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Facility Layout Design, Simulation, and Optimization for Kaolin Beneficiation Plant Using Flexsim

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Abstract

Nigeria has huge deposits of kaolin spread across the country. Yet, Kaolin and its derivatives cost Nigeria around 14 million USD annually, and they have diverse industrial applications such as the manufacturing of paper, ceramics, cosmetics, medicine, paints, and porcelain. This loss of revenue is due to the under-tapping of the mineral due to the absence of beneficiation plants. Currently, the mining is primarily done crudely by artisan miners. Implementing modern manufacturing infrastructure requires adequate attention to cater to facility layout and future improvements, reduce costs, improve customer satisfaction, space utilization, etc. Simulation exercises proffer solutions to these problems in a virtual environment. This work reports a proposed facility layout design for kaolin beneficiation. The proposed plant was designed using Systematic Layout Planning (SLP) methodology and tested using FLEXSIM Simulation software to optimize the plant's production capacity. The results from the design showed that the optimized production plant had an annual production capacity of 95,328 tons, which was higher than the initial layout, with 69,120 tons per annum. The workstations utilization for the optimized layout showed better results than the initial layout design, with the optimized results showing improvements in the efficiency of the workstations as follows (after the simulation): fluid mixer1 had 73.77%, sedimentation tank had 18.44%, rotary drum dryer had 18.44%, packaging line had 63.87%, Screener_washer had 74.46%, and magnetic separator has 63.94% utilization.

Keywords: Facility layout, SLP, Flexsim simulation, Kaolin ore beneficiation.

1 | Introduction

Cores Manufacturing transforms raw materials and information into finished goods and services to improve human needs [1]. To achieve this capability in a competitive business environment, manufacturers must adopt advanced systems to produce goods quickly at the least cost [2], [3].

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Designing and planning manufacturing plants is a tedious and complex process. With the global change in the pace and depth by which manufacturing has advanced, smart technologies are adopted to give more flexible and robust designs [2], [4]. Having the right design ensures that the manufacturing systems are effectively conceived. Around 50% of the total operating cost of manufacturing plants is related to plant layout development. The material handling function encompasses transportation, Work-In-Process (WIP), finished goods, materials and tools used between workstations [5]. Therefore, it is imperative to give adequate attention to reduce these costs to the minimum [6]. Production plant simulation identifies likely bottlenecks in production by highlighting the effectiveness of the design, workstation utilization and plant capacity to boost productivity, reduce wastes and make suggestions about what facility will be much more convenient to optimize the production line rather than on real-life plant [7], [8]. There are several applications of simulation optimization of production plants in diverse sectors of the industry, such as the manufacturing of automobiles [9], food processing plants [5], mechanical production [2], [10], [11] logistics and warehousing [12].

Systematic Layout Planning (SLP) is a tool used to arrange workstations in a plant to derive an optimal facility layout through five-step layout planning procedures developed by Richard Muther [13]. The steps are identifying the activities, relationships, space, adjustments and evaluation.

Identifying activities involves the input data and activity areas, which are achieved through five elements: product (what), quantity (how much), route (how), supporting services (with what), and time (when) [14]. These elements help us understand what we need to produce, how we can produce it, what volume we need, what equipment or tools we need, and how long it will take to manufacture the desired product [15].

Relationships: identifying the relationships consists of the flow of materials, activity relationship and relationship diagram. The material flow analysis will provide data and an understanding of the sequence of how effectively materials will flow through the system [14], [16]. Relationship diagrams showcase how the materials can be streamlined in a process flow chart within a layout [17]. Activity relationship charts consider the attributes of the relationship diagram and classify them according to the degree of importance of having workstations/departments adjacent to each other.

Space: this step considers the space requirement, space availability and space relationship diagram. The focus is to ensure space provision for staff, equipment and other factors are catered for from the theoretical analysis [18].

Adjustments: the step elaborates on the need for modification and the limitations and alternatives we have in designing a practical layout [19].

Evaluation: having accomplished the four steps earlier mentioned, the qualitative and quantitative layout evaluation criteria to determine the need for optimization of resources, space, flow of materials, handling and use of equipment [14], [16].

