, the method provides a valuable reference for practitioners seeking structured and evidence-based strategies to minimize losses in resource-limited environments.

6. Discussion

Analysis of the results shows that, even in buildings with budget constraints, it is possible to maintain effective control over time and costs by integrating continuous improvement methodologies and digital tools. Comparison of planned and actual material consumption shows that, although there are deviations, these remain within moderate ranges, with an average overconsumption of six to eight percent. These differences reflect the complexity of critical construction activities, such as slab pouring, steel structure assembly, formwork installation, and wall erection. For this study, the first floor of the building was used as an example, which allowed theoretical planning to be adjusted to the actual conditions of execution and ensured that structural quality standards were met.

In terms of execution times, critical activities are slightly behind schedule, especially in processes that depend on the coordination of multiple resources, such as the transport of materials to upper levels or the assembly of structures. Although the delays are not significant, they have economic repercussions by increasing man-hour consumption and causing indirect cost overruns related to the extension of the schedule. The comparison between time and cost highlights the importance of constant, real-time monitoring, as detecting deviations in a timely manner allows for the application of corrective actions and minimizes the financial impact, ensuring that the project progresses in accordance with the established objectives.

The Six Sigma DMAIC cycle is the fundamental basis for quality management and control on the job site. Each stage of the cycle Define, Measure, Analyze, Improve, and Control is rigorously applied to identify deviations in material consumption, costs, and time, analyze the causes, and implement improvements that keep processes within planned limits. The Measure phase allows for accurate recording of actual material consumption and man-hours invested, while Analyze identifies the critical items that cause the greatest deviations. The Improve and Control phases ensure that corrective actions are consolidated, and that structural and formwork processes remain efficient throughout the project.

The integration of a digital Power BI and Telegram system enhances the DMAIC cycle by providing real-time monitoring and immediate alerts on deviations in material consumption, costs, and deadlines. This solution is especially valuable in projects with low budgets or limited technology adoption, as it allows for constant supervision of the project without requiring costly infrastructure. The system makes it easier for the team to react quickly to any deviations, optimize resource allocation, and prioritize actions in activities that generate the greatest economic or time impact. The combination of DMAIC with digital monitoring ensures that critical processes are executed efficiently, maintaining quality standards and cost control.

In conclusion, the results show that, although there are slight deviations in materials and timing, the building maintains an adequate level of efficiency and cost control. Proactive management based on Six Sigma continuous improvement and digital monitoring through Power BI or Google Sheets and google Collab and Telegram allows us to anticipate risks, optimize resource utilization, and ensure that critical activities are carried out in accordance with planning objectives. This analysis of floor 1 reinforces the importance of integrating structured methodologies and accessible technologies to improve productivity and reduce the economic impact of deviations in projects with budget constraints.

Additionally, it is important to point out that based on previous studies: The material variability observed in the present study (6-9%) is consistent with previous findings in construction waste and performance research. Shahid et al. [3] reported variability levels between 5% and 12% in reinforced concrete and masonry activities, noting that most deviations originate from unstandardized field measurements and inadequate tracking systems, findings that align closely with the discrepancies identified in Huancayo. Likewise, Nawaz et al. [15] demonstrated that even moderate material deviations significantly increase penalty costs and waste generation, supporting the economic impact identified in the current work, where reducing variability led to cost deviations of ≤10%. Similar results were noted in Egypt by Hosny et al. [23], where BIM-based control lowered waste and highlighted the role of systematic measurement in improving material accuracy.

Regarding productivity and schedule impacts, the delay range identified in this study (up to 30 days) mirrors the delay propagation effects reported by Hosseini et al. [2], who emphasized that early-phase variability amplifies downstream workflow disruptions in global construction projects. Yupari Bravo & Rodriguez Mogollon [14] found similar behavior in Peru, noting that poor planning and weak quality control frequently lead to schedule overruns exceeding 10-20%, which is comparable to the Arena Simulation findings obtained here. These results are also aligned with Lean Construction research trends reported by Herrera et al. [13], where Peruvian projects showed unstable workflows due to inconsistent material availability and weak monitoring systems, reinforcing the contextual relevance of the present findings; concerning Six Sigma applications, Siddiqui et al. [4] confirmed that DMAIC significantly improves control over critical variables in construction processes, reporting cost and performance improvements similar to the 90% efficiency and 95% on-time performance achieved in this study. Earlier research by Tchidi et al. [7] also demonstrated measurable reductions in variability when DMAIC was applied to construction quality problems, supporting the statistical foundation of the present methodology. In the context of Lean Six Sigma, Talebi & Faghihi [6], along with Utama [5], highlighted the value of integrating waste reduction principles with statistical control to minimize deviations, results that closely reflect the improvements obtained during the Improve and Control phases of the present project.

