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Construction 4.0 Application: Industry 4.0, Internet of Things and Lean Construction Tools' Application in Quality Management System of Residential Building Projects

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Abstract: The advent of Construction 4.0 has played a major role in construction industry development through the improvement of quality performance. One of the parameters that have contributed immensely to the management of construction quality in the industrial revolution era is Industry 4.0, the Internet of Things (IoT), and Lean thinking concepts. Lean construction is characterized by a set of clear objectives in project delivery involving the concurrent design of products and processes. The study aims to carry out an exploratory study of the application of Construction 4.0 and Industrial 4.0 in quality management of building works and the development of Lean-based quality management models: The study engaged a survey design approach, and a random sampling technique was used to select the study samples. A structured questionnaire designed on a Likert scale 1–5 was used to collate data on the quality aspect of a construction project, and the data were used in model creation. The parameters that emerged are cast as the quality management model. The resultant factors were categorized into three (3) quality categories, which are the Zero level Defect range, Medium Quality, and High-Level Quality Range. The three (3) quality factors were recommended for adoption for quality management of residential building projects.

Keywords: Internet of Things; lean; waste; quality; regression; factor

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Citation: Lekan, A.; Clinton, A.; Stella, E.; Moses, E.; Biodun, O. Construction 4.0 Application: Industry 4.0, Internet of Things and Lean Construction Tools' Application in Quality Management System of Residential Building Projects. *Buildings* **2022**, *12*, 1557. https://doi.org/10.3390/buildings12101557

Academic Editors: Tarek Zayed and Heap-Yih Chong

Received: 1 July 2022
Accepted: 5 September 2022
Published: 28 September 2022

1. Introduction

The building is one of the construction products often patronized in the economy. It is responsible for the provision of shelter and dwelling space for the masses. The essentiality of shelter provision is of utmost importance, therefore there is a need to maintain quality at the production stage. The construction process for building production requires quality of the procurement system, material processing, planning process, and post-occupancy stage. However, in recent times, the focus has been on the need to maintain quality in the construction process. Clients are gradually complaining more about the requirements for the cost, time, quality, and performance of the building products. Government and statutory organizations are also formulating standards and laws that are focused on meeting the basic building regulation requirements that border on cost, quality, and time parameters. The developed countries of the world have patterned their laws around health and safety practices on site, while in developing countries and the underdeveloped world, the bane has been a compromise on the quality of the final construction process [1].

In the developing world, a system that would enable zero error right from the beginning of the production process is necessary. Maintaining a high-quality production process would enable the attainment of zero defects, which in turn would reduce production costs. One such system that could assist in error reduction at the early and later stages of a project and as the project progresses is Lean applications. Lean applications have gained much publicity in the manufacturing sector but is now spreading through the construction industry [2,3]. One of the major problems in residential building project delivery is poor quality management on construction sites. Poor quality management often leads to delay, time wastage, cost increase, poor performance, and poor productivity amongst others in construction projects. Poor quality management on site often leads to waste generation and non-value-adding activities such as re-work, etc., which sometimes results in a drop in the quality of the project and leads to customer dissatisfaction [4].

However, high-quality management eliminates waste and increases productivity at a minimum cost. It is, therefore, against this background that this research work has demonstrated how the Lean concept could be deployed to create a regression model that could help in creating a quality model for a construction work application, to prevent poor-quality management on sites. In the context of this study, the following objectives were articulated: Exploring (i) the extent of the current level of the wastage threshold on construction sites, (ii) the influence of Construction 4.0 parameters on the quality management of building projects, (iii) the impact of the Internet of Things (IoT) and Industry 4.0 tools in the quality management process of a construction project, and (iv) critical success influencers of construction quality management using the Lean construction concept and developing a Lean-based quality management framework for residential projects. As regards the statement of the problem of this study, which borders on quality management and control in a construction project, in construction work, the risk is inherent in most of the construction portfolio, which tends to make proper planning essential. One of the areas that constitute risk is the quality management of construction activities.

Poor quality management on site always has negative consequences for the project's overall success. Therefore, quality management must be defined clearly from all the stakeholders' perspectives to a great extent, determining the overall success of a project. In terms of risk management and its impact, previous research [4] stressed the negative consequences that could arise on account of the project including cost overrun, a poor project, and delayed projection completion. There are dependent variables in a project that need to be observed, which has been referred to as risk management, while the independent project variable, on the other hand, is project success. For instance, risk management was described in [4,5] as something that needs to be committed to other project parties by the project managers on a project while relying on the framework of implementation as appropriate. Communicating risk in quality management on a project is, however, important, in a bid to communicate the risk of the project. Various methods are often used, and some of the methods exist in the form of categorical regression models, frameworks that are stochastic-based and formed from a recent expert model, artificial intelligence, Lean applications, and the Internet of Things (IoT). For instance, several types of frameworks have been employed in risk quality management in the construction industry. In recent research work, the structural modeling equation (SME) was used to model risk quantification by identifying the risk involved in managing quality.

In recent times, different paradigms have been used to develop frameworks and models for quality management. Artificial intelligence models are vastly being used to develop quality models. For instance, previous authors [6] presented models to be used in quality management and included quality cycles, Taguchi methods, the price-criteria approach, Japanese total quality, the approach company model, total quality management, the element approach, and the Guma approach. The types of models mentioned were alluded to by [4,7,8]. Similarly, the use of the TQM model has been prevalent in the construction industry for decades in developed countries, without prejudice against developing countries such as Nigeria. For instance, previous research [8] presented a mechanism and a model that could be used to manage the quality of residential building projects with different models and frameworks. In the past, regression and stochastic models were used in quality monitoring, until the advent of Industry 4.0 introduced expert models. Categorical regression was used in modeling Lean frameworks in the past, such as the Lean production model, just-in-time production models, six sigma, and total quality management (TQM). In the recent period of the industrial revolution, there has been an emergence of expert models, which include the Artificial intelligence (AI) model, the Neural network model, the Internet of Things (IoT), and the Lean model.

The models are considered composite expert models and are neuro-regressive in structure. Therefore, in the context of this study, a composite model was presented that illustrates the relationship that exists between the three systems, i.e., Industry 4.0, Internet of Things (IoT), and the Lean concept. The concepts of IoT, Lean, and Industry 4.0 show a paradigm shift in the sphere of industrialization and technological development. The main common objective of the concepts is to eliminate onsite waste as much as possible. The adoption of the Lean concept targets the elimination of waste and maintaining quality output and zero defects as a process and product. The Internet of Things (IoT) tends to enable a smooth interconnection of components to enhance the quality of performance and output, while Industry 4.0 is the bedrock of technological change through an adaptable tool to ensure desirable change and automation occur in the process of adopting IoT and Lean concepts, which was supported in [7–10].

Therefore, in the context of this study, Industry 4.0 tools and technology were combined with the parameters of the Lean concept and IoT concepts to develop a composite Construction 4.0 framework, which could be used in the quality management of residential building projects.

Development of Research Hypotheses

A hypothesis is a conjectural statement, a statement of fact that is regarded as incomplete and needs further validation through the support of additional information, facts, and data. A hypothesis usually forms part of the objectives and is a further platform for the cross-examination of facts for the purpose of establishing a validation platform for basic research questionnaires and data collation. In this study, the hypothesis was drawn from some of the objectives set earlier to validate their content reliability. Research gaps were established through the review of related concepts in the study. The gaps identified include the extent of onsite wastage, the impact of Industry 4.0 tools, especially IoT, the influence of Construction 4.0 in quality management, the influencers of success in construction quality management, and the challenges of Lean thinking in construction. The gaps led to the evolution of the pertinent research questions, from which the hypothesis emanated. Some of the questions are as follows: What is the extent of measurable wastage onsite to ensure quality management? What impact does Industry 4.0 have? What are the necessary tools in quality management? What are the success enablers in Construction 4.0 on construction projects? What are the influencers of success in construction quality management? Is it possible to develop a Construction 4.0 quality framework application model with Industry 4.0 and Lean construction?

With the aim of further expansion on selected pertinent objectives, the hypothesis was developed from the objectives. Three hypotheses were proposed to further validate some of the objectives. The hypotheses are as follows: (i) Hypothesis 1 H1 (objective 3): There is consistency in the opinions on the impact of the Internet of Things (IoT) and Industry 4.0 tools on the quality management process; (ii) Hypothesis 2 H2 (objective 2): There is positive agreement as regards the wastage threshold on construction sites on account of process automation; and (iii) Hypothesis 3 H3 (objective 4): There is variation in the opinion of respondents related to the rating of success influencers of a construction project.

The integration of structural components of the quality management system with other research domains is presented in the chart in Figure 1. The structure is based on the input process–output structure, as well as other domain activities geared toward the fulfillment of the content of the structure. This is reflected in quality being observed at the three stages of the construction process. The bedrock of the whole process is the development of a framework that integrates Lean construction, the Internet of Things, and Industry 4.0 tools Therefore, the developed quality management system integrated Internet of Things (IoT) parameters, Lean construction parameters, and Industry 4.0 parameters to develop the quality monitoring system. Therefore, the inter-phase used in the development of the framework includes IoT tools, Industry 4.0 tools, and Lean construction. The objectives represent the quality-oriented input articulated through tools to be able to achieve output in the form of an operationalized model.