A study [20] was conducted to design an improved layout for a steel processing plant using SLP and lean manufacturing techniques. The study, in reference, implemented an improvement in the facility to manage space, efficiency and resource utilization and observed a 26% improvement in space utilization and a 34% reduction in material flow [17]. In another study, SLP methodology was integrated with simulation to design and evaluate a facility layout for industrial head lettuce production to maximize production capacity and efficiency. The optimal layout had a 67.3% improvement in plant efficiency than the initial layout plant [20].

Simulation is a strong analytical tool used in evaluating and improving manufacturing systems to perform effectively with increased productivity [21], [22], [23]. Simulation models are classified according to three dimensions: timing of change, randomness and data organization [24], but when considered in terms of time factor, the simulation is regarded as either static or dynamic. The latter is interesting in this study as it depends on time and is further divided into continuous or discrete simulations [25]. Discrete simulation is driven by time or event. When time is of interest, it means that over a time interval, an alteration takes place, and output is expected to be generated to analyze and understand the dynamics of the manufacturing systems [24]. Computer simulation uses computer models to simulate a system of interest that will produce results to support decision-making], [15]. Keith Douglas Tocher developed a General Simulation Programme (GSP) to build and simulate an industrial plant that comprises machines and other states of utilization such as idle, busy, unavailable and failed. This invention paved the way for a mixture of discrete and continuous model execution [21]. FlexSim is a simulation software equipped with 3D visualization of resources, workers and robust means of data presentation [6]. The ideal thought behind the simulation is to give an in-depth behaviour of how manufacturing processes will behave in a virtual world without the need for building a real-life structure or process, how designed processes will be effective and also the estimated output to save costs of production, improvements and time [26]. Simulation is used to model complex non-linear systems with elements and their components and view their relationship in a virtual environment using computer-generated animations for ease of understanding [27]. One of the advantages of simulation over other modelling techniques is the decision support system, which is much easier to grasp through the visual display of the model [1], [28]. The visual display of FlexSim positively impacts the performance of the simulation tasks and activities of the entire simulation process; it helps in model development, verification [27], validation and ease of interpretation of output which will further enhance the credibility, reliability and acceptance of the data [22], [23], [28]. Some authors [29] have used material flows to design and optimize a production line. The study results showed higher continuity of material flows, large space for material handling, and better production performance on the optimal production line than another old line [29]. In the same vein, several authors have explored the use of FlexSim to perform analysis of logistics, healthcare, manufacturing facilities and processes [8], [12], [25], [30], [31]. The results have proven that FlexSim is a veritable tool for virtually designing a plant before physically building it.

This study aimed to design a proposed plant using SLP and perform a simulation analysis on the production capacity of the kaolin beneficiation plant using FlexSim software.

2 | Methods

2.1 | Principles of Systematic Layout Planning

SLP methodology provides a step-by-step guideline for designing plants from input data to evaluation of the best layout [17], [20]. This methodology is viewed to have three large building blocks: analysis, research, and selection phases [13]. SLP has five elements with acronyms of PQRST translating to Product (P), Quantities (Q), Routing (R), support Services (S) and Time (T) [32]. Product (P) and Quantities (Q) relate to the product to be developed in the plant. The proposed plant's estimated throughput capacity is 500 tons/day. The products will be manufactured according to the flowchart in *Fig.1*, which depicts the routing. The established Routine (R) was broken down into processes (unit operations) for the beneficiation plant, classified as screening, hydraulicking, blunging, deflocculation, leaching, sedimentation, clarification, drying, grinding, packaging and dispatch. After that, the production capacity was simulated using FLEXSIM software to validate the plant's design.

