

# Application of Six Sigma DMADV Methodology Approach for Improving Concrete Masonry Mixing Process



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**ABSTRACT:** Building collapses in Nigeria has been linked to poor quality of concrete masonry, which is frequently caused by irregular material composition and inefficient manufacturing processes. The Six Sigma DMADV (Define, Measure, Analyse, Design, and Verify) methodology is used in this paper to improve the concrete masonry mixing procedure. The study takes on a case study design to identify the process deficiencies, which leads to the development of a mechanised mixing system to improve the masonry aggregates. Finite Element Analysis (FEA) optimises the new concrete block designs to reduce weight and maintain structural integrity and ergonomic efficiency. The results show that implementing the Six Sigma DMADV improves manufacturing quality, reduces defects, and ensures consistency in concrete masonry manufacturing. Among the 12 model samples produced by the FEA for the new concrete masonry machine design, model L is the most optimal, with volume, weight, stress, and the factor of safety measuring 364440 mm<sup>3</sup>, 8.773 kg, 5.271 MPa, and 1.01, respectively. The paper concludes that the integration of systematic quality control measures as well as automation in the production of small and medium-scale concrete can reduce construction failures, leading to safer and more durable buildings.

**KEYWORDS:** Six Sigma, Concrete Masonry, Process Improvement, Quality Control, Finite Element Analysis.

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## I. INTRODUCTION

Nigeria has experienced a significant increase in building collapses over the years, resulting in fatalities, loss of income, and the displacement of families. Recently, Nigeria experienced the most frequent and severe building collapses in Africa Okagbue et al., (2018). The main causes of building collapse are structural failure, substandard materials, design errors, and violation of planning regulations. Over 89% of the physical infrastructure in Nigeria is built with concrete masonry blocks, making it a crucial building material that requires quality standards Ealefoh, (2024). It has been suggested that the degree of building collapse is related to the level of inconsistency in the quality of construction materials, especially from concrete masonry manufacturers (Alaneme et al., 2020). Drawing from secondary data from diverse sources, including journals, reports, the internet, and earlier studies by other authors, the failure of structures was linked to the use of substandard materials Ichendu et al., (2024). Figure 1 illustrates the factors contributing to building collapses in Nigeria during the years 2013 and 2014, based on the research conducted by Odeyemi et al., (2019). Figure 2 represents the building collapse in Nigeria, from 2001 to 2021, as reported by Ohenhen and Shirzaei (2022). Figures 1 and 2 are evidence that the problem of building collapse in Nigeria has been long-standing, and there is an urgent need to address it.

Figure 2 depicts the records of buildings collapsed in Nigeria from 2001 to 2021, totalling 164. This number is a

huge loss of resources, resulting in the loss of life, environmental hazards, pollution, etc. This study will address these unpleasant occurrences.

Since building collapse in Nigeria is connected to the quality of concrete masonry as reported by Ayininuola and Olalusi, (2004), the issue can be effectively solved by using Six Sigma, which offers products or services that are defect-free, delivered on time, and at a low cost. Six Sigma is a method for examining, evaluating, experimenting, improving, and managing the quality and efficiency of the production process. In the 1980s, Motorola launched Six Sigma, leading the way in a novel quality idea. The Six Sigma method differs from conventional quality enhancement programs due to its focus on input variables. Six Sigma is subdivided into DMAIC (Define, Measure, Analyse, Improve, and Control) and DMADV. Six Sigma DMAIC aims at improving existing processes within specifications through gradual modifications, whereas Six Sigma DMADV is used for developing new processes or enhancing product quality (Francisco et al., 2020). Six Sigma employs statistical tools and techniques such as checklists, fishbone diagrams, control charts, pie graphs, and SIPOC diagrams. Six Sigma aims to reduce defects to 3.4 per million as a technique for improving quality Dominic et al., (2021).

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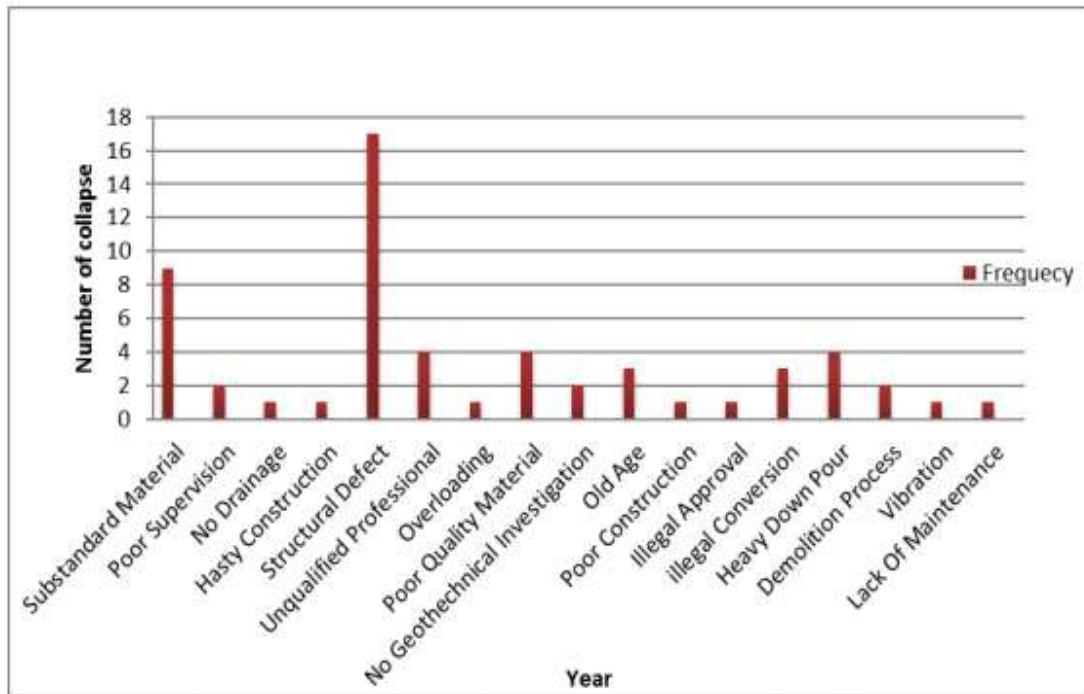


Figure 1 Causes of Building Collapse in Nigeria Odeyemi et al., (2019)