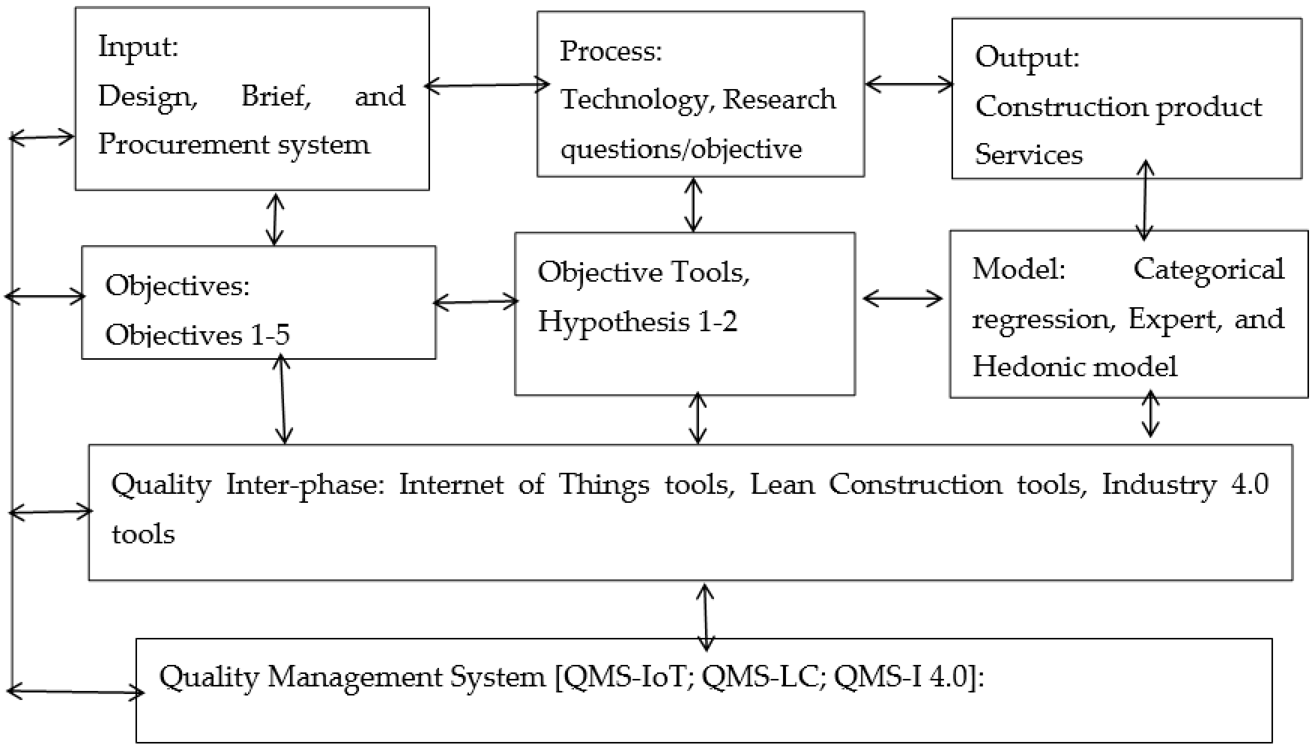

Figure 1. Integration of quality management system with the Internet of Things (IoT), Lean Construction (LC), and Industry 4.0 (I 4.0) domains.

2. Literature Review

2.1. Construction 4.0 (C 4.0)

Construction 4.0 has been an interesting phenomenon. It entails the application of Industry 4.0 tools in creating a good output environment in the construction industry. Construction 4.0 introduces the application of new dimensions in the design, construction, and management of construction works. In design, there are different dimensions such as 2D, 3D, 4D, 5D, 6D, and 7D, with an era of smart technology that helps solve the issue of client and construction challenges on site. Therefore, Construction 4.0 is the integration of Industry 4.0 technology and tools to enhance production and manufacturing efficiency. Construction 4.0 also bridges the gap that exists between the organization or client and the technology. Therefore, an adaptation of technology and its application of technology plays a major role in the adoption and utilization of Industry 4.0. The construction industry has challenges that border on work organization, productivity, and process management, which Industry 4.0 provides means to overcome. Therefore, C 4.0 utilizes Industry 4.0 tools that assist in decision making, planning, organization work, site productivity enhancement, cutting-edge tools, and process management. In the current dispensation, some applications have been enhanced through several applications in the construction field, including robotics, application in the design and construction process, embedded systems, additive manufacturing/production, the introduction of human–computer application, and automation, among others.

Similarly, some applications are interconnected by internet applications and functions, which enable fast and easy access to functions in the construction process. For instance, Construction 4.0 has led to the introduction of smart technologies in the design process and facility maintenance work. In recent times, construction building information modeling (BIM) has come with 2D and 3D applications (see Figure 2). They include Primavera and Revit, which enable the modeling of realities of 2D and 3D printing applications in construction design quality management and assurance. The most recent 4D application in smart systems emerged recently, which enables more access to applications in which smart construction applications were developed. Expert systems of artificial intelligence came to the fore in the C 4.0 era and have accelerated the ways things are conducted in manufacturing and industrial production. Some programs think independently, although not without human effort in formulating a solution to various site challenges, which involve cost, time, and resources. Furthermore, Construction 4.0 has enabled enhanced printing, providing smart printing over analog types. In [5], the authors alluded to the fact that additive manufacturing or 3D printing has led to automation in design printing for local industrial manufacturing, including the Internet of Things (IoT).


3D MODEL OF WHEEL

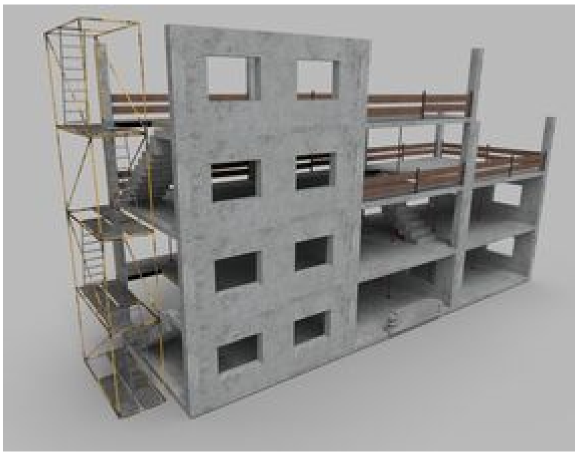
4D BUILDING MODEL

Figure 2. 3D and 4D Models http://3dexport.com/free-3d-models (accessed on 23 May 2022).

In recent times, several studies have been carried out in a bid to situate the application of Construction 4.0 and Industry 4.0 in the construction industry. The documentation covers the education application of smart technology and blended technology application on construction sites and deployment in the manufacturing and production sectors. For instance, [6] focuses on an overview of Construction 4.0 and also leverages the application of four-layer implementation strategies being considered for industrial application, which was also alluded to in [7]. In the development of Construction 4.0 applications in construction, there are basic elements of Construction 4.0 necessary for its success. In [6,7], the elements include virtual reality, augmented reality, robotics, 3D printing, BIM, IoT, big data, artificial intelligence, and drones. However, contributions abound in financial applications on construction sites, and the emergence of systems based on intelligence systems has made the introduction of productivity enhancement functions to the extent of monitoring quality on site possible. Cryptocurrency has the promise of virtual payment of services and duty on construction sites. It is regarded as the technology of the future [8,9].

2.2. Industry 4.0 (I 4.0) and the Construction Industry

The industrial revolution has been a major addition to contemporary society. Industry 4.0 (I 4.0) induces enhanced productivity in the construction industry, and it was reported to increase the global GDP of countries by 6% and the construction industry's GDP by

8%. According to [8] in [10], global building investment had reached $11 trillion by 2019 and is projected to reach $14 trillion by 2025. Industry 4.0 was initiated as far back as the eighteenth century (the 1800s). It stemmed from the coal era to the iron era, up until the mid-eighteenth century, which witnessed mechanization. A synopsis of the process of the industrial revolution was illustrated in [11]. Regarding the submission in [11], the authors alluded to the fact that the Industrial Revolution began in 1800 with industry 1.0, which was mainly focused on the development of steam power plants and locomotive innovations. This continued until the beginning of the 20th century, which birthed Industrial revolution 2.0 (I 2.0). Industry 3.0 (I 3.0) came at the onset of the 20th century with the evolution of industrial automation with artificial intelligence and robotics. The digitization era started when equipment and tools that had been manually operated were replaced with sensor-based appliances. The era of process digitalization is what is encapsulated in Industry 4.0. Industry 4.0 has led to the development of construction automobiles and accessory items that are equipped with laser lights that enable enhanced output and operations. Industry 4.0 started in 2013, while industry 5.0 was birthed in 2020. Industry 5.0 entails innovations of 5D, which enables cooperation between humans and machines through robotics and intelligent manufacturing/production. Industry 4.0, however, according to [11–13], still has a promising future. For instance, some of the good prospects of Industry 4.0 is the digitization of the value chain in material and construction management and intelligent manufacturing with sensor-based applications.