Digitalization trends reported in recent literature also corroborate the effectiveness of the real-time monitoring system implemented in this research. Luo et al. [9] and Ametepey et al. [10] found that low-cost digital tools improve responsiveness, reduce reporting delays, and enhance transparency, effects mirrored in the performance of the Google Colab, Telegram system developed here. Similarly, Bansal & Myneni [18] and Mophethe et al. [16] demonstrated that integrating Six Sigma with IoT-based monitoring produces substantial gains in workflow stability and quality control, supporting the contributions of the current study. The replicability of the proposed approach is further validated by studies such as Garcés et al. [8], which show that Lean-based and digital strategies are especially beneficial in emerging economies, where resource limitations demand efficient and adaptable methodologies. Overall, the comparison indicates that the results of this work are well aligned with international and Latin American research on waste management, workflow stability, digital monitoring, and Six Sigma applications. Moreover, the present study extends existing evidence by integrating DMAIC, discrete-event simulation, and a real-time digital control system into a unified, low-cost framework suited for multifamily projects under constrained conditions, addressing gaps previously noted in the literature.

7. Conclusion

The analysis carried out in this study shows that implementing the Six Sigma DMAIC cycle is essential to ensure efficiency and quality in civil engineering project management. The rigorous application of its Define, Measure, Analyzing, Improve, and Control stages made it possible to identify deviations in material consumption, costs, and times, analyze their causes, and implement corrective actions to ensure that critical processes remain within planned limits. This methodology provides a structured framework that facilitates decision-making based on accurate data, reduces rework, and minimizes risks in project execution. In building projects, its application has led to a 15% improvement in the optimization of material use and a 10% reduction in schedule delays, generating a tangible impact on overall efficiency. The inclusion of new technologies, specifically the integration of Telegram, enhances the effectiveness of the DMAIC cycle by enabling real-time monitoring, generating automatic alerts for deviations, and providing immediate information for resource optimization. These tools are especially valuable in projects with budget constraints or limited technology adoption, as they provide constant control without the need for costly infrastructure, improving the team's ability to react promptly to any eventuality and ensuring that critical construction activities, such as slab pouring, structure assembly, and wall erection, are carried out within the planned time and cost objectives.

The results obtained show that, although there are slight deviations in materials and timing, the project maintains an adequate level of efficiency and cost control, confirming the team's ability to effectively manage critical activities. The combination of the DMAIC cycle with digital tools strengthens the planning, supervision, and control of the project, increasing the reliability of the results and generating a significant positive impact on civil engineering project management. This approach not only allows for the anticipation of problems, the optimization of resource utilization, and the consistent fulfillment of quality, time, and cost objectives, but also proves to be applicable in multi-family building projects, public infrastructure works, and industrial projects, where the control of materials and time is critical. In addition, it establishes a replicable model for future projects, promoting a culture of continuous improvement and the strategic adoption of accessible technologies in construction, which contributes to the development of more efficient and sustainable processes within the professional practice of civil engineering.

Unexpected findings were observed during the implementation of the DMAIC cycle. While the methodology structured the improvement process, certain stages showed limitations in Six Sigma's effectiveness due to the significant variability in data, which depended heavily on each operator's level of experience and on how each area manager handled process execution. This highlighted the challenge of obtaining consistent and reliable measurements, suggesting that statistical tools alone may not fully capture process performance without considering human factors and managerial practices.

8. Declarations

8.1. Author Contributions

Conceptualization, K.W.C.N. and E.D.C.; methodology, K.W.C.N., J.B.C.V., and E.D.C.; software, J.B.C.V. and E.D.C.; validation, J.B.C.V., E.D.C., and J.S.A.A.R.; formal analysis, K.W.C.N.; investigation, K.W.C.N., J.B.C.V., and E.D.C.; resources, J.B.C.V. and E.D.C.; data curation, K.W.C.N.; writing—original draft preparation, K.W.C.N., J.B.C.V., and E.D.C.; writing—review and editing, J.S.A.A.R.; visualization, E.D.C. and J.S.A.A.R.; project administration, K.W.C.N., J.B.C.V., and E.D.C. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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8.5. Conflicts of Interest

The authors declare no conflict of interest.

9. References

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