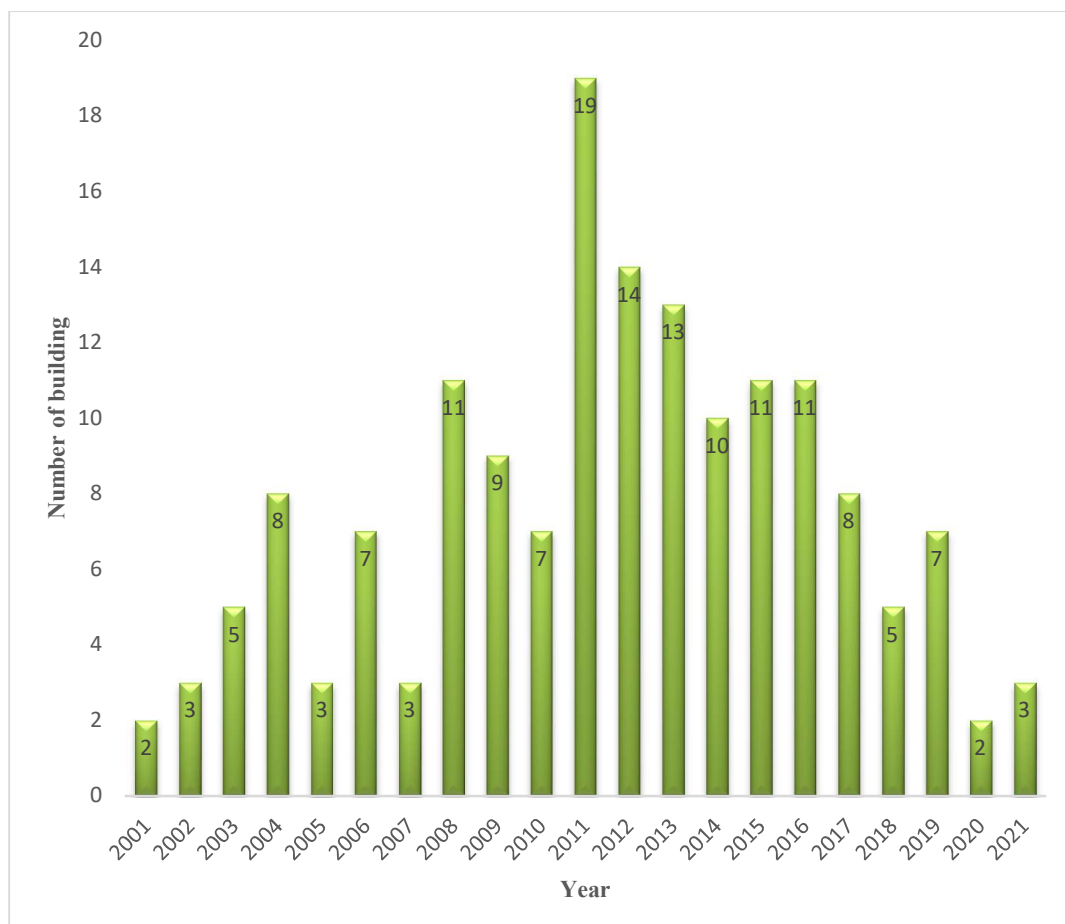


Figure 2 No. of Building Collapsed in Nigeria, from 2001 to 2021 Ohenhen and Shirzaei, (2022)

The philosophy of Six Sigma seeks to meet customer needs by delivering flawless products or services at a lower cost (Pakdil, 2020). It is a strategy focused on identifying and correcting process errors or mistakes by emphasising factors that are crucial to customers. Six Sigma can reduce errors while improving process effectiveness in systems Okwu *et al.*, (2021). Six Sigma seeks to improve process results by recognising and eliminating failure causes and decreasing process deviation Sunder and Kunnath, (2020). The use of quality control is very significant in achieving consistent quality in the batches of concrete masonry production processes.

Quality control involves employing methods and practices to manage, maintain, and enhance the quality of a product or service. Within the concrete masonry sector, the quality control techniques employed for inspection and testing include screening, sampling, lot-by-lot inspection, and process evaluation. Regrettably, current concrete masonry products are quite brittle and weak and struggle to withstand modest impact loads. The continuous occurrence of building collapse is becoming regular, and this may be linked to issues such as faulty concrete masonry used in the building process Alabi *et al.*, (2023). Since concrete masonry is a commonly used construction material in Nigeria, according to Eboibi *et al.* (2022), it is necessary that adequate attention be given to concrete masonry production quality to put an end to or drastically reduce its visible defects, such as cracks, honeycombing, or irregular shapes. Common factors that influence the strength of concrete masonry consist of the brand of cement, level of compaction, curing technique, and aggregates. In the production of concrete masonry, some factors may go unnoticed and are frequently overlooked, which may affect the quality of the product. These factors include the brand of the cement, the grade of aggregates, the feature of the mix, the delay between mixing and placing the mix into the mould, the method of pouring the mix into the mould before compaction, the curing process, and adverse weather conditions.

Ayininula and Olalusi (2004) highlighted that the quality of blocks employed in the Nigerian construction industry plays a significant role in the occurrence of building failures. It was noted that nine-inch (230 mm) hollow blocks used for the external walls of structures are critical for bearing the weight of the decking and upper floors, in addition to supporting the columns. The strength of these blocks is dependent on the cement-to-sand ratio applied during their production; thus, it is imperative to adhere to the appropriate proportions to ensure their strength and longevity. Furthermore, Nwosu and Zima (2021) asserted that the quality of blocks in the Nigerian construction sector is a contributing factor to building failures. They pointed out that the increasing demand within the industry has led block manufacturers to prioritise quantity over quality, often resulting in the use of excessive sand ratio to cement, which ultimately produces weaker blocks.

It is a misconception that Six Sigma is effective solely in large organisations. Six Sigma has developed into a business approach for many large corporations, and its significance in low-scale industries is on the increase (Wessel *et al.*, 2004), De Mast, (2006), and; Deshmukh and Chavan, (2012). Various

research efforts have explored the reasons for building collapses and associated studies, yet none have utilised the Six Sigma DMADC to improve the concrete masonry mixing process.

Six Sigma methodologies have been applied across both manufacturing and service industries. Research by Deshmukh and Chavan (2012), Stankalla *et al.*, (2019), and Prasanna and Vinodh (2013) clarified the growing application of Six Sigma within small and medium-sized enterprises (SMEs). Furthermore, Francisco *et al.* (2020) underscore the significance of Six Sigma in enhancing product design processes. A review publicised by Dominic *et al.*, (2021) examined the applications of Six Sigma in manufacturing operations. However, numerous small and medium-sized concrete block manufacturers fail to employ adequate process quality control measures. Prior investigations have revealed inconsistent cement-to-sand ratios in different locations, which have led to the production of substandard concrete blocks Anosike *et al.*, (2012; Shahzad and Li (2023). Many current masonry products exhibit brittleness and weakness, rendering them incapable of withstanding even moderate impact loads, thereby contributing to structural failures (Varum *et al.*, 2014). The traditional method of manually mixing aggregates results in a lack of uniformity, causing variations in compressive strength. Additionally, many industries do not comply with the recommended curing times, further compromising the integrity of the blocks.

Numerous investigations into quality concerns within concrete masonry have been conducted, including the works of Ayininuola and Olalusi (2004) and Nwosu and Zima (2021), both of which indicate that substandard masonry quality is a significant factor contributing to construction failures in Nigeria. Alabi *et al.* (2023) highlighted that defects occurring during the construction phase are primary contributors to building collapses. Additionally, Sojobi *et al.* (2021) and (Rahman *et al.* 2025) addressed the inconsistencies in the mix ratios of hollow masonry blocks. (Andohful *et al.* 2021) examined the compressive strength variations across different block manufacturing industries, identifying notable irregularities. Noriega *et al.* (2016) applied Six Sigma methodologies to enhance the operational efficiency of concrete block machinery. Their findings revealed substantial benefits, including the reduction of machine downtime, a decrease in scrap rates from 18% to 2%, and enhancements in plant layout and production facilities aimed at boosting productivity. Other studies related to Six Sigma within the concrete sector include the works of (Gamboa and Singgeih 2021) and (Pratiwi *et al.*, 2021).

Though previous studies have used the DMAIC methodology to promote operational efficiency in concrete block machinery to reduce scrap rates and machine downtime, there is a deficit of literature in DMAIC methodology for the design of the concrete masonry mixture process. This study investigates the DMADV framework for process redesign and innovation in concrete masonry. It introduces a mechanised mixing system aimed at mitigating human error in the mixing of aggregates and incorporates finite element analysis (FEA) to develop concrete blocks that are not only stronger and lighter but also ergonomically designed. This research

addresses a notable gap in the literature by enhancing the process, optimising structural integrity, and preparing for future automation of concrete masonry through the application of Six Sigma DMADV.