2.3. Construction 4.0 and Internet of Things (IoT) Application in Quality Management in the Construction Field

The construction industry all over the world is noted for provisioning real estate products, which in turn satisfies the needs of consumers. Products include major housing and accommodation facilities. The production of construction products, however, is labor-intensive and demands a great deal of effort. The input in this context refers to the input on the part of construction project actors whose efforts determine the quality of the construction products. In light of the above, monitoring and control is essential for quality results and output in the construction industry. The quality, therefore, has to be holistic, covering the life cycle of a product. The life cycle of construction starts from the idea conception stage, which invariably implies that quality formulation and implementation begin right at the idea conception stage. Before the advent of Construction 4.0, the analog model of reality was predominantly in use in the design decision support system and construction monitoring and control. The analog model was reputed for its time-consuming and cost-intensive characteristics, as well as its non-flexibility in function adaptation, among other reasons. However, the advent of Construction 4.0 has an enhanced model output. For instance, in the Construction 4.0 era, sensor-based 3D systems are in use in construction product modeling. The advent of computer-aided design (CAD) in the construction industry has enabled quality assurance in the design process. CAD enables designers to visualize how the drawing appears or the drawing outlook. This allows for on-time adjustment and manipulation. According to [11–14], the calibrated application has gained access to the construction industry. In Construction 4.0, quality management quantitative tools that capture function and form are being used in decision support systems and in quality parameter formulation and development, while virtual reality and augmented reality applications help one to visualize how the effect of quality could be quantified in the construction process. Therefore, opportunities abound in the application of Industry 4.0 in construction quality management.

2.4. Lean Construction (LC): Adopting Lean Construction Technique in the Construction Field

Although LC implementation in the construction industry has been fraught with difficulties, several industries have seen value in embracing advancements through Lean implementation [13]. Many advantages and benefits have been identified by researchers. One of the major advantages of employing Lean construction in businesses is the minimization of waste [14]. Lean construction encourages the following, by eliminating waste in the construction process: Reducing the duration that equipment and workers are handled, balancing the team, coordinating the flow of information, removing any limitations imposed by material constraints, reducing input variance and changeovers as well as difficult setups, and decreasing interpersonal tensions.

Similarly, the most important benefit, according to [15], is increased customer satisfaction. Construction companies that implement Lean construction with a customer focus can meet the needs of the client, define value from the perspective of the project, respond to opportunities and changing needs with flexible resources and adaptable planning, and apply targeted cost and value analyses.

Sanitation and coordination are important benefits because they often obscure opportunities for improvement and the sources of problems. According to [16], when one has a clean workplace, cracks, missing parts, or leaks in equipment are more visible, which increases workplace safety and reduces the risk of accidents to a minimum. In addition, Lean construction promotes equipment productivity, skilled operators, the use of appropriate equipment, and high equipment performance. Housekeeping is a good starting point and a successful way to cultivate and strengthen important work customs, behaviors, and skills for waste reduction, continuous product improvement, and Lean building. According to [17], the Lean construction benefits that flow from construction organizations, and are known to be the most important gains of implementing the Lean construction technique in the construction industry, are as follows: Enhanced security, reduced waste, reduced expenses, increased productivity, shorter schedules, improved trustworthiness, higher standard of living, increased customer satisfaction, higher predictability, and improved design for easier construction

According to [18], Lean construction practitioners believe that Lean construction helps organizations to reduce their inventory, increase the use of multi-skilled workers, eliminate the management structure, and focus resources on the most effective tasks. Furthermore, according to [18], the benefits of using the Lean construction technique in the construction industry include shorter lead times, lower costs, higher efficiency, less waste, better quality or fewer defects, and shorter cycle times. The following are the labor-related advantages of Lean construction, as discussed by [18]: Reduced labor while the output is maintained or increased, maximized use of multi-skilled workers, increased effectiveness of stakeholder relations, higher level of encouragement for working together, and more encouragement for all project participants to think in a Lean way.

2.5. Review of Application of Quality Management Framework

The review was carried out on the frameworks and concepts of Construction 4.0, Industry 4.0, Internet of Things (IoT), and Lean and quality management in residential work, regarding the processes and products. In construction work, there are two types of quality being enforced, namely quality enforcement in terms of the process of construction and the quality of the product produced. In [4,5], quality was viewed as a subjective concept. It is subjective in terms of parameters often dictated by consumer needs, client needs, and professional input in one of the quality standards. In the submission of the ISO 9001 standard, quality management as a process entails quality in the component as a process to achieve quality in the construction project. This involves focusing on the consumer's needs and requirements, leadership, involving people, adopting a system approach, enforcing continual improvement, using facts in decision-making, and establishing a mutually beneficial relationship. The quality management system ensures compliance with quality regulations to satisfy customers' requirements, the continual improvement of quality processes, and ensuring the product and services are in line with company objectives and standards. Similarly, quality management in a residential project as a product could be viewed from the perspective of the component that is summed up as quality in the finished product. It entails achieving zero defects in the final product generated. In [5–8], the quality component as a product could be summarized as a required composition, the reported quality management, quality system, quality management team, and the degree of quality achieved. Summarily, the quality of the products could be measured based on the perceived quality of the final product, the quality of the management process, the set of interrelated systems, and the set of requirements incorporated in a way that modeled the finished product.

2.6. Justification of Proposed Quality Management Frameworks

In the construction industry, there have been several types of research on the quality management of construction projects. Frameworks based on stochastic and regression models abound. Some of these frameworks include total quality management (TQM), hedonic models, case-based models, Lean models, expert models, and artificial intelligence models. A study carried out by [16,19] submitted that the current regression-based models are lacking in data processing and consistency. The TQM model and related framework according to [16] is limited in data application and restricted in its capacity to predict variables, ability to update data, and data parsimony, among other factors.

However, there are reasons why new frameworks and models are needed, and this reason lies in the fact that the previous model, according to [13,15], is based on a step approach in structure, while the proposed framework in this study is based on the system approach. However, their similarity lies in the following facts: A tendency to be condensed into a single framework, the capacity to incorporate detailed goals, objectives, and plan implementation, and the tendency to update the framework component, which was alluded to by [12,13,19]. In the context of this current study, however, no study has used the three Construction 4.0 tools in the way they have been applied in the context of this study to develop a quality framework. Therefore, this study attempted to use Industry 4.0 tools and the Lean concept to develop a model that could be used to monitor project quality holistically through the project cycle.

In the context of this study, Industry 4.0 tools, i.e., the Internet of Things and Lean thinking tools, were used in the configuration of the structure of the framework. The choice of the systems was unique due to the positive attributes of the Lean concept and the Internet of Things. The holistic model enables the use of the good attributes of IoT in the automation base, while the parameters of Lean construction were used to formulate the quality dichotomy of the resultant model. The attributes include zero defects, effective quality communication, quality monitoring and control, and training and development, among others.

3. Materials and Methods

In this section, the methodology used in the research is presented.

3.1. Research Design

The qualitative research approach was used with purposive sampling methods centered on professionals and construction companies, where industry tools, the Internet of Things, and the Lean concept approach are practiced, as indicated in the questionnaire that was used to collate responses from the respondents. The survey was carried out with the aid of a structured questionnaire, designed with a semantic rating scale.

3.2. Population Frame

A sample of 250 medium and large-scale construction companies was used in this study.

3.3. Sample Size

The sample used in this study constitutes the professionals that work in the construction companies sampled, constituting a total of 150 construction professionals. The questionnaires were designed on a Likert scale of scale 1 to 5 and administered to 150 respondents. The sample size was determined using this relationship:

$$n = N/[1 + ((S-1))/N] \quad (1)$$

where n is the sample size, N is the population, and S is the margin error.

The respondents include professionals such as builders, architects, engineers, and contractors, comprising architect = 30, builders = 30, quantity surveyors = 30, engineers = 30, and contractors = 30.

3.4. Sampling Techniques

The random sampling technique is often used to pick a sample from a population frame in a qualitative and quantitative method used in research work. Therefore, the random sampling method was used to select the 150 respondents that constituted the research sample used in the study. The respondents were picked from different construction firms, and personal interviews were collected from professionals from the construction firms.

3.5. Research Data

The secondary data for the study were collected through the exploration of various relevant literature and previous research conducted in the area of study. These include data from textbooks, learned journal articles, peer-reviewed research papers, academic articles, conference proceedings, and electronic sources. Respondents were asked to indicate their level of understanding by ticking a column of relative importance.