The Support Services (S) considered (deployed) within the plant include air conditioning, air compressors, lighting, ducts and other utilities. Time (T) refers to the period for deriving an optimum design. Currently, the production plant runs two shifts, 12 hours a day, and 7 days a week. Material flow analysis assessed the closeness factor that deals with moving materials from one department to another. The from-to-analysis deals with the relationship between material flow and the departmental interactions between processes. Using closeness ratings between each process (*Fig. 2*), the processes with the highest closeness ratings were placed next to each other and helped tackle the problems encountered in plant layout design. The closeness ratings were guided by codes and ratings based on the range from the highest to lowest ratings denoted by symbols A, E, I, O, U, and X. Refer to *Table 1* for a detailed description of the symbols. The common from-to-chart in *Fig. 3* was designed through this step [17]. Activity relation analysis deals with the study of the relationship between various operations taking place in the plant. The details about the methodology employed in this study concerning the plant design using SLP are the steps previously reported in various literatures precisely

[13], [17], [22], [33], [34], [35], [36]. *Fig. 1* to *Fig. 4* in this manuscript were designed using Microsoft Visio software, while the remaining figures were generated from the Flexsim software environment.

2.2 | Simulation Modelling using FlexSim

FlexSim is an object-oriented program that can model, visualize, monitor the flow process, and simulate system processes of a manufacturing environment with animations in 3D [5]. It entails artificial intelligence, simulation, data processing, and three-dimensional image processing [11], [16]. FlexSim offers a variety of formats of data [6]. In the work reported in this paper, the simulation software version used was FlexSim 2023 Version 23.2.2. Flexsim software simulation involves the following steps to achieve an output: building the simulation model layout, defining the processes, setting parameters, compilation, and running the model [37], [38], [39].

2.3 | Establishment of the process in the FlexSim Simulation Environment

The simulation process was established according to literature prescriptions contained in [5], [6], [30], with all stages, processes, and arrival schedules presented in the simulation environment with the data generated as an output.

2.4 | Building the Simulation Model in FlexSim Environment

The required elements for the simulation were added to the FlexSim environment; parameters were set accordingly, as shown in *Fig.1*, while *Table 1* highlighted the simulation entities and their description.

Table 1. Summary of model elements used during the simulation.

S/N	Model Elements	Description	System Elements
1	Source	Raw material creator	The raw material source point
2	Flow items	Products to be processed	Raw kaolin
3	Fixed resources	Workstations	For processing and transporting of raw materials
4	Fluid element	For converting solid to fluid materials	Processing and transporting of materials
5	Culls	Collection of waste products	Waste bin

2.5 | Simulation Assumptions

The following assumptions were adopted to ensure proper data was recorded during the simulation period:

I. That each flow item from the source is 10 Kg.

II. That each fluid per discrete item is 10 litres.

III. That each discrete unit per item is 20 Kg/ item.

IV. That the deflocculation and blunging processes are simultaneous.

V. The pulp (slurry) inside the sedimentation tank has settled.

3 | Results

3.1 | Product Layout for the Beneficiation of Kaolin

The proposed product layout was drafted after the local mining sites were visited. The product layout showcased the processing sequences of kaolin beneficiation from raw material to finished product. *Fig. 1* highlights the proposed process flow chart for the beneficiation of Kaolin.

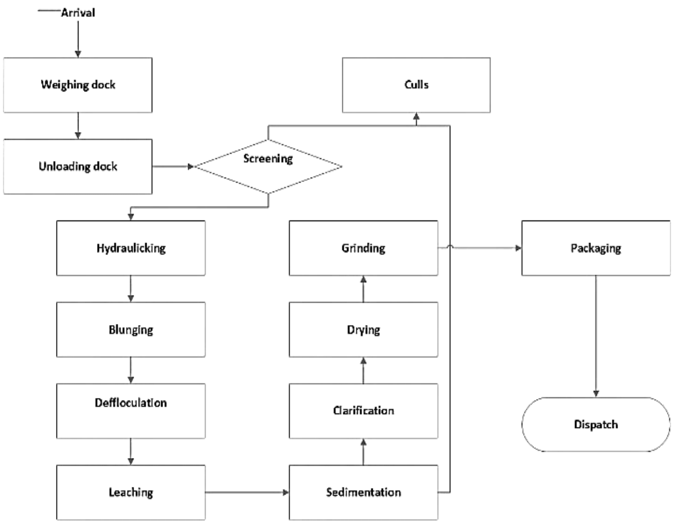

Fig. 1. Process flow chart for beneficiation of Kaolin.