## II. MATERIALS AND METHODS

This study uses a case study and the Six Sigma DMADV framework. The case study approach was favoured due to its flexibility in both design and application, allowing for quantitative and qualitative assessments of specific phenomena within the concrete masonry industries. The DMADV methodology adopts a methodical, organised strategy that includes setting the project goal and objectives, assessing and analysing the existing process, creating the new process, and confirming that the new process achieves the required performance standards (Bonnell et al., 2018). Through the DMADV approach, companies in the concrete masonry sector can enhance their production quality and minimise process variability, resulting in greater efficiency and improved customer satisfaction. In addition to improving the quality of production processes, the DMADV process has also been cost-effective. By implementing the DMADV process, organisations in the concrete masonry industry can realise significant cost savings while improving their products' quality.

### A. Materials

Constituents that are used in the production of concrete masonry are listed:

- 1) Cement: It binds the aggregates together to form a composite matrix
- 2) Aggregates: They are granular natural materials (sand). For the production of concrete masonry, four different types of sand may be used: river sand, sea sand, crushed stone, and pit sand. Sand makes up 75% of the mixture in terms of volume.
- 3) Water: In the cement and concrete Industry, water is typically mixed with cement and other aggregates, such as sand and gravel, to create a wet, concrete-like mixture. This mixture is then poured into moulds to form the concrete, which can cure and harden over time. The amount of water used in the mixtures will depend on the specific type of cement and the desired properties of the concrete.
- 4) Vibration Machine: A concrete vibration machine is a piece of equipment that vibrates concrete to compact it and remove air pockets or voids. These machines are used in the construction industry to produce high-quality, dense concrete for walls, foundations, and other structural elements.

### B. Methods

The DMADV quality improvement method was implemented. During the define stage, problems were identified through customer feedback, corporate strategy, and mission. This study aims to enhance the concrete masonry mixing process. During the measurement phase, validation was carried out to assess key steps. A procedure flow diagram and fishbone diagram were created, alongside a quantitative analysis of the final product's components. Various techniques were utilised to identify the root causes of the deficient concrete masonry mixing process. The Design stage identifies and implements solutions to eliminate the root causes of the concrete masonry mixing process deficiency. FEA was used to provide solutions

to the identified problems in the concrete masonry industry, and ultimately, the verification phase entails consistently assessing the performance of the process and validating its operational effectiveness.

### 1) Define Phase

This is a foundational and crucial aspect of this study. The aim of the define phase in a Six Sigma initiative is to outline the project with all essential information such as the goals, scope, timeline, action plan, etc. (Ray and Das, 2010). This is the initial task in a Six Sigma project, and if the selection of the project and the establishment of goals are not executed correctly, it may result in the project's failure. (Francescatto et al., 2023). Therefore, following thorough brainstorming and discussions, a comprehensive flowchart of the concrete masonry industry is presented in Figure 4. Factors that significantly impact the objectives of a business are referred to as critical quality (CTQ) parameters. During the defining stage, the CTQ goals are determined through the Voice of Customer (VOC). The project charter, CTQ flow down, and process mapping are key tools utilised in this phase. A project charter is a document outlining the objectives of the project. It includes components like a business case, issue description, and objective statement. The business case outlines the project's purpose, detailing the goals and objectives that are set. The following component is the problem statement, which articulates the issue to be addressed. Once the problem statement is defined, the subsequent step is to determine the target values by carefully analysing historical data. These values are referred to in a declaration known as the Goal statement. Process mapping is a crucial step in comprehending the processes associated with concrete masonry industries. The process map (SIPOC chart) begins with the supply of raw materials and concludes with the advantages gained by the customer. A case study within this research focuses on applying Six Sigma DMADV to enhance the manufacturing process of the concrete masonry sector. The concrete masonry sector included individuals along the Ikole-Ekiti axis in Nigeria. There are times when concrete masonry is moved during curing or stacking, and sadly, it ends up breaking. The investigation showed that one bag of cement is used to produce 40 to 45 units of 225 mm concrete masonry. The compressive strength of concrete masonry is generally documented as the primary parameter for quality control, and this quality relies on the type and characteristics of the constituent materials. (Ikeagwuani et al., 2020).

**Cement:** The cement used by the industries primarily comes from the Ashaka Cement factory in Nigeria, which produces ordinary Portland cement. Low-quality cement often shows in the strength of the final product (Robalo et al., 2021)

**Sand:** Sand is a natural aggregate that can be isolated through gentle mechanical agitation in water, indicating that it is a cohesion-less aggregate of rounded, angular, or sub-angular fragments derived from relatively unaltered rocks or minerals. Particles measuring up to 5 mm are known as sand.

**Mix Ratio:** The mix ratio for cement concrete masonry indicates the proportion of cement to the quantity of sand. The typical mixing ratio for concrete masonry should be between 1:6 and 1:8, or generally, a maximum of twenty-five (25)

concrete masonry units can be made for every 50 kg bag of cement (Sojobi et al., 2021).

**Correct Curing:** Curing is another key factor that influences the achievement of the intended strength of cement concrete masonry. The curing method and duration require careful consideration for the concrete masonry to achieve its intended strength, regardless of the materials' quality and the mix ratio being correct.

## 2) Sipoc Chart

The Sipoc chart related to the current research has been created by carefully analysing the suppliers, input, different processes, outputs, and customers, as shown in Table 1. Figure 3 depicts the process map for a concrete masonry plant showing guidelines, policies, and regulations to achieve quality products.

Table 1 SIPOC Chart

Suppliers	Inputs	Processes	Outputs	Customers
Who supplies the process inputs?	What inputs are required?	What are the major steps in the process?	What are the process outputs?	Who receives the outputs?
Merchant	Phone call	Order for raw materials	Arrival of raw materials	Warehouse manager
Workers	Raw materials	Mixing	Homogeneous mixture	Workers
Workers	Homogeneous mixture	Molding	Compacted concrete masonry is placed on pallets.	Workers
Workers	Pallets of concrete masonry are orderly arranged on a flat surface	Curing	Gets strengthened	Workers
Workers	concrete masonry standing on one side of its cross-section on the floor	Stacking	Readiness for sales	Purchaser

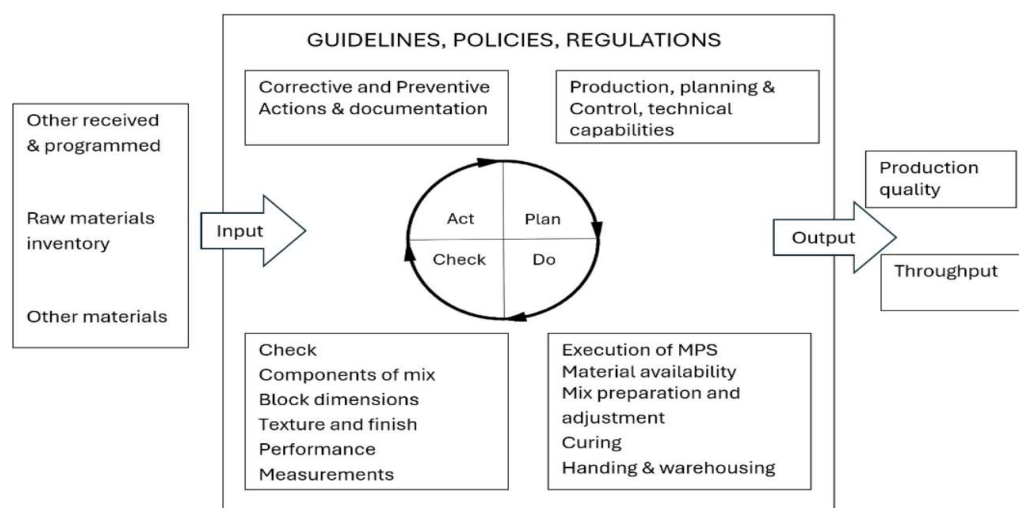


Figure 3 Process map for concrete masonry plant

Figure 4 shows the flow process of activities carried out by the concrete masonry industry. The recommended mix ratio of cement and aggregate for concrete masonry should be one portion of the cement to six parts of the volume of combined aggregate, that is, a ratio of 1:6 or 1:8 maxima (Akpokodje et al., 2021). Concrete masonry can be produced manually or using machines. The concrete masonry is subsequently cured in a water tank or courtyard for a minimum of 14 days (water should be replaced at least every 4 days). Following the curing process, the concrete masonry is dried for 4 weeks before its application in masonry construction. They ought to be arranged with gaps in the horizontal direction to allow for simple drying, or they should be dried and steam-cured. The entire procedure enables the full contraction of the concrete masonry to occur as they are positioned on the wall, which is crucial for robust walls.