3.6. Data Analysis

The analysis aimed to establish the validity of the data collated in terms of justifying the research variables. Some of the methods used in analyzing the collated data include the simple percentage, Chi-square, Mann–Whitney U test, Spearman rank test, and mean item scores. The Relative Mean Index (RMI) and Relative Importance and Agreement Index of Mean item scores were calculated using the equation stated below, as used in Likert (2004) following a Likert scale of 1 to 5 [20]:

$$\text{Relative Agreement Index (RAI)} = 5SA + 4A + 3N + 2SD + 1D\ [5(SA + A{+}N + SD + D)^{-1}] \quad (2)$$

where SA represents Strongly Agree, A represents Agree, N represents Neutral, SD represents Strongly disagree, D represents Disagree, RII represents the Relative Importance Index, and RAI represents the Relative Agreement Index.

$$\text{Relative Importance Index (RII)} = 5SI + 4I + 3N + 2SNI + 1I\ [5(SI + I{+}N + SNI + NI)] \quad (3)$$

where SI represents Strongly Important, I represents Important, N represents Neutral, SNI represents Strongly Not Important, and RII represents the Relative Importance Index.

3.7. Factor Rotation and Extraction for Model Development

A quality management model was developed in this study, using parameters that cut across the three (3) concepts, i.e., Lean concept, Industry 4.0, and Internet of Things (IoT) parameters. The raw data from the survey were extracted from the three (3) concepts and used in the model developed with the aid of SPSS statistical analysis software. The factors were subjected to factor rotation to reduce the factors from twenty-four to twelve, which would represent other factors using Direct Obilim and Varimax with Kaiser Normalization, while the factors with small coefficients were suppressed, only extracting factors with Eigenvalues between 0.97 and 1.0. The resultant factors were used to produce the composite model. The scores obtained from each of the independent variables, that is, the Lean construction principle-based parameters, Internet of Things (IoT), and Industry 4.0 parameters for managing quality, were cross-examined to determine the parameters to be included in the model. The Eigenvalues of the parameters were used to classify the factors into high-, medium-, and low-quality factors. An Eigenvalue of 1.0 was accepted as the point of highest perfect reliability, and therefore the closer the value to 1.0 the more reliable. Therefore, values between 0.9 and 1.0 were classified as the highest point of quality reliability, scores between 0.7 and 0.8 were classified as medium reliability or medium quality, and scores between 0.5 and 0.6 were classified as low-quality values, in accordance with [20,21].

4. Results

4.1. Respondents' Bio-Data Information

Bio-data information of the respondents is presented in Table 1. The status of the companies used in this study includes property development firms, contracting organizations, project clients, and consultancy firms. The respondents were taken from the company categories presented in Table 1.

Table 1. Bio-data information of respondents.

Parameters	Category	Frequency	Percentage
Are you exposed to C 4.0 and I 4.0	Yes	80	79.21
	No	20	19.80
	Neural	1	0.99
Age Group	21–30 y	60	59.41
	31–40 y	30	29.70
	41–50 y	11	10.81
Years of Experience	≥15 y	45	44.55
	11–15 y	29	28.71
	5–10 y	19	18.82
	≥5 y	8	7.92
Placement in the Company	Project Manager [Builders]	41	41.00
	Design Specialist [Architect]	30	29.70
	project site Coordinator [Civil engineer]	15	14.85
	Quantity Surveyor	15	14.85
Company Status	Developer	41	40.59
	Contractor	30	29.70
	Client	15	14.85
	Consultant	15	14.85

Source: Author's field survey, 2021. C 4.0–Construction 4.0; I 4.0 (Industry 4.0).

4.2. Normality Test for Variables

A reliability test was carried out on the research variables to establish the extent of their reliability using 99 variables from research variables.

The test was carried out based on standardized items using 'N' numbers of variables and the results are presented in Table 2. The reliability of a variable often falls between 0 and 1, and the closer the Cronbach alpha value is to 1, the higher the reliability of the research variables. In the context of this study, the Cronbach alpha test value obtained was 0.839. The value obtained through statistical analysis (0.839) was close to 1.0, indicating a strong correlation and strong reliability. It also indicated, as alluded to in [16,19], consistency in the calibrated data collection instrument and other research variables.

Table 2. Cronbach alpha test statistics on research variables.

Reliability Statistics		
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	Number(N) of Items
0.839	0.259	99

Source: Author's field survey, 2021.

4.3. Influence of Construction 4.0 on Quality Management of Building Projects

The influence of C 4.0 is presented in Table 3, where both intelligence manufacturing and the development of digitalization initiatives in quality management have RAI values of 0.897 and were ranked first. Additive manufacturing was ranked third with an RAI value of 0.895, while other factors were ranked in the following order, according to their respective relative agreement index (RAI): Artificial intelligence in quality management and mobile computing systems was ranked fifth with an RAI of 0.979, social media and multimedia systems was ranked sixth with an RAI score of 0.871, while innovative robotics in quality assurance and the automation of construction systems quality management was ranked 7th with RAI scores of 0.870. The remaining factors were ranked ninth to thirteenth in the following order: Big data application was ninth, cloud computing application was tenth, virtual reality and augmentation was eleventh, 3D printing and quality output in documentation was twelfth, and expert system and neural networking was thirteenth.

Table 3. Influence of Construction 4.0 on quality management.

Construction 4.0 Influence Parameters	Mean	RAI	Rank
Intelligence Manufacturing	4.485	0.897	1st
Development of Digitalization Initiative in quality management	4.485	0.897	1st
Additive Manufacturing	4.475	0.895	3rd
Artificial Intelligence in quality management	4.440	0.888	4th
Mobile Computing System for quality management	4.395	0.879	5th
Social media and Multimedia System	4.355	0.871	6th
Innovative Robotics in quality assurance	4.350	0.870	7th
Automation of Construction Systems quality management	4.350	0.870	7th
Big data application	3.990	0.798	9th
Cloud Computing and Applications	3.975	0.795	10th
Virtual Reality and Augmentation	3.755	0.751	11th
3D-Printing in quality output in documentation	3.750	0.750	12th
Expert system and Neural Networking	3.745	0.749	13th

Source: Author's field survey, 2021 RAI- Relative Agreement Index.

The importance of Construction 4.0 has largely contributed to the changes in productivity experienced in the construction industry and enhanced delivery all over the world with the adoption of intelligent manufacturing and the development of digitalization initiatives in quality management. Intelligence manufacturing has enabled risk reduction on account of the automation of the construction process. In quality management, the manual approach to quality assurance in the construction process has been replaced with automation systems. For instance, artificial intelligence-based support and decision-based systems are widely in use, with tremendous results. In the design stage, decision support systems have helped to maintain automation in design, thereby eliminating waste and ensuring quality decisions. Some such systems include AutoDesk, Revit, Orion, and Primavera [20,21]. These systems have helped to ensure quality in processes and products. The role of Industry 4.0 in the construction industry has been mentioned in other submissions such as in the works of [22–24], in which the challenges involved in C 4.0 quality issues were mentioned in [22], risk management was studied in [23], and a solution to quality management in construction was stressed in [21,24,25]. Furthermore, Construction 4.0, as presented in Table 3, has influenced the construction industry positively, and according to submissions in [20,21], which explored issues around Construction 4.0, the areas of influence of Construction 4.0 in the construction industry include automation, robotics, mobile computing, cybernetics, and additive and intelligent manufacturing. It has tremendously impacted the ecological landscape; therefore, in the context of this study, the area of influence of Construction 4.0 was identified to include intelligence manufacturing, the development of digitalization initiatives in quality management, additive manufacturing, artificial intelligence in quality management, and mobile computing systems for quality management, among others.

4.4. Impact of Industry 4.0 Tools on Quality Management Process of Construction Project

Industry 4.0 (I 4.0) induced Construction 4.0 (C 4.0), and since then, Industry 4.0 (I 4.0) has become the center of industrialization, which has led to enhanced construction productivity. Research has been exploring Industry 4.0 and Construction 4.0 earnestly. The impact has cut across industries and organizations across the world, for instance [26] presented Industry 4.0 attributes concerning future industrial opportunities and challenges, a major factor identified is enhanced productivity and enhanced industrial productivity. Similarly, [27] explored the design and control of the logistic process in an Italian company, stressing the design and quality control process in Italian construction and industrial organization based on Industry 4.0 principles.

Therefore, in the context of this study, the impact of the Internet of Things (IoT) as an Industry 4.0 tool in the quality management process of a construction project was explored and is presented in Table 4. Some of the biggest impacts were observed for the introduction of robotics automation in construction, which was ranked first by the three categories of respondents used in the study, including design specialists, project site coordinators, and project managers. The respondents rated the same parameters as being of high impact or influence in the construction industry. The following factors were rated on a scale of 1 to 6: Additive product manufacturing was ranked first, development of the Internet of Things for system development was ranked second, mobile computing was ranked third, and the digitalization of functions and processes in construction was ranked fourth, while big data application in the construction process was ranked fifth.

Table 4. Industry 4.0 tools' impact on quality management process of a construction project.