3.1.2 | Activity relationship chart

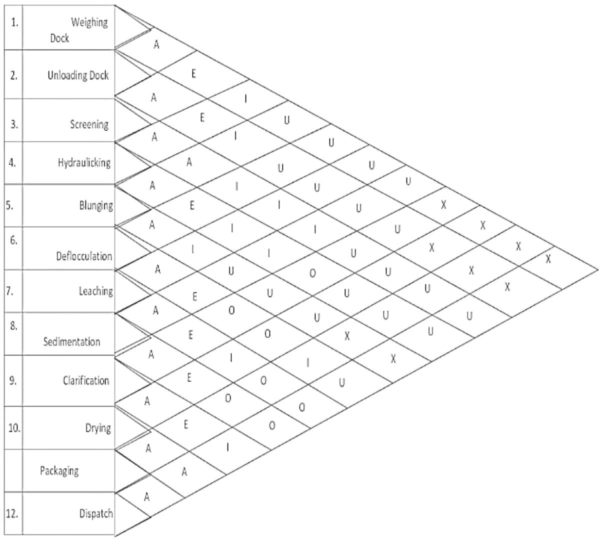

Fig. 2. Activity relationship chart for beneficiation of Kaolin.

	Departments	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Weighing Dock		A / 1,2	E / 1	I / 1	U / 1	U / 1	U / 0	U / 0	U / 0	U / 0	U / 0	U / 0	U / 0
2	Unloading Dock	A / 1,2		A / 1	E / 1	I / 1	U / 3	U / 0	U / 0	U / 0	X / 0	X / 0	X / 0	X / 0
3	Screening	E / 1	A / 1,4		A / 1	O / 1	O / 3	O / 1	U / 0	U / 0	U / 0	U / 0	U / 0	X / 0
4	Hydraulicking	U / 0	E / 1	A / 1		E / 1	A / 1	I / 1	O / 0	U / 0	U / 0	U / 0	U / 0	U / 0
5	Blunging	U / 0	O / 1,2	I / 1	E / 1,2		E / 1,2	I / 1	U / 0	U / 0	U / 0	U / 0	U / 0	U / 0
6	Diffloculation	U / 0	U / 0	O / 1,2	I / 1	E / 1,2		A / 1,2	A / 1	A / 1	U / 0	U / 0	U / 0	U / 0
7	Leaching	U / 0	U / 0	O / 0	I / 1	I / 1	A / 1,2		A / 1,2,4	O / 1	U / 0	U / 0	U / 0	U / 0
8	Sedimentation	O / 0	U / 3	U / 3	O / 3	U / 3	A / 1	A / 1,2		A / 1	O / 1,2	U / 0	U / 0	U / 0
9	Clarification	U / 0	U / 3	U / 3	U / 3	U / 3	O / 1	A / 1,2,4	A / 1,4		A / 1,4	U / 0	X / 0	X / 0
10	Drying	X / 0	X / 0	X / 0	X / 0	X / 0	U / 1	O / 1	I / 1	A / 1,4		A / 1,2,4	I / 1,4	O / 1,4
11	Grinding	X / 0	X / 0	X / 0	X / 0	U / 1	U / 1	U / 1	O / 1	O / 1	A / 1,4		A / 1,2,4	E / 1,2,4
12	Packaging	X / 0	X / 0	X / 0	X / 0	X / 0	X / 0	X / 0	U / 0	U / 0	I / 1,4	A / 1,4		A / 1,4
13	Dispatch	X / 0	X / 0	X / 0	X / 0	X / 0	X / 0	X / 0	U / O	U / 0	U / 0	I / 1,2,4	A / 1,2,4	