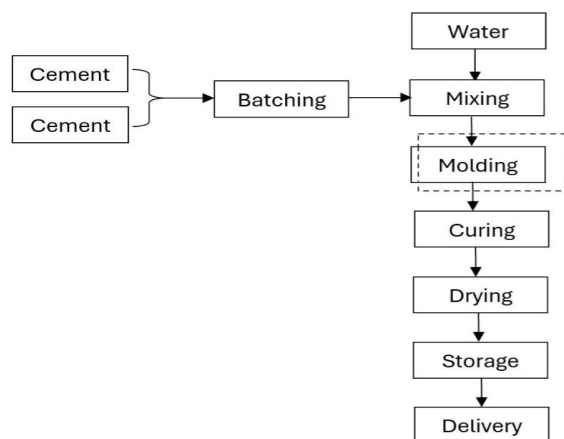


Figure 4 Flow process of activities carried out by the concrete masonry Industry

## 2 Measure Phase

During this stage, data from the current process is gathered to assess the baseline condition of the process. Improper homogeneity of the mixture of concrete aggregate was noted in each process as the potential cause of the issue. The potential causes of the issues are identified and evaluated using a trial-and-error approach in every process. Results were obtained to examine the structural tests of the concrete masonry produced. The survey was conducted in Ikole Ekiti, Nigeria. The industry stated that it uses a mix ratio of 1:6 to manufacture 35 concrete blocks of 9 inches and 50 concrete blocks of 6 inches. The aggregates are combined by hand using a shovel. The concrete masonry is made using a vibrating machine that creates one concrete masonry unit for each vibration. The length of curing in the industry reaches a

maximum of 5 days. The reason for this is that compressive strength is one of the two major characteristic requirements that the NIS specified for testing and verifying the quality of concrete masonry, apart from the appearance and dimension (NIS 587: 2007, P8-9) and (Abiodun et al. 2023).

The problem statement of this work is highly concerned with the compressive strength of the bricks as a result of the deficiency in achieving mixture homogeneity. Their compressive strength was determined using a compression test machine. Equation (1) is used to determine the compressive strength.

Compressive strength test procedures:

- i. uses a compression testing machine to apply a load uniformly on the block.
- ii. The block is placed flat or on its bedding face.
- iii. Record the maximum load at failure and calculate the compressive strength

$$\text{Compressive Strength} = \frac{\text{Failure Load}}{\text{Loaded Area}} \quad (1)$$

## 3) Analysis Phase

In this phase, statistical methods were used to analyse the process data to find out the root causes of improper concrete masonry mixture. Then, the quality control officer evaluates how the root cause impacts the concrete masonry production processes. It is necessary to brainstorm and use statistical tools in this phase to explore the main root cause of the discrepancies that occur in actual results and expected results. Then, the study identifies the potential variables that will impact the results and provides solutions.

### 3.1 The Fishbone Diagram

A fishbone diagram is a tool that can be used in the DMADV methodology to identify and analyse potential causes of a problem. In the context of the concrete masonry industry, a fishbone diagram could be used to determine the possible causes of problems, such as low production rates or poor product quality. To create a fishbone diagram, the study identifies the problem to address. then brainstorm on the potential causes of the problem and organise these causes into categories such as materials, machinery, management, and people. A diagram that resembles a fish skeleton, with the various categories of causes branching off from the spine of the fish. This helps to visualise the potential causes of the problem and identify which ones are the most likely to be contributing to the problem. The current study uses this information to design and implement solutions to address the problem, as shown in Figure 5.

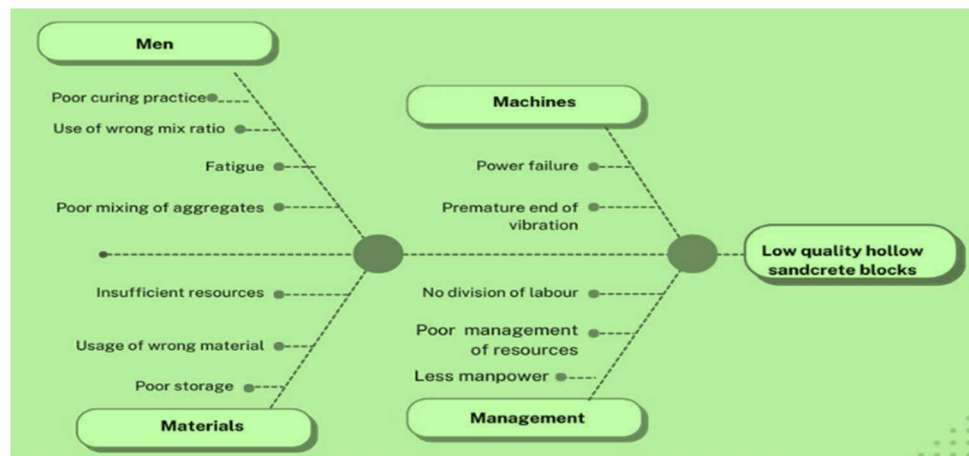


Figure 5 Fishbone diagram

The bonefish diagram was used to find the possible factors affecting the deviation of the compressive strength, and a brainstorming team will be constituted to identify and tackle the most critical problem.

Fishbone diagrams help to pinpoint and organise the various root causes that can be linked to an issue. Consequently, these diagrams aid in identifying which of multiple causes produces the strongest impact. By examining the fishbone diagram insights, the primary cause can be comprehensively examined by exploring the sub-causes and their effects on quality traits. The Fishbone diagram assists in examining the causes of any quality variation (Coccia, 2020). The fishbone diagram helps to narrow down numerous causes to a select few critical ones.

After a critical study of the fishbone diagram, it can be seen that an intuitive approach needs to be applied to tackle the main section of the diagram, as it has a way of minimising the causes present in other sections within the fishbone diagram, as depicted in Figure 5.

Other causes identified can be easily solved because they require less technicality and can be solved by administrative procedures.

The concrete masonry industries visited only manual methods of mixing the aggregates before pouring them into the mould, and the integrity of this is very hard to determine. This prompted a mechanical means to solve the mixing aggregate problem. Though it is cost-effective to use manual mixing, mixing cement and aggregate is the major cause of homogeneity and variability of the compressive test.

Similarly, many of the products made were wasted before curing took place, and some of the products contained excess materials that contributed to overweight due to the absence of a model mechanism to cater for overdesign concrete masonry.

#### 4 Design Phase

The design stage broadens the conceptualisation of design components. The focus continues to be on creating machines that meet the needs of the process outputs. The research aims to gather sufficient information to assess and examine the design's effectiveness through a pilot.

In this phase, a design is developed and tested

#### 4.1 Material Considerations for the Concrete Masonry Mixer Design:

**Cylindrical tank:** This is meant to hold the constituents to be mixed. Stainless steel is used because of its resistance to corrosion, attractive appearance, lower maintenance, higher strength, and hardness.

**Shaft:** It transmits the torque and motion from the electric motor to mix the constituents within the tank. Stainless steel is used because of its resistance to corrosion, attractive appearance, lower maintenance, higher strength, and hardness.