Construction 4.0 Influence Parameters	PM	Rank	DS	Rank	PSC	Rank
Introduction of Robotics	0.897	1st	0.867	1st	0.931	1st
Automation in Construction	0.897	1st	0.867	1st	0.915	2nd
Additive Product Manufacturing	0.888	3rd	0.856	3rd	0.907	3rd
Development of the Internet of Things for system development	0.888	3rd	0.854	4th	0.903	4th
Mobile Computing	0.886	5th	0.854	4th	0.853	5th
Digitalization of Functions and Processes in Construction	0.885	6th	0.843	6th	0.842	6th
Big data application in the construction process	0.875	7th	0.843	6th	0.842	6th
Simulation Models Development	0.871	8th	0.843	6th	0.753	8th
The invention of Social Media applications	0.798	9th	0.822	10th	0.757	9th
Advent of Cybernetics	0.790	10th	0.757	11th	0.753	10th
Synthesization of Augmented Reality and Virtual Reality	0.770	11th	0.745	12th	0.745	11th
The proliferation of Encoding System	0.770	11th	0.681	13th	0.681	12th
The advent of Building Information Modelling(BIM)	0.751	13th	0.657	14th	0.680	13th
Introduction of Human-Computer Interaction	3.725	14th	0.650	15th	0.645	14th
The advent of Embedded systems and Encryption	3.705	15th	0.541	16th	0.541	15th

Source: Author's field survey, 2021, DS: Design Specialist; PSC: Project Site Coordinator; PM: Project Manager.

4.5. Perpetual Comparison of Construction Stakeholders on the Impact of Internet of Things (IoT) and Industry 4.0 Tools in the Quality Management Process

A Chi-square analysis of the data is presented in Table 5. The parameters of the impact of IoT on the total quality management process in the construction field were subjected to Chi-square analysis to validate the hypotheses based on the level of agreement of opinions on the impact of the Internet of Things on the quality management of construction processes and technology. It was discovered that the major impact of IoT, according to the data analysis, was found to include the advent of robotics and the automation of construction content in product manufacturing and development. Table 5 presents a Chi-square analysis using four categories of respondents, that is, project managers, design specialists, project site coordinators, and contractors. The Chi-square analysis was carried out at an alpha value of 0.05 with varying degrees of freedom based on the test parameters adopted. It was noted that the asymptotic significance of all the categories of respondents was greater than 0.05. This shows that the Chi-square result was greater than 0.05. The implication of this result lies in the fact that there is no divergence of opinions among the respondents and in the ranking of the factors. The null hypothesis was rejected at a *p*-value greater than 0.05. Therefore, there is a similarity in the opinions of the project managers, design specialists, project site coordinators, and contractors as regards the impact of the Internet of Things and Industry 4.0 tools on the quality management process in the construction industry. Asymptotic significance values were observed in the resultant analysis, including project manager (0.963), design specialist (0.801), project site coordinator (0.990), and constructor (0.480). Previous authors [26,28] posited the industrial application of Industry 4.0 tools, of which the Internet of Things was among. It was regarded as the future of industrialization, and this could have alluded to the reason behind the trend in the respondents' opinions reported in this stud

Hypothesis 1 (H1): *There is consistency in the opinion on the Impact of Industry 4.0 Tools in 115 Quality Management process 116.*

Hypothesis 1 (H2): *There is no consistency in the opinion on the Impact of Industry 4.0 Tools in 117 Quality Management processes.*

Table 5. Chi-Square test analysis on the extent of opinion consistency on Industry 4.0 tools.

Statistics Variable	Project Managers	Design Specialist	Project Site Coordinator	Contractor
Chi-Square	1.000 [a]	1.000 [b]	0.750 [c]	0.500 [d]
Degree of Freedom (df)	5	3	6	1
Asymp. Sig.	0.963	0.801	0.993	0.480

Source: Author's field survey, 2021.

4.6. Industry 4.0 Impacts on Quality Management Process of Construction Project

The statistical test results on the Internet of Things (IoT) and Industry 4.0 impacts on the quality management process of a construction project are further presented in Table 6. The table presents an analysis of the impact of IoT on the quality management process in the construction industry. The test analysis was carried out on the variables of Industry 4.0 and IoT. The Internet-of-Things measures include mobile computing, computer networking, data banking, big data application, sensor-based applications in building, and human–computer interaction, among others. Mann–Whitney U and Wilcoxon U tests were carried out on the IoT and Industry 4.0 parameters and are presented in Table 6. It was discovered that the asymptotic significance value of the parameters tested was higher than the *p*-value of 0.05. Therefore, some of the areas of consensus on the impact of IoT and I 4.0 with high values include the advent of robotics applications in the industry, the introduction of automation in the construction process, and the quality assurance of construction processes and procedures and the post-occupancy period. A new area that was recently introduced was the aspect of additive manufacturing. In the construction field, quality assurance has recently been carried out with the aid of robotic applications. Robotics has found applications in material production and processes, as in the case of advanced countries such as European countries and Asia countries. For instance, Refs. [12,23] explored the application of automation and the Internet of Things in managing construction processes to maintain quality and ensure seamless production and manufacturing. Similarly, previous authors [27–31] presented opportunities for industrial applications of I 4.0 and IoT in construction based on the paucity of their applications for enhancing construction products.

Table 6. Mann–Whitney U and Wilcoxon W statistical test results on Internet of Things (IoT) and Industry 4.0 impacts on quality management process of a construction project.

Industry 4.0 and Internet of Things Impact Parameters		N	Mean Rank	Mann-Whitney U	Wilcoxon	Asymp Sig.
Introduction of Robotics [I4.0]	0.00	4	2.00	1.000	4.00	1.00
	1.00	4	2.00			
Automation in construction [I4.0]	0.00	4	2.25	0.500	1.50	0.48
	1.00	4	1.50			
Additive production and manufacturing [I4.0]	0.00	4	2.00	1.000	4.00	1.00
	1.00	4	2.00			
Internet of things application [IoT]	0.00	4	2.50	0.000	1.00	0.157
	1.00	4	1.00			
The advent of Mobile computing [IoT]	0.00	4	1.75	0.500	3.500	0.480
	1.00	4	2.50			
Digitalization of construction functions [IoT]	0.00	4	2.00	1.000	4.000	1.000
	1.00	4	2.00			
Big data application in the construction process [I4.0]	0.00	4	1.50	0.000	3.000	0.157
	1.00	4	3.00			
Simulation models development [I4.0]	0.00	4	2.00	0.000	3.000	0.157
	1.00	4	2.00			
The invention of Social Media applications [IoT]	0.00	4	2.25	0.500	4.000	0.480
	1.00	4	1.50			
The advent of Cybernetics application [IoT]	0.00	4	2.25	0.500	1.500	0.480
	1.00	4	1.50			
Synthesization of Augmented Reality and Virtual Reality [I4.0]	0.00	4	2.25	0.500	1.500	0.480
	1.00	4	1.50			
The proliferation of Encoding systems [I4.0]	0.00	4	2.50	0.000	1.000	0.221
	1.00	4	1.00			
The advent of Building Information Modelling [I4.0]	0.00	4	2.25	0.500	1.500	0.480
	1.00	4	1.50			
Introduction of Human-computer interaction [IoT]	0.00	4	2.25	0.500	1.500	0.480
	1.00	4	1.50			
The advent of Embedded System and Encryption [I4.0]	0.00	4	2.25	0.500	1.500	0.480
	1.00	4	1.50			

Source: Author's field survey, 2021, C 4.0—Construction 4.0; I 4.0—Industry 4.0; IoT—Internet of Things.

4.7. Project Stakeholder on Impact of Industry 4.0 Tools in Quality Management Process

Statistical analysis was carried out on project consultants' responses regarding the impact of the Internet of Things (IoT) and Industry 4.0 (IoT) tools in the quality management process as they relate to the applicability and potential advantages of the Internet of Things. The results are presented in Table 7. Mann–Whitney U and Wilcoxon U test results tended to agree on the extent of the impact of the Internet of Things and Industrial 4.0. There was uniformity and agreement in the respondents' opinions. This validates the applicability of IoT in changing the terrain of productivity in the construction industry.

Table 7. Project consultants on impact of Industry 4.0 tools in quality management process.

Statistical Parameters	DS	PSC	PM
Mann-Whitney U	2.500	3.000	3.000
Wilcoxon W	17.500	18.000	18.000
Z	−1.547	−1.350	−1.358
Asymp. Sig. (2-tailed)	0.122	0.177	0.174
Exact Sig. [2*(1-tailed Sig.)]	0.143 [b]	0.250 [a]	0.250 [b]

[a] Grouping Variable; [a&b] Not corrected for ties. DS: Design Specialist; PSC: Project Site Coordinator; PM: Project Manager. Source: Author's field survey, 2021.

4.8. Developing Lean Thinking Tools—Internet of Things (IoT) and Industry 4.0 (I 4.0) Based Quality Management Model for Residential Projects

The model was premised around Lean thinking's main parameters, which were further consolidated into a few factors, such as establishing quality cost objectives, communication, authority and responsibility, monitoring, and control. Several factors were grouped under these variables and were later subjected to factor analysis. In creating a dynamic model to manage quality in residential building projects, certain Industry 4.0, Internet of Things, and Lean Construction tools' parameters were used in the model developed in this study. The parameters include quality cost objective, monitoring and control, communication, authority, and responsibility. The model was premised around the Lean thinking concept, Internet of Things (IoT), and Industry 4.0 (I 4.0)-based parameters. The parameters are consolidated into five parameters, which are establishing quality cost objectives, communication, authority, responsibility, monitoring, and control.