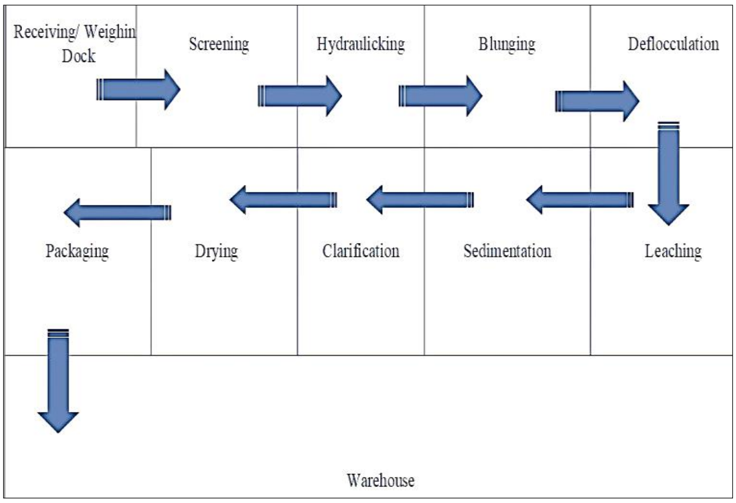

Fig. 4. Process layout for beneficiation of Kaolin.

Table 1. Activity relationship ratings.

Value	Relationship	No of Ratings
A	Absolutely important	4
E	Especially important	3
I	Important	2
O	Closeness ok	1
U	Unimportant	0
X	Not desired	-1

3.2 | Simulation Results Analysis

Table 2 and designed according to the process flow chart depicted in *Fig. 1*.

Table 2. Summary of simulation data.

S/N	Working Process	Description	Working Time
1.	Screening/ washing	For screening and washing of kaolin	13.88 Kg/min
2.	Magnetic separation	For removal of metal impurities and separation of particles	8.33 Kg/min
3.	Sedimentation	Used for the sedimentation process	5000 L
4.	Drying	Rotary drum dryer for drying materials	150-1300 ^{o}C 25t/h
5.	Packaging line	Used for filling and sealing to desired requirements	25 bags/ min

Fig. 5 shows the highlights of the proposed simulation model for the beneficiation of Kaolin.

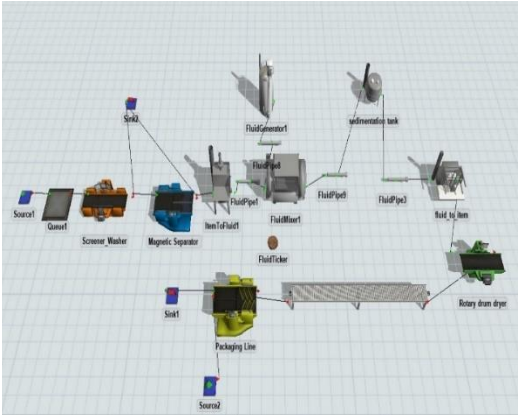

Fig. 5. Proposed simulation model for the beneficiation of Kaolin.