The machine mixing process is an improvement over manual mixing, which exposes the concrete masonry constituents to impurities. This is the justification for designing and manufacturing concrete masonry mixing machines from locally sourced materials.

A tank is used to hold the constituents, and the electric mixer is used for mixing the constituents.

The tank is cylindrical; the volume is governed as stated in equation (2):

$$V = \pi r^2 h \quad (2)$$

For design and simulation simplicity, a radius of 0.2 m and a height of 0.8 m are given to the tank, which results in a volume of 0.1 m<sup>3</sup>

**Determination of the mixing force of the concrete**

Mixing force is calculated by using equation 3():

$$W = \text{total weight} \times \text{gravity} \quad (3)$$

Weight of the constituents: 42 Kg

Weight of the proposed mixer: 1.58 Kg

$$W = 427.52 \text{ N}$$

It can be said that the mixing force of the constituents is 430 N

**Torque Determination:**

Equation (4) is used to calculate the torque of the mixing shaft

$$T = FL \quad (4)$$

$$F = 430 \text{ N}$$

$$L = 0.4 \text{ m}$$

$$T = 430 \times 0.4 = 172 \text{ Nm}$$



The mixer was subjected to 100rpm, which yielded a homogeneous mixture after a certain duration, as shown in Equation 5.

$$\omega = 100 \times 0.10472 = 10,472 \text{ rad/s} \quad (5)$$

Power of the mixer

Power consumption of the electric motor is determined by equation 6.

$$P = T\omega \quad (6)$$

$$P = 172 \times 10.472$$

$$P = 1801.2 \text{ W} = 2.4 \text{ hp}$$

Considering a power safety of 1.25, the required power is 3hp.

Diameter of the shaft

A solid shaft was considered for the design. Shaft diameter is determined by using equation 7:

$$d^3 = \frac{16}{\pi S_s} \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad (7)$$

Where,

Mt: Torsional Moment (Nm)

Mb: Bending moment (Nm)

Kb: Combined shock and fatigue factor applied to the torsional moment

Ss: allowance shear stress (N/m<sup>2</sup>)

For this type of vertical shaft, the bending moment (Mb) is zero.

Equation 8 was used to determine the Torsion Moment

$$M_t = \frac{P}{2\pi N} \quad (8)$$

Using a 3hp. 100rpm electric motor,

$$M_t = \frac{3 \times 750}{2 \times \pi \times 100}$$

The diameter of the shaft is:

$$d^3 = \frac{16}{\pi \times 55 \times 10^6} \sqrt{(1 \times 3.58)^2}$$

The calculated shaft diameter is used for the design

#### 4.2 Mixing Procedure

Different mixing procedures were simulated as depicted in Figures 6a, 6b, 7, and 8 before achieving the one that gave the required homogeneity. Consideration was also given to the direction of rotation of the machine.

Sand is put first, then cement, and finally the necessary amount of water.

The proportion of the constituents being simulated abided with the standards laid down by Nigerian Industrial Standards (NIS). The constituents only mixed at the top, which is not what is expected, and in the long run, the cement remained around the container's edge.



Figure 6 First Mixing Simulation

The second mixing process depicted in Figure 7 is an advanced form of the Figure 6 mixing process, but it involves agitation of the tank. It produced a quality job, but the operational process looks complex.

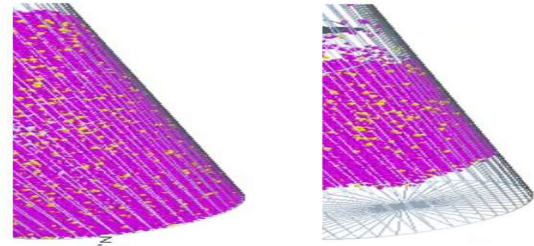


Figure 7 Second Mixing Simulation

For the third mixing attempt, Figure 8, the diameter of the mixer was reduced and allowed to rotate within the drum while it went up and down within the mixture, and this yielded a homogeneous mixture as the constituents were evenly dispersed. The mixing allowed for strong top-to-bottom turnover.

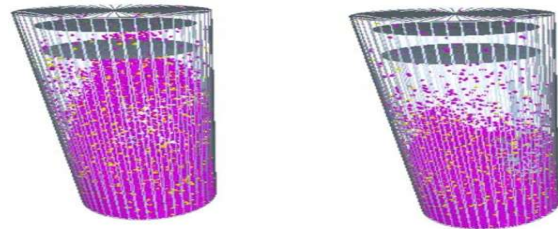


Figure 8 Third Mixing Simulation

A design for the concrete masonry being manufactured can also be considered to lessen weight, maintain the structural properties, and enhance the grip of the hand mixer to avoid musculoskeletal injuries often experienced by workers. The design of the specific concrete masonry will also take ergonomics into account.

#### 4.3 Geometrical Models of Concrete Masonry

In this study, thirteen types of concrete masonry meeting the structural criteria were examined to identify the optimal option based on structural integrity and ease of handling.

The construction workers face a considerable risk of experiencing musculoskeletal injuries, as the typical concrete masonry used for building external walls is heavy, averaging between 17.9 kg and 22.79 kg, Ndiwa, (2020). Majority of construction tasks are repetitive, require a lot of labour, pose hazards, and are ideally suitable for robotic automation. Robots possess the agility, speed, and strength needed to revolutionise construction. In particular, bricklaying may evolve into a significant aspect of contemporary construction, yet the heaviness and the inconvenience of handling the concrete blocks are crucial elements in this technology (Bello et al. 2024, Gharbia et al., 2020; Melenbrink et al., 2020). Hence, there is a need to design a new, lighter concrete masonry that is robust and suitable for I4.0 adoption as depicted in Figure 9.