4.9. Detailing Objectives for Project Quality Cost

Setting quality objectives first, before allocating resources to their fulfillment, and then the provision of means of carrying out the specifics of the objective, are the priorities in quality monitoring. Furthermore, project expenditure benchmarking, objective operationalization, and, above all, expenditure, should be minimized in all phases of quality management. To this end, Table 8 presents the parameters of the quality cost objectives. The results reveal that allocating contingency allowances for the provision of tools and equipment and improving construction processes, thereby reducing project costs, each with a corresponding relative importance index value (RII = 0.84), were rated as the most important factors among the variables examined, followed by benchmarking project expenditure on account of machine and plant maintenance (RII = 0.83). Minimizing expenditure to maximize profit was rated the lowest by the respondents (RII = 0.81) [32–34]. Summarily, quality cost objectives, considering the importance of quality management in building construction management as identified in the study, constitute allowing contingencies for tools and incidentals for internal and external failure, improving construction processes and thereby reducing project costs, benchmarking project expenditure on account of machines' and plants' maintenance, and minimizing expenditure to maximize profit. Statistical analysis was carried out on the parameters and is presented in Table 9. The cost quality objectives highlighted in Table 8 are in accordance with previous research [35–38], which recommended a system approach to quality management in construction project quality management. Setting quality objectives comes first before allocating resources to their fulfillment, which is then followed by the provision of means of carrying out the specific objectives, project expenditure benchmarking after the objectives' operationalization, ad then, above all, expenditure should be minimized in all phases of quality management.

Table 8. Parameters on quality cost objectives.

Parameters	Mean	RII	Rank
Allowing contingencies for tools and incidental for internal and external failure	4.290	0.858	1st
Improving construction processes thereby reducing Project cost	4.240	0.848	2nd
Benchmarking project expenditure on account of machine and plants maintenance	4.185	0.837	3rd
Minimizing expenditure to maximize profit	4.135	0.827	4th

Source: Author's field survey, 2021 RII—Relative Importance Index.

Table 9. The Chi-Square test's statistical results on quality cost objectives of construction quality management.

	Allowing Contingencies	Improving Construction	Periodic Establishment	Minimizing Expenditure
Chi-Square	0.400	0.600	0.600	0.000
df	2	3	3	4
Asymp. Sig.	0.819	0.896	0.896	1.000

Source: Author's field survey, 2021.

The Chi-square results of the analysis are presented in Table 9. The Chi-square test examined the alignment of cost and quality. Some of the parameters that were considered important in formulating quality objectives tested in this study include allowing contingencies as part of the means of funding the quality cost, improving the construction process and procedure, the periodic establishment of quality assurance training and empowerment, and minimizing expenditure onsite. The SPSS values obtained for the factors were higher than the *p*-value of 0.05, therefore the null hypothesis is accepted as the Asymp. Sig. is higher than the *p*-value of 0.05. Therefore, there is a significant difference in the opinions of respondents on three of the four factors presented. However, there was agreement among the respondents on the fourth factor, which focuses on minimizing expenditure on construction sites. In [35], objectives come first before resource allocation, and the system approach was advocated as one of the ways to solve the quality problem at the outset of project development, while objectives should be further expressly stated in clear terms to ensure the team is aware of the objectives of the operations to be carried out. Similarly, Refs. [37,38] described cost quality as a necessity that is of utmost importance at every stage of the building process, while setting quality objectives is important as is communicating the quality review carried out to team members.

The survey data presented in Table 10 indicate some of the parameters measuring communication, authority, and responsibility. The results reveal that promoting effective communication of information on work quality standards to the maintenance personnel received the highest support among the surveyed professionals (RII = 0.896), followed by the delegation of responsibilities (RII = 0.877) and management periodically holding meetings on quality in maintenance issues (RII = 0.860). The last factor identified by the respondents was designing a future value stream mapping of materials (RII = 0.791). Effective communication of quality issues is an important aspect of quality monitoring and benchmarking in the construction field. The decisions made about quality issues should be communicated to all project team members. Similarly, the following parameters are also important as regards quality issues in the construction process: Setting up an effective communication strategy for work quality and the improvement of the quality of work and operational standards, the delegation of responsibilities, the periodic establishment of quality and maintenance management meetings on sites, and the establishment of a policy implementation committee ([35–38]).

Table 10. Parameters on communication, authority, and responsibility.

Parameters	Mean	RII	Rank
Setting up an effective communication strategy for work quality and improvement of quality of work and operational standard	4.480	0.896	1st
Delegation of responsibility is essential	4.385	0.877	2nd
Periodic establishment of quality and maintenance Management meetings on sites	4.300	0.860	3rd
A policy implementation committee needs to be established	4.265	0.853	4th
Establishing a line of command is essential	4.220	0.844	5th
Identify value from the client's perspective	4.240	0.848	6th
Benchmarking project expenditure on account of machine and plants maintenance	3.955	0.791	7th

Source: Author's field survey, 2021 RII-Relative Importance Index.

A test of the agreement was carried out on the parameters to model the proposed model and the results are presented in Table 11. The main group concept tested was parameters on communication, authority, and responsibility. The number of components of the group parameter that were tested is seven in total. The Chi-square test was conducted with a *p*-value of 0.05, and the null hypothesis is usually rejected when the asymptotic significance is less than the *p*-value of 0.05. Conversely, the null hypothesis should be accepted when the asymptotic significance is higher than the *p*-value of 0.05. Therefore, there is a significant difference between the responses of respondents to the tested parameters, i.e., setting up an effective communication strategy for work quality, improving the quality of work and operational standards, and establishing a line of command are essential as their values are higher than *p*-value 0.05. Similarly, there was no significant difference between the responses of respondents regarding the other five factors, which include the delegation of responsibility, the periodic establishment of quality and maintenance management meetings onsite, the establishment of a policy implementation committee, the identification of value from the client's perspective, and the benchmarking of project expenditure on account of machine and plant maintenance, which was supported in [26,29,32].

Table 11. Chi-square statistical analysis on communication, authority, and responsibility parameters of the proposed model.

Test Statistics							
	Setting Up an Effective System	Delegating Responsibility	Periodic Establishment	Policy Implementation	Establishing Communication Line	Identity Value-Adding Activity	Benchmarking Project Expenditure
Chi-Square	0.600 [a]	0.000 [b]	0.000 [b]	0.000 [b]	0.600 [a]	0.000 [b]	0.000 [b]
df	3	4	4	4	3	4	4
Asymp. Sig.	0.896	1.000	1.000	1.000	0.896	1.000	1.000

Source: Author's field survey, 2021. [a] 4 cells (100.0%) have expected frequencies less than 5. The minimum expected cell frequency is 1.3. [b] 5 cells (100.0%) have expected frequencies less than 5. The minimum expected cell frequency is 1.0.

4.10. Framework for Managing Quality System Building Construction Project

Table 12 presents the ratings of the respondents concerning monitoring and control in the conceptual phase. The results reveal that demonstrating organizational features, Lean knowledge training, and establishing communication, each with a corresponding relative importance index value of (RII = 0.86), received the highest rating from the respondents, while defining assessment matrices received the lowest rating (RII = 0.79) from the surveyed building professionals [39]. The study also itemizes the essential components that could be adopted in the design phase, including associating waste practices, identifying waste types, waste analysis, questionnaire and work sampling assessment, SWOT analysis for Lean supply, a Lean transformation plan, and documenting the current state gap.

Table 12. Monitoring and controlling quality in the management of the construction process.

Conceptual Phase	Mean	RII	Rank
Demonstrating organization features	4.435	0.887	1st
Lean knowledge training	4.390	0.878	2nd
Establish communication	4.325	0.865	3rd
Review potential waste and lean practice	4.325	0.865	3th
Define assessment matrices	3.955	0.791	5th

Source: Author's field survey, 2021.

A Chi-square test was conducted at a *p*-value of 0.05. The null hypothesis is usually rejected when the asymptotic significance is less than the *p*-value of 0.05 and the null hypothesis should be accepted when the asymptotic significance is higher than the *p*-value of 0.05. Similarly, there should be an efficient line of communication, a review of waste practices, and the setting up of assessment matrices to ensure quality. According to Table 13, there is no significant difference in the responses of respondents regarding five factors, which include demonstrating organizational features, Lean knowledge training, establishing communication, and reviewing potential waste and Lean practices. The value should be identified from the client's perspective and the benchmarking of project expenditure on account of machine and plant maintenance, which was supported in [26,28,29]. In the context of the analysis, in the monitoring and control of quality, knowledge of the Lean technique in eliminating waste is essential to ensure quality [24,39].

Table 13. Chi-square statistical analysis of parameters of monitoring and controlling quality in the management of construction processes.

Test Statistics	Demonstrating Organization Features	Lean Knowledge Training	Establish Communication	Review Potential Waste Practice	Define Assessment Matrices
Chi-Square	0.000 [b]	0.000 [b]	0.000 [b]	0.600 [a]	0.000 [b]
Df	4	4	4	3	4
Asymp. Sig.	1.000	1.000	1.000	0.896	1.000

Source: Author's field survey, 2021. [a] 4 cells (100.0%) have expected frequencies less than 5. The minimum expected cell frequency is 1.3. [b] 5 cells (100.0%) have expected frequencies less than 5. The minimum expected cell frequency is 1.0.