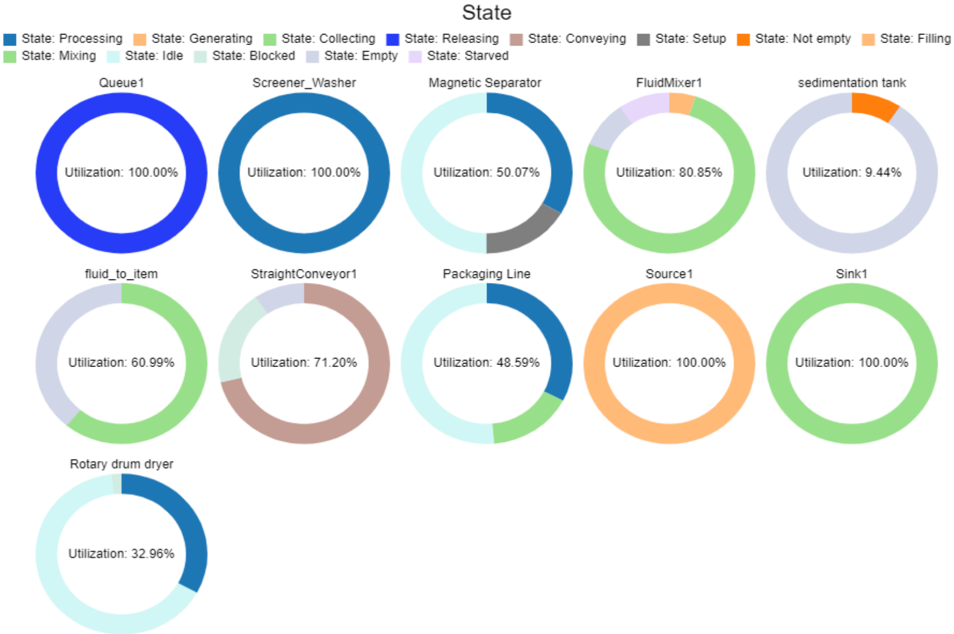

Fig. 6. Summary of workstations utilization.

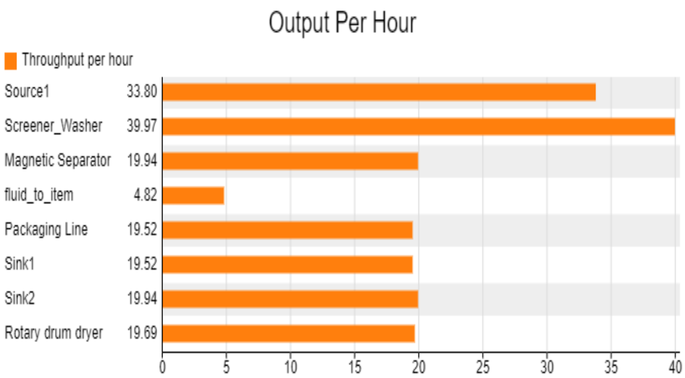

Fig. 7. System throughput per hour.

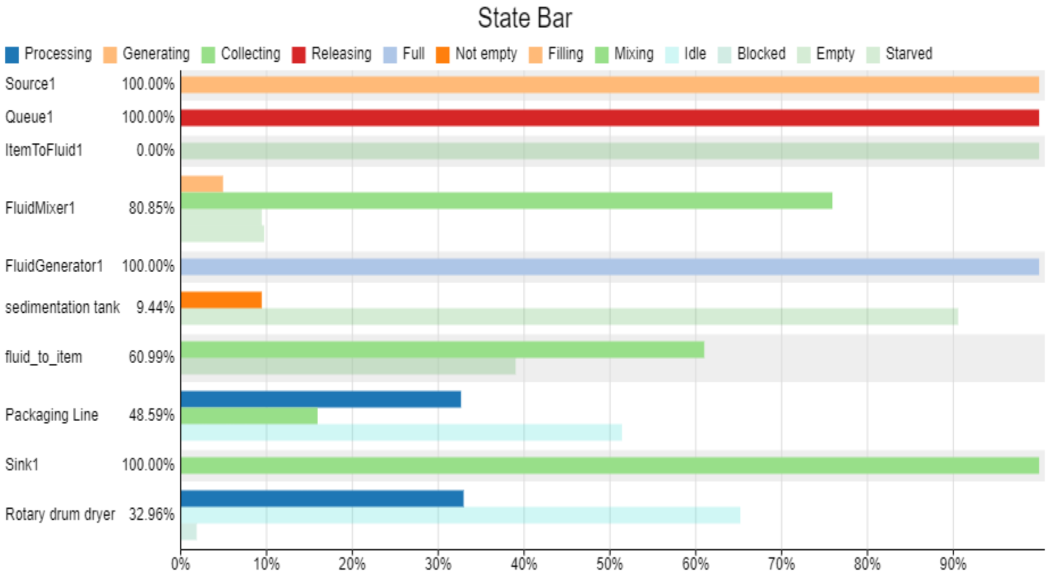

Fig. 8. System state of all workstations over simulation period.