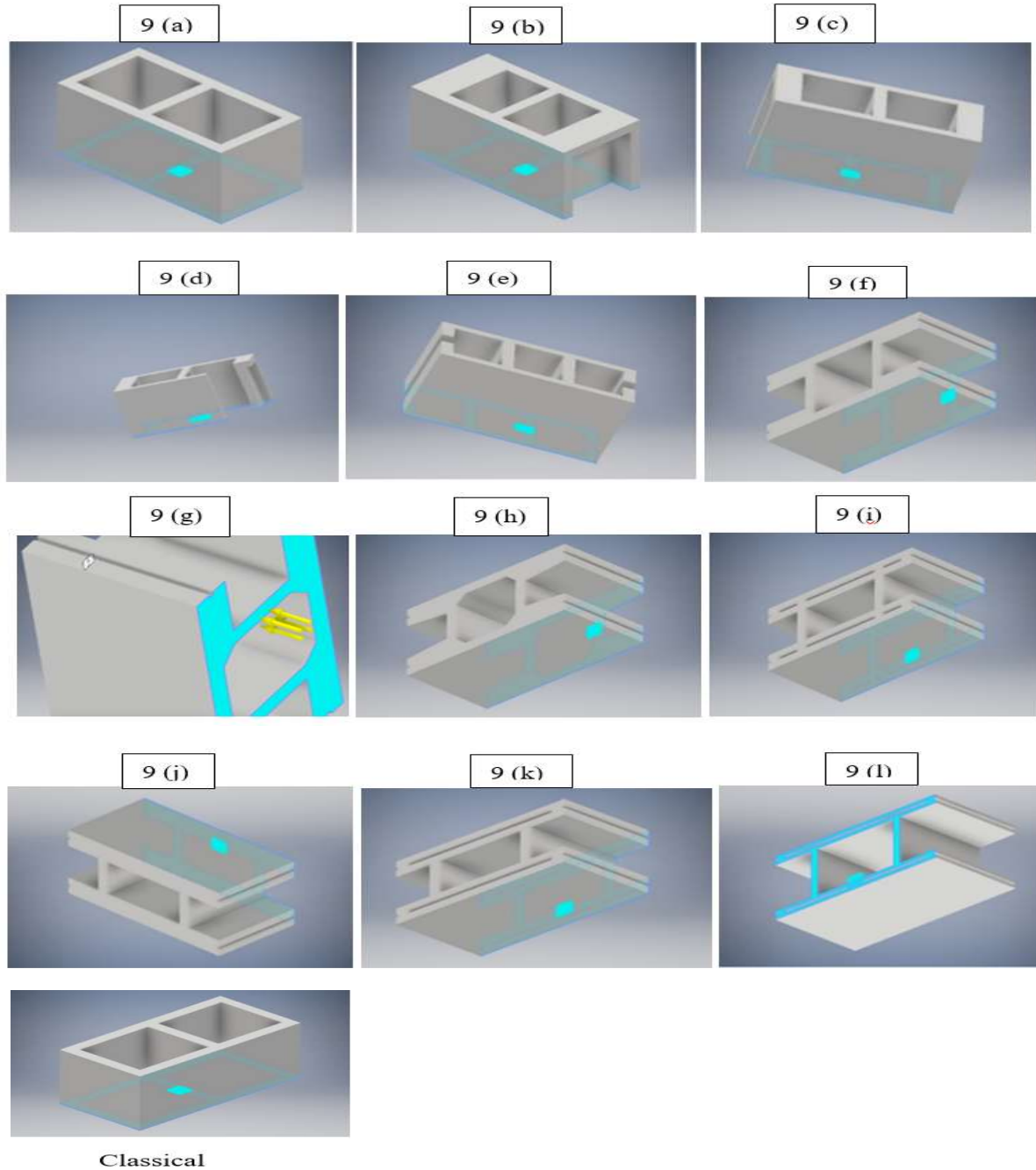


Figure 9 New concrete masonry 9 (a-l) with Handle to Aid Future Industry 4.0

It is essential to incorporate handgrips in the design of the new concrete masonry shown in Figure 9 to reduce its weight, maintain its structural load capacity, and lower the chance of musculoskeletal injuries for construction workers, which may support the use of robotic systems. To achieve this aim, the study used the geometry of classic concrete masonry, as illustrated in Figure 9, as a pilot sample, then designed twelve new concrete masonry units while maintaining the total external dimensions: 0.4 m in length, 0.2 m in width, and 0.2 m in height. Initially, we enhanced the traditional concrete

masonry by adding two handles 9 (a). Secondly, we have enhanced the handles 9 (b) and 9 (c). Third, we have thoroughly revamped the fundamental design of the brick by adding one central indentation and altering the shape to facilitate gripping it 9 (d). Fourth, we have enhanced the earlier design by maintaining the central recess and modifying the handles 9 (e). Fifth, the updated design features a larger central recess and reduced thickness 9 (f). Sixth, we have enhanced the design of the handles 9 (g). Seventh, four indentations have been incorporated in the wings 9 (h). Eighth, the four recesses in the wings have been linked to the central recess 9 (i). Ninth,

the middle recess has been extended, and the four side recesses have been eliminated 9 (j). Tenth, two longitudinal grooves have been incorporated, maintaining the central groove 9 (k). Ultimately, the wall thickness of the concrete masonry has been minimised to achieve the least weight 9 (l).

#### 4.4 The FEA

The newly designed masonry was exposed to an operating condition of 3.5 MPa, as this represents the maximum compressive strength that concrete masonry must withstand, particularly in a load-bearing context.

Size of the concrete block: 400 mm × 200 mm × 200 mm. The operating pressure was applied consistently downwards, directed at the top of the concrete masonry, while the lower section of the concrete masonry was secured in place. Conversely, the movements in the X, Y, and Z directions have been restricted for every node on the bottom surface. The designed concrete masonry was subjected to an operating condition of 3.5 MPa, considering that this is the maximum compressive strength that a concrete masonry should be able to bear, especially when in a load-bearing situation.

Dimension of the concrete masonry: 400 mm × 200 mm × 200 mm. The operating pressure acted uniformly downwards

and was directed towards the top of the concrete masonry, while the lower part of the concrete masonry was held fixed. On the other hand, the displacements in the X, Y, and Z directions have been constrained for all nodes on the lower face

#### 4.4.1 FEA Mathematical Model

To solve the mathematical model of this problem, the following assumptions for FEA were made.

- Solver

Highest number of h refinements: 0

Stop criteria (%): 10

h refinement threshold (0 to 1): 0.75

- Meshing

Run-of-the-mill element size: 0.1

Average element size in shells: 0.05

Least element size: 0.2

Grading factor: 1.5

Maximum turn angle: 60 degrees

### III. RESULTS AND DISCUSSION

Table 2 shows the performance optimisation models by studying them from a structural perspective.

Table 2 Result for FEA Performance Optimisation

Concrete masonry	Volume(mm <sup>3</sup> )	Weight (Kg)	Max. Von Mises stress (MPa)	Max. deformation(mm)	Max. Deformation (%)	Max. factor of safety
Classical	6160000	14.829	5.338	0.031	3.1	1.01
A	6512500	15.678	48.845	0.383	38.3	1.31
B	6437500	15.497	17.916	0.122	12.2	1.99
C	5424020	13.057	18.073	0.145	14.5	3.16
D	6600000	15.888	4.969	0.032	3.2	0.99
E	7473420	17.991	5.074	0.031	3.1	1.01
F	7702450	18.542	5.145	0.031	3.1	1.03
G	8193590	19.725	5.200	0.031	3.1	1.04
H	6836000	16.456	5.144	0.031	3.1	1.00
I	6488000	15.619	4.959	0.031	3.1	0.98
J	8973420	21.602	5.523	0.032	3.2	0.97
K	8160000	19.644	5.185	0.032	3.2	0.98
L	364440	8.773	5.271	0.031	3.1	1.01

Concrete masonry types A, B, and C exhibit poorer performance structurally, with shear failures occurring in their corners and triangular bands under reduced pressure loads. Concrete masonry types F, G, and H exhibit intermediate structural behaviour, demonstrating a more consistent stress distribution than the earlier bricks. Ultimately, concrete

masonry types D, E, I, J, K, and L demonstrate strong structural performance, and they will undergo additional assessment for ergonomic and efficiency aspects to identify the optimal concrete masonry option. From this perspective, concrete masonry types K and L represent the top candidates for concrete masonry. Figures 10 and 11 depict the maximum Von

Mises stress across the designed concrete masonry models and the maximum deformation of the designed concrete masonry models, respectively.