Figure 3 presents the ratings of the surveyed respondents regarding the implementation phase of a framework developed for the paradigm of residential building projects. The survey data reveal that expanding Lean practice received the highest rating (RII = 0.88), followed by employees organizing and training and standardizing the Lean practice, each with a corresponding relative importance index of (RII = 0.87), while pilot project implementation received the lowest rating (RII = 0.81) from respondents.

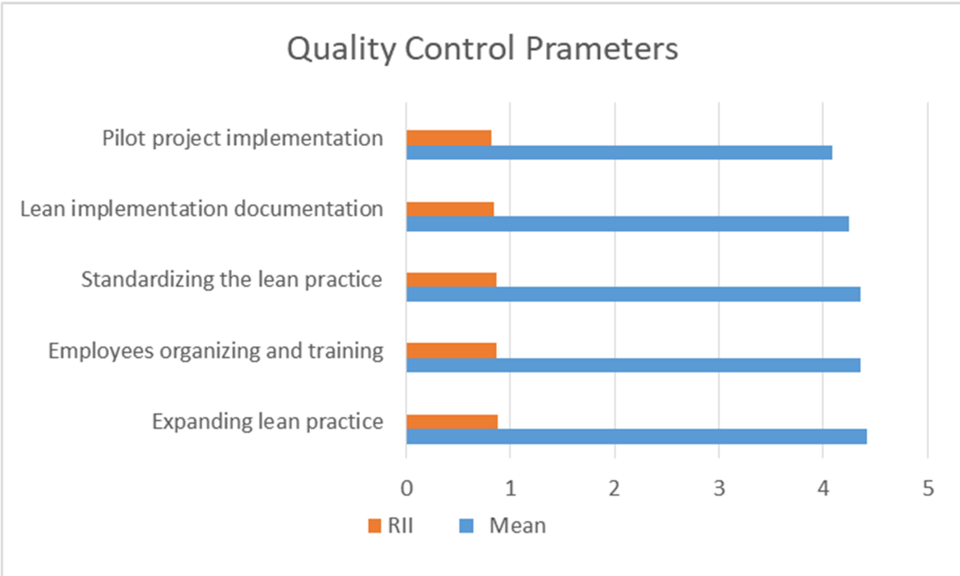

Figure 3. Lean thinking quality control parameters. Legend: RII—Relative Important Index.

4.11. Framework for Managing Quality System Building Construction Project

The creation of a model for management quality on residential projects was performed using factor analysis, with principal component analysis (PCA) used as the method of extraction and Varimax with Kaiser Normalization used as the method of rotation. Factor analysis was used to classify the forty-two items in section F of the research instrument. Factor analysis was used to determine which group or theorized constructs of the factors identified in the research instrument are important for managing the quality of residential building projects and which factors can be removed to reduce the number of factors to only those that are significant. The first step was to determine the number of components to be selected for the factor analysis. This can be achieved by either examining the scree plot or the total variance explained. Therefore, for this study, the latter method was adopted. As seen in Table 14, eleven components were extracted with the factor reduction method and used for the analysis. The analysis was set at an Eigenvalue of 0 to 1. The variables with low Eigenvalues were suppressed while those with values between 0.8 and 1.0 were extracted for representative factors. The extraction of the eleven components was justified by the total variance explained for the identified components, which describe the important parameters for managing quality in residential buildings (i.e., 66.546%). The Kaiser–Meyer–Olkin (KMO) measure of sample adequacy was 0.558. Bartlett's test of sphericity provided a *p*-value of 0.001. The highly significant values of Bartlett's test ($p < 0.001$) indicated that factor analysis was appropriate for the data [24,38]. To optimize the factor structure and search for the best explanation for the patterns in the data, factor rotation (Varimax with Kaiser Normalization) was applied. According to Kaiser's criterion [24], eleven factors with eigenvalues greater than 1 were extracted.

Table 14. Statistical parameters of sampling test (executing Bartletts' Test and KMO Characteristics).

KMO and Bartlett's Test		
Sample Adequacy Test of Kaiser-Meyer-Olkin		0.658
Bartlett's Test of Sample Sphericity	Approx. Chi-Square Value	925.187
	Degree of freedom [df]	675
	Asymptotic Significance.	0.001

Source: Author's field survey, 2021.

4.12. Model Correlation Matrix for Quality Management System for Residential Building Management Model

The quality management correlation matrix is presented below in model groups. The model group was classified into 10 quality models. The factors were picked based on their respective Eigenvalues with a magnitude of less than 1 or equal to 1. The model contains a pairing of variables that could be used each time for the quality management of a building. The group factors based on their Eigenvalues are stated below [38–40]:

Model Group F1 I (Performance monitoring factors [1.0]); Model Group F2 II (Establishing Communication line factors [1.0]); Model Group F3 III (Adopting expert system and Industry 4.0 tools in quality management [1.0]); Model Group F4 IV (Quality cost objective factors [0.99]); Model Group F5 V (Communication, authority, and responsibility factors [0.87]); Model Group F6 VI (Communication/quality cost objective-related factors [0.89]); Model Group F7 VII (Manpower training and development-related factors [0.82]); Model Group F8 VIII (Measurement and precision-related factors [0.99]); Model Group F9 IX (Quality cost objective [0.97] and performance monitoring [0.83]-related factors); Model Group F10 X (Quality cost objective-related factors [0.98]); Model Group F11 XI (communication [0.92] authority [0.97]); Model F12 XII (Internet of Things parameters [0.92]) and Construction 4.0 tools-related factors [0.89]). The model is in accordance with [28,39,40].

However, the application of Lean principles gives little or no opportunity for changes in the construction process as corroborated in [41–47]. Finally, one of the main parameters of the Lean concept is just-in-time deliveries, which are applicable in the context of this study to supply chain management of construction resources. The just-in-time delivery habit tends to induce congestion in the supply chain system, thus there is a need for an early warning system in the project. This trend is in accordance with the research in [46–49].

4.13. Benchmarked Quality Parameters

4.13.1. Modelling Parameters

The parameters used in modeling were articulated and are presented in Tables 8–11.

The following summary can be drawn from Figure 4: The zero-defect range: 1F1 + 1F2 + 1F3; the medium-quality range: 0.87F6 + 0.8F11 + 0.82 F14 + 0.82 F11; and the high-quality range: 0.97F9+ 0.9F8 + 0.99 F10 + 0.9F11.

4.13.2. Description of the Emerged Factors after Rotation

"F1Performance monitoring factors [1.0].

"F2Establishing Communication line factors [1.0]).

"F3Adopting expert system and Industry 4.0 tools in quality management [1.0].

"F4Quality cost objective factors [0.99].

"F5Communication, authority, and respondent factors [0.87]).
"F6Communication/quality cost objective related factors [0.89].
"F7Manpower training and development-related factors [0.82]).
"F8Measurement and precision-related factors [0.99].
"F9Quality cost objective [0.97] and performance monitoring [0.83].
"F10Quality cost objective related factors [0.98].
"F11Communication [0.92] and authority [0.97]).
"F12Internet of Things parameters [0.92] and Construction 4.0 tool-related factors [0.89].

Zero Defect: 1F1 + 1F2 + 1F3

The Medium Quality Range [80%] : 0.87F6 + 0.8F11 + 0.82 F14 + 0.82 F11

The High Quality Range [90%]: 0.97F9+ 0.9F8 + 0.99 F10 + 0.9F11

Figure 4. Framework of the benchmarked quality parameters for residential building projects.

4.13.3. Description of the Components of the Framework

Three groups of models emerged after the factors were rotated, and the factors were grouped using the following labels: (i) The quality management system (QMS) linked to Lean Construction (LC) [QMS-LC]; (ii) the quality Management System (QMS) linked to Construction 4.0 (C 4.0); and (iii) the quality management system (QMS) linked to the Internet of Things (IoT).

Therefore, six groups of factors, F2, F4, F5, F6, and F9, are associated with a quality management system with Lean construction (QMS-LC). The factors are F2Establishing Communication line factors [1.0])l F4Quality cost objective factors [0.99]; F5Communication, authority, and respondent factors [0.87]); F6Communication/quality cost objective related factors [0.89]; and F9Quality cost objective [0.97] and performance monitoring [0.83].

Similarly, the Quality Management System (QMS) linked to Construction 4.0 (OMS-C 4.0) consists of four factors, which include F1, F3, F8, and F12. The details of the factors are as follows: F1Performance monitoring factors [1.0]; F3Adopting expert system and Industry 4.0 tools in quality management [1.0]; F8Measurement and precision-related factors [0.99]; and F12Internet of Things parameters [0.92] and Construction 4.0 tool-related factors [0.89]

Furthermore, the third quality management system is referred to as the quality management system linked with IoT (QMS-IoT) and consists of five factors, which are F2, F7, F8, F11, and F12. The details are as follows: F2Establishing Communication line factors [1.0]); F7Manpower training and development-related factors [0.82]); F8Measurement and precision-related factors [0.99]; F11Communication [0.92] and authority [0.97]); and F12Internet of Things parameters [0.92] and Construction 4.0 tool-related factors [0.89]

F5 refers to Lean thinking quality control parameters, including pilot project implementation, Lean implementation documentation, standardizing the Lean practice, organizing and training employees, expanding Lean practice, manpower training, measurement and description, zero defects, six sigma parameters, and communication and Lean quality.