3.3 | Design and Optimization of Production Line Scheme 1

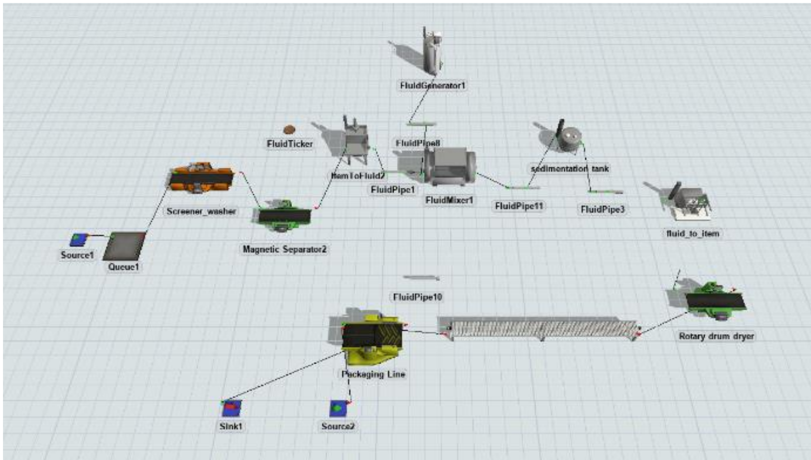

Fig. 9. Improvement layout.

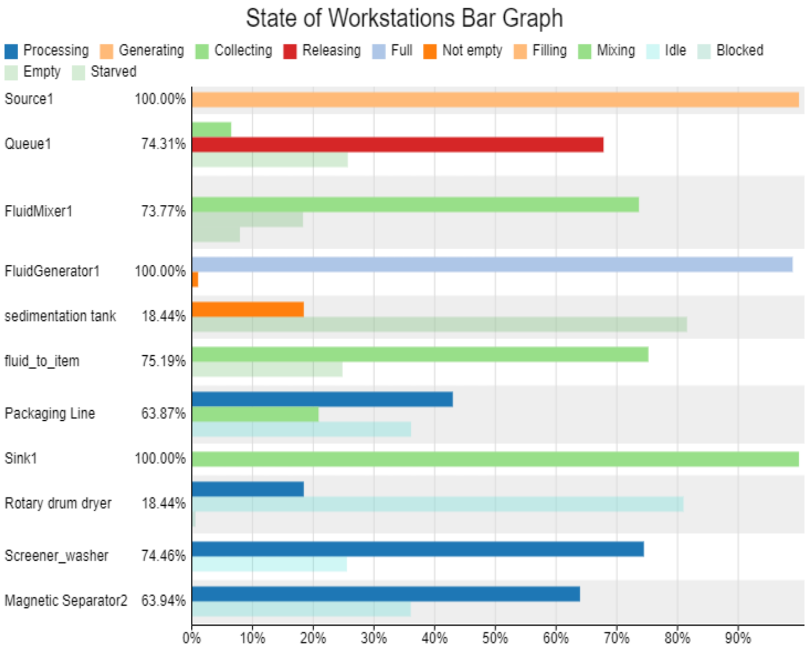

Fig. 10. State of the workstations.

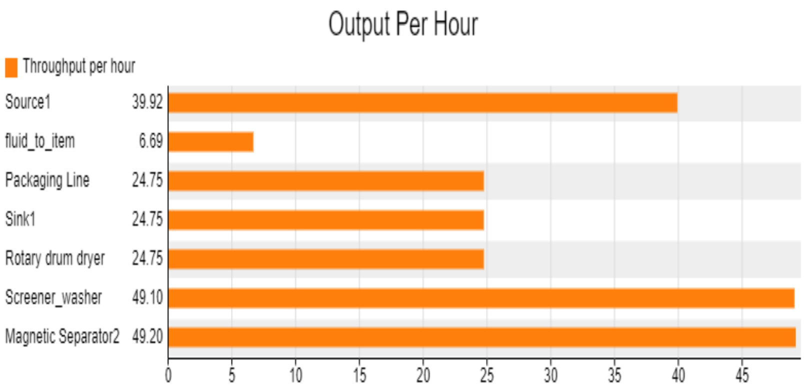

Fig. 11. Throughput per hour.

Table 3. System throughput.

Workstation	Throughput
Queue1	491
Screener_washer	492
Magnetic Separator2	493
Rotary drum dryer	331
Packaging Line	331
Sink1	331

3.4 | Comparison Between the Initial Model and Optimised Model Layout

The basis of comparison was on workstation utilization and throughput per hour for the system, as shown in *Table 4* below.