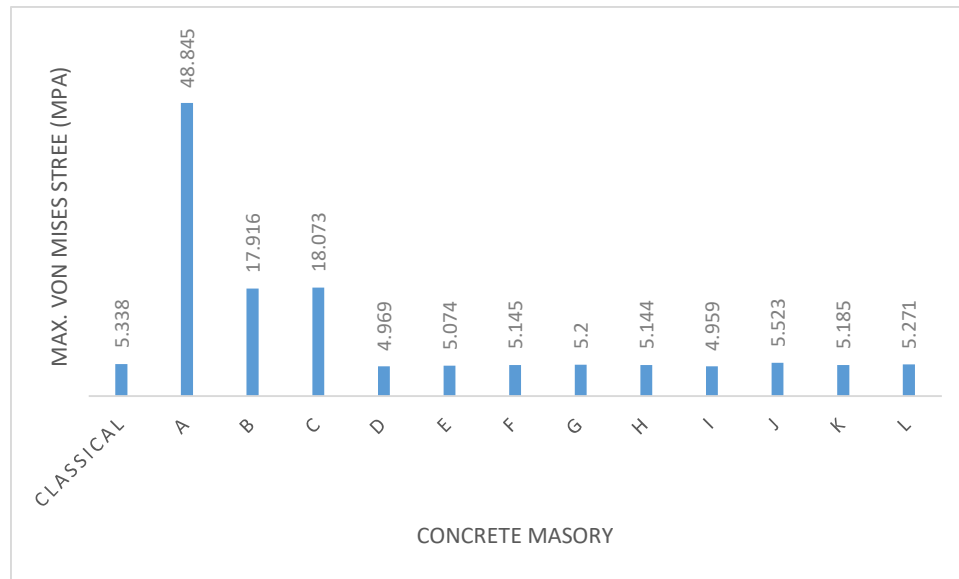


Figure 10 Maximum Von Mises Stress Across the Designed Concrete Masonry Models

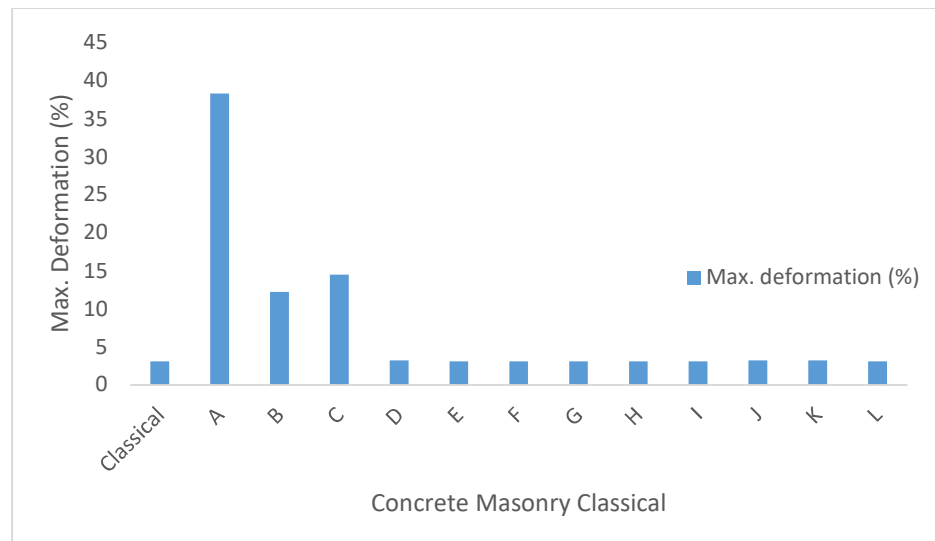


Figure 11 Maximum Deformation of the Designed Concrete Masonry Models

The value of the von Mises stress and deformation of concrete masonry A, B, and C, indicated in Table 2, shows that the model will fail.

Concrete masonry types 12 (a, b and c) show worse behaviour from the structural point of view, with failure loads as seen from Figure 12 (a-l) after they have been subjected to the same operating conditions.

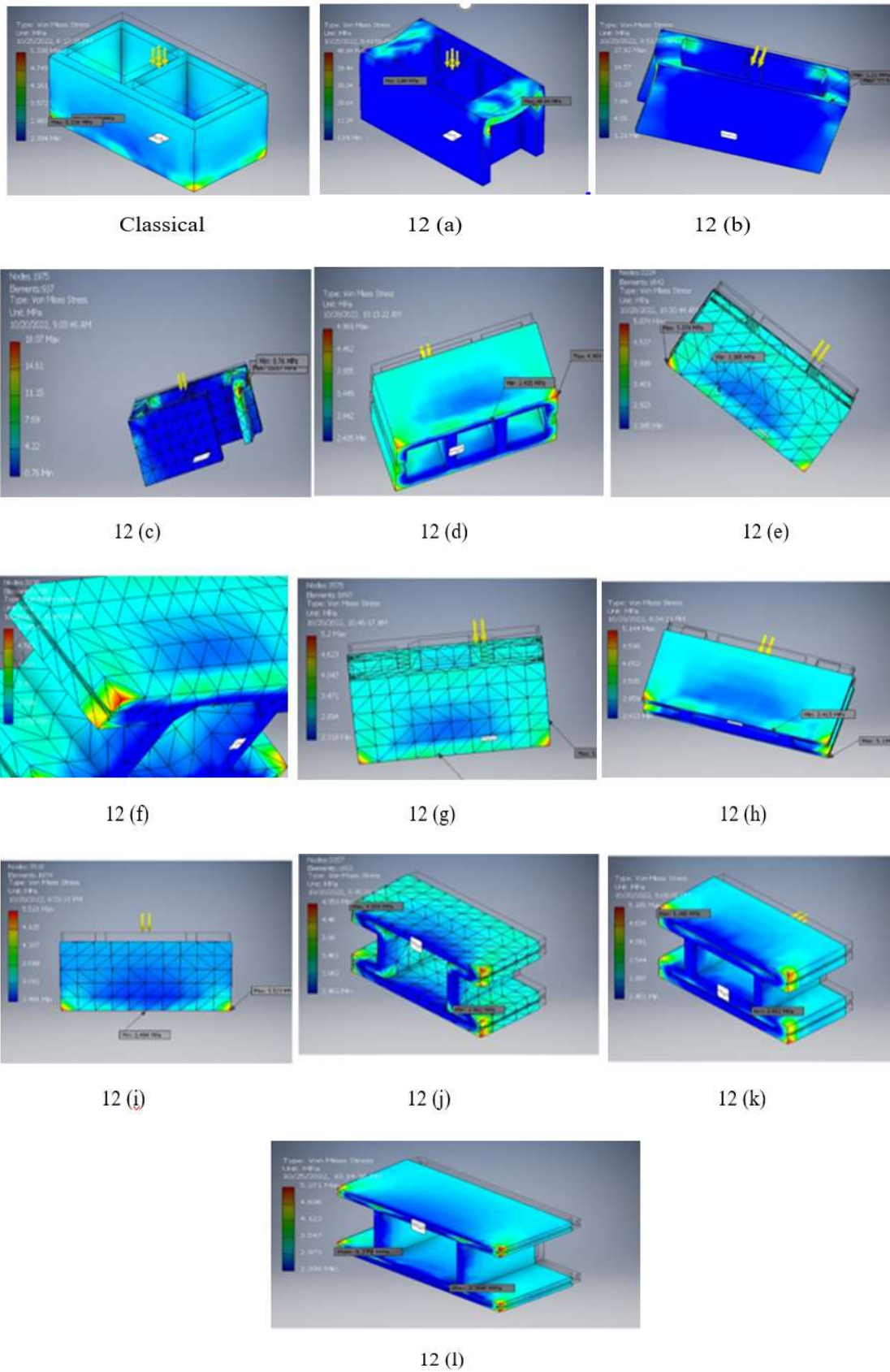


Figure 12 (a-l). Stress variations across different geometrical models of concrete masonry

It should be known that Von Mises Stress is considered to be a haven for engineers as it is proven to be more sufficient to determine if a material will fail as compared to normal stress. Von Mises stress arises from the distortion energy theory.

There is a need to analyse other important aspects of the remaining models to streamline the model that tends to perform the best. Figure 13 presents the designed model's factor of safety.