F12 Industry 4.0 parameters are linked to the Internet of Things parameters. A motion-controlled lighting system should be installed to aid energy management system practices. The implementation of cardholder energy-saving switches should be connected to lighting circuits and air conditioning systems. The implementation of building automation systems should be used to provide data from HVAC operations. The use of sensory nodes of lighting and HVAC should be incorporated into building design. There should be a central monitoring controlling system of electrical energy. There should be the implementation of smart energy management. A smart energy-saving air conditioning system should be installed in buildings. A computer-based energy management system should be adopted in buildings. A computer-based energy management system should be implemented to improve energy efficiency. A computer-based energy management system should be employed to reduce energy waste. The introduction of robotics and automation in construction and additive product manufacturing and the development of the Internet of Things are beneficial for system development.

5. Discussion

The global construction industry is noted for provisioning real estate products, which in turn, satisfy the needs of consumers. The products include major housing and accommodation facilities. The production of construction products, however, is labor-intensive and demands a great deal of effort. The input in this context refers to the input on the part of construction project actors whose efforts determine the quality of the construction products. In light of the above, monitoring and control is essential for quality results and output in the construction industry. The quality, therefore, has to be holistic, covering the life cycle of a product. The life cycle of construction starts from the idea-conception stage, which invariably implies that quality formulation and implementation begin right at the idea-conception stage. Before the advent of Construction 4.0, the analog model of reality was predominantly used in design decision support systems and construction monitoring and control. The analog model was disadvantaged in terms of its time-consuming and cost-intensive characteristics, and its non-flexibility in function adaptation, among other factors. However, the advent of Construction 4.0 resulted in enhanced model output. For instance, in the Construction 4.0 era, sensor-based 3D systems are in use in construction product modeling. The advent of computer-aided design (CAD) in the construction industry has enabled quality assurance in the design process. CAD enables designers to visualize the drawing outlook or how the drawing appears. This allows for on-time adjustment and manipulation. According to [11,23], calibrated applications have gained interest in the construction industry. In Construction 4.0, quality management and quantitative tools that capture function and forms are being used in decision support systems in the formulation and development of quality parameters. Furthermore, in the Construction 4.0 era, virtual reality and augmented reality applications help to visualize how the effect on quality could be quantified in the construction process. Therefore, opportunities abound in the application of I 4.0 in the quality management of construction. In [8,50], the authors alluded to the fact that high-tech applications enable the easy application of quality appliances in the construction field. Artificial intelligence-based applications equipped with 4D and 5D capabilities have been of immense help in quality monitoring and assurance in the construction process, maintenance, and facility post-occupancy management. 2D and 3D printing applications have had an immense contribution to automated printing applications. This has reduced the lead printing time in the documentation of quality documents in the construction industry. These facts are supported by [7,23,50].

Moreover, issues of quality are of utmost importance in the construction industry and the creation of construction products. In the current era, the production and marketing of construction products have quality management parameters embedded in most of the concurrent applications. In contemporary quality management systems in the construction industry, there are expert-based and intelligence-based quality management applications, as presented in [28]. Some of the identified applications, as alluded to in the text, assist in the digitalization of quality management of the construction process, additive quality manufacturing, intelligent manufacturing, the automation of construction processes, and robotics applications [50–53].

In this study, a quality management framework was developed for quality management applications in residential building projects. There are related frameworks that have been used in quality management in building works. Some of the frameworks that are comparable to the one developed in this study include hedonic models, artificial intelligence models (AI), total quality management (TQM), case-based models, and Lean thinking models. The structure, function, similarities, and differences are outlined in previous research [54–56].

Hedonic models are types of models that provide space for continual updating and they are mathematically based. They could be referred to as one type of a stochastic model. The Hedonic model, which is stochastic, differs from the framework developed in this study, which is deterministic in structure. Similarly, total quality management models, Lean thinking models, and case-based models are deterministic in structure. The deterministic model has the capability of engaging multiple variables, which can be updated continually. The advantage of this lies in the fact that the model has all the variables required to predict the outcomes of models with certainty [56–60].

However, in a nutshell, Industry 4.0 was described in [60] as a framework that incorporates individual production, cyber-physical systems, and digital computing technology to provide basic industrial and manufacturing production. In [60,61], the components of Construction 4.0 were described to include mixed-reality applications, additive manufacturing, BIM application, data analytics, and domain knowledge endowment, among others. Similarly, [61,62] mentioned additive manufacturing as one of the major fulcrum for enabling digital configuration in Construction 4.0, which toes the line of submissions in [60,62,63] and Supplementary Materials.

Moreover, regarding drawing a comparison between the framework and model developed in this study and other relevant frameworks, the current model appeared to be one step ahead of some models, while the current model has many variables. There are areas of similarity and dissimilarities between the current model and other related models. However, the uniqueness of the current model lies in the incorporation of Industry 4.0 tools and Lean tools. Areas of dissimilarity include the incorporation of certain elements such as the Internet of Things components, Lean construction components, and positive attributes of Industry 4.0 [55,57–61,63,64].

The model is deterministic considering the background of multiple variables involved, which can be used to predict the future of other variables for consistency. Therefore, the quality management framework presented in this study, which is based on Construction 4.0 and uses Industry 4.0 tools and Lean concept parameters, creates a system that is unique from the stochastic models available in the construction industry.

6. Conclusions

High-quality management eliminates waste and increases productivity at the minimum cost. It is against this background, therefore, that this research work has demonstrated how the Lean concept could be deployed to create a regression model that could help in creating a quality model for construction work applications to prevent poor-quality management onsite.

In the context of this study, the following objectives were articulated for study: The influence of Construction 4.0 parameters on the quality management of building projects, the impact of the Internet of Things (IoT) and Industry 4.0 tools in the quality management process of a construction project, Critical success influencers of construction quality management using the Lean construction concept, and developing a Lean–based quality management framework for residential projects. In the outcomes of the research, the study identified the challenges involved in the integration of technology domains such as Lean and Industry 4.0 in the framework, including a reduction in flexibility to react to new conditions during the execution of the project, the process of management becoming expensive and cost-intensive, and the fact that the application of Lean principles provides little or no space for changes in the construction process, among other factors. Similarly, the developed model has practical applications in quality management in terms of the input process and the product, as presented in this study [60–64].

The parameters of the developed model could be used to monitor the quality process to be able to achieve high-quality decisions in projects. Finally, the limitation of the study lies in the applicability to the life cycle process of a building, which covers the input stage, process stage, and modeling of the final construction product. The model could also be applied to industrial production processes and manufacturing that entail processing the input and output in the form of the product.

The Lean tools need to be communicated to the stakeholders for implementation. According to the outcomes of this study, it is necessary to take the following factors into consideration in the initial part of the project: Integrating waste and error reduction practices, identifying waste types, waste analysis, questionnaire and work sampling assessment, SWOT analysis for Lean supply, a Lean transformation plan, and documenting the current state gap. Similarly, the following procedure is necessary for the implementation of a Lean framework in the residential building construction quality process: Expanding Lean practice, organizing and training employees, standardizing the Lean practice, Lean implementation documentation, and pilot project implementation. Comparing the developed model with other types of models mentioned earlier, the model accommodates multiple variables that are easy to interpret and update. The model is deterministic as compared to similar models such as total quality management, the case-based reasoning model, and the hedonic model, among others [65].

Moreover, issues of quality are of the utmost importance in the construction industry and the production of construction products. In recent times, the production and marketing of construction products have quality management parameters embedded in most of their concurrent applications [28,51,52].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings12101557/s1.

Author Contributions: Conceptualization, A.L. and E.S.; methodology, A.L.; software, E.M.; validation, A.C.; formal analysis, A.L.; investigation, E.S. & O.B. resources, A.C.; data curation, O.B. & A.C.; writing—original draft preparation, E.M.; writing—review and editing, all authors; visualization, A.C.; supervision, A.L.; project administration, E.M.; funding acquisition, A.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Covenant University Centre for Research Innovation and Discovery (CUCRID) and the Cidb Center of Excellence, Faculty of Engineering and Built Environment, University of Johannesburg, Doorfotein Campus Johannesburg, South Africa. The authors appreciate the sponsorship of this research publication.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent of respondent was included on the questionaire used for the study before individual respondent filled the questionaire.

Data Availability Statement: Not applicable.

Acknowledgments: The authors appreciate the Cidb Center of Excellence, Faculty of Engineering and Built Environment, University of Johannesburg, Doorfotein Campus Johannesburg, South Africa for the administrative and technical support of this research endeavor.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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