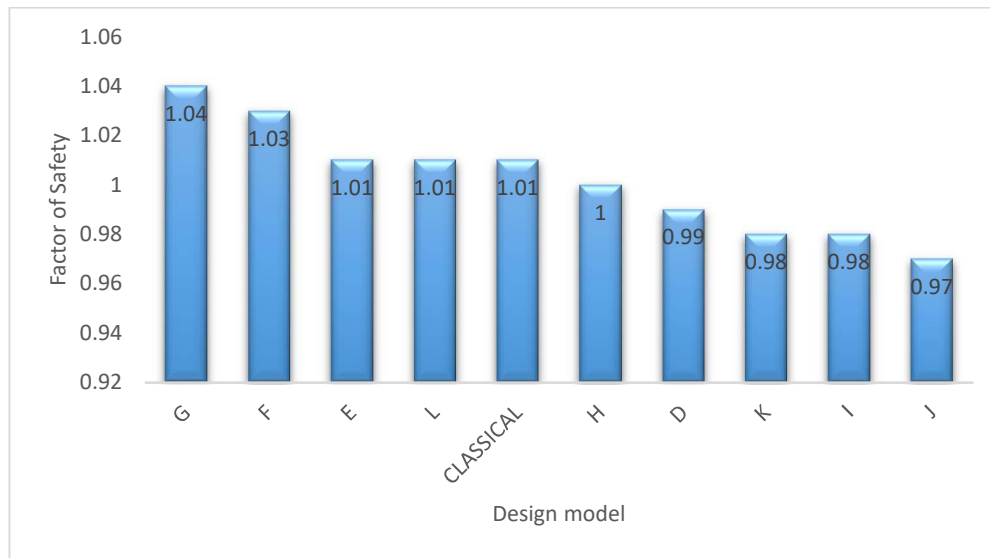


Figure 13 A factor of safety for the designed models

Models (D, K, L, and J) did not satisfy the 1-unit minimum value of the factor of safety; therefore, only 5 models (G, F, E, H, and L) remain. Considering that model L has a lesser volume and a lesser weight, as seen from Table 3, and still compares better to the classical model, it is recommended to adopt model L.

#### 5. Verify Phase

The verification stage is the final part of the DMADV procedure for enhancing the design of current products, processes, and systems. The emphasis of this stage is to comprehensively record and document the enhancements made, as well as assess the performance, contentment, and outcomes. Consequently, it is vital to evaluate the performance of the revised project model concerning the CTQs and to determine whether the performance is predictable. Through the integration of the DMADV methodology, a uniform and standardised approach to designing enhancement projects has been created across the process. According to (Kristensen, 2021), DMADV determines the gains and verifies, measures again, and sets new operating standards. Implementing a change to maintain the improvement over time is challenging, as we recognise that this aspect of project management does not evolve rapidly. A system of checks and balances is created to guarantee that performance enhancement persists without deviation. Ultimately, the modules and insights gained from the DMADV process need to be thoroughly documented, along with recommendations for potential enhancements in the revised model.

During the verify phase, the design is tested and evaluated. All aspects of project, process, and change management converge for a comprehensive implementation

and rollout of the new process. The outcomes of the execution are checked against the initial CTQs, specifications, and objectives. The project cannot be completed until the solution is standardised and handed over to operations and process management.

This marks the final stage of the DMADV approach. During this stage, the prototype of the optimal design is verified for its intended purposes. The final element model (FEM) serves as an effective tool for modeling and analysing singular structures, including shape optimisation and nonlinear structural analysis of hollow concrete masonry. In this study, the ergonomic principle is utilised to enhance the everyday tasks of bricklayers through numerical analysis of the ideal hollow brick design, factoring in the lifting conditions. Defining the geometry of a hollow concrete masonry structure like this is quite challenging when using a finite element analysis program. Consequently, a three-dimensional parametric design software was utilised to create a single hollow brick. In this study, we employed a refined FEM mesh. The examination of the collated data revealed that the mechanised concrete masonry industries are the ones that implement process quality control principles, and they are few, whereas those masonry industries that use manual operation do not implement quality control principles, and they are the majority.

Examination of the research findings also indicated that there is no notable correlation between educational qualifications and employee performance in those small and medium-sized concrete masonry industries. Data analysis also revealed that, overall, concepts of process quality control are typically not implemented in the production of concrete masonry in many SMEs' concrete masonry industries. The data

indicate that customers primarily source their supplies from the SME masonry industries.

Following various mixing techniques in the simulation, the third mixing method (Figure) was selected, where the mixer's diameter was decreased, enabling it to rotate inside the drum while moving up and down through the mixture, resulting in a uniform mixture with evenly distributed components. The blending facilitated robust vertical turnover.

Calculations revealed that a diameter of 35 mm is recommended for the shaft of the electrically powered mixer, considering a speed of 100 rpm.

Concrete masonry 12 (a, b and c) exhibits poorer performance structurally, displaying shear failures at its corners and triangular bands under reduced pressure loads. Concrete masonry types F, G, and H exhibit intermediate structural performance, demonstrating a more consistent stress distribution compared to the earlier bricks. In conclusion, concrete masonry 12 (d, e, i, j, k, and l) demonstrates strong structural performance, and it is essential to consider additional ergonomic and efficiency factors to choose the most suitable concrete masonry option. From this perspective, concrete masonry 12 (k) and 12 (l) are the most suitable candidate bricks.

The Von Mises Stress and deformation of concrete masonry 12 (a, b, and c) indicate that the model is set to fail.

Concrete masonry 12 (a, b, and c) demonstrates poorer performance structurally, exhibiting shear failures at their corners and triangle bands under lesser pressure loads, despite all models being exposed to identical operating conditions.

Models (D, K, I, and J) show a maximum safety factor that is below the acceptable minimum value of safety (L), which directs our attention to models (G, F, E, H, and L). Notably, model (L) exhibits a smaller volume and lower weight as indicated by the table, while still outperforming the classical model, making it advisable to adopt this model.

#### IV. CONCLUSION

This study analysed the process of making concrete masonry and identified the main areas where it could be improved. The areas looked into were how to reduce wastage and increase efficiency, as well as incorporate new technologies. Six Sigma's DMADV methodology is quite effective in the enhancement of process quality, reduction of visible defects such as cracks, honeycombing, or irregular shapes, and improvement in design efficiency. The introduction of this framework was able to help concrete manufacturers reduce inconsistencies in materials, enhance the production process, and improve structural integrity. For example, the study found that the introduction of a mechanised concrete mixing system improved homogeneity by 70%, in addition to reducing the rate of human error and material variability. The application of Finite Element Analysis (FEA) in the optimisation of new concrete block designs also led to an 8.777 kg weight reduction, thus maintaining both durability and ergonomic efficiency. Furthermore, these innovations were instrumental in improving performance efficiency in masonry units while also ensuring their compliant use in robotic applications. The integration of a quality control

mechanism with automation into small and medium-scale concrete manufacturing is an essential way to foster safety and reduce construction failures. The study, therefore, highlights the importance of process control in ensuring both durability and reliability in the use of construction materials.

The key findings in the present study are outlined as follows:

- A massive concrete masonry weight reduction is obtained (8.777 Kg). Concerning the weight of the classical concrete masonry, this will help to maximise the usage of resources available.
- Lesser Von Mises stress is being experienced as compared to what the classical concrete masonry experienced.
- The factor of safety provided a reasonable value considering the alterations it encountered.
- The proposed design can be seen to expose more surface area of the concrete masonry, and this will help the curing process of the concrete masonry.

The aspect of the mixer proposed has been verified to have a great influence on the final output of the production process, as it can yield better quality in a short time and can overcome the time-consuming nature of conventional mixing of aggregates in concrete masonry industries. It will also save human capital costs as there will be a massive reduction in the number of staff to hire in a bid to coordinate the mixing process. It will also promote a less hazardous environment as opposed to the manual techniques maintained by the workers of brick moulding companies, which can expose them to injuries. It will also promote a tidy environment

#### AUTHOR CONTRIBUTIONS

**K. A. Bello:** Conceptualization, Methodology, Validation, writing – original draft, writing – review and editing. **R. W. Maladzhi:** Visualization, writing, review and editing. **K. A. Bello:** Formal analysis, Validation, writing, review and editing. **R. W. Maladzhi:** Supervision, Project administration, writing, editing. **K. A. Bello:** Supervision, Funding acquisition, writing, review and editing; all authors have read and agreed to the published version of the manuscript.

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