Table 4. Comparison between initial and optimized models.

Basis of Comparison	Workstations	Initial Model	Optimized Layout
Workstation Utilization	Screener_washer	100%	76.46%
	Magnetic Separator	50.07%	63.94%
	Packaging line	48.59%	63.87%
	Rotary drum dryer	32.96%	18.44%
Throughput per hour	Screener_washer	39.97 Kg	49.20 Kg
	Magnetic Separator	19.74 Kg	49.20 Kg
	Packaging line	19.69 Kg	24.75 Kg
	Rotary drum dryer	19.52 Kg	24.75 Kg

4 | Discussions

The Process flowchart for the beneficiation of kaolin shown in *Fig. 1* highlighted the various unit operations in sequence for all the materials that move between workstations. *Fig. 2* and *Table 1* show the relationship between pairs of activities preceding a process operation, with intersections to two dividing lines showing a letter that symbolizes the importance of their closeness. This allows for optimal sequencing with the corresponding block layout [5], [40]. *Fig. 3* showcases the from-to-chart, a tabular record of the movement of materials among departments and activities in a qualitative unit per *Table 1*, which displays the activity relationship ratings. The parameters of the simulation model elements were configured according to *Table 2* and designed according to the process flow chart depicted in *Fig. 1*, which is also plainly represented in *Fig. 4* for emphasis.

Fig. 5 shows the proposed simulated kaolin beneficiation plant model with well-connected simulation elements. The simulation time was 43,200 seconds (12 hrs), and the model speed was moderate. The model was validated through visual analysis and verified for errors before the simulation started. After the simulation exercise, the process was statistically analyzed to check for the workstations' material input/output, processing time and system performance.

Fig. 6 shows the summary of each workstation during the simulation period of 43200 seconds. The Figure highlighted the workstation's efficiencies. The Fig. 6 highlights the system utilization of workstations. It could be observed from *Fig. 6* that the sedimentation tank recorded the lowest utilization at 9.44 %, followed by the rotary drum dryer, which had 32.96 %. The packaging line had 48.59%, the magnetic separator had 50.07%, the fluid mixer had 80.85%, and the conveyor had 71.20%. The workstations with the highest utilization percentage were screener_washer, queue and sinks with 100% utilization, respectively. The system throughput per hour is indicated in *Fig. 7*. Based on the above data, the simulation showed that about 34 tons/h was moved into the production process. At the same time, the workstation (Screener_Washer) can process up to 40 tons/h, and in the same vein, the Magnetic Separator station can process around 20 tons/h, while the rotary drum dryer has the capacity to produce 20 tons/h, the same as the packaging line which could handle 20 tons/h of refined kaolin.

Fig. 8 depicts the system state in a bar chart, and from *Fig. 8*, it could be seen that only Queue1, source1 and fluid generators were free of materials, while other workstations have materials as WIP. The workstation termed fluid mixer had around 20%; the sedimentation tank had 9.4%; the rotary drum dryer had 32%; and the Packaging line 48.59% of WIP, respectively. This is a clear indication that the current state of production and simulation time are not enough to produce effectively; hence, there is a need for optimization of the manufacturing process through the introduction of other workstations. The optimization led to an improved layout shown in *Fig. 9*. The improved layout has a replacement of the Initial Magnetic Separator with a processor, and also the fluid mixer (fluidmixer1) functions were modified to function simultaneously with the blunging and deflocculation processes. The simulation timer was set to reset and set to 43200 seconds again, and a re-run was performed.

Fig. 10 shows the state of the system after the simulation period and careful observation of the workstations (Fluidmixer1, sedimentations tank, packaging line and rotary drum dryer), which in the initial model layout had 88.85, 9.44, 48.59 and 32.96% utilization which prompted the improvement layout. After the simulation re-run with the optimized model, the observed improvements in the efficiency of workstations are: fluid mixer1 had 73.77%, sedimentation tank had 18.44%, rotary drum dryer had 18.44%, packaging line had 63.87%, Screener_washer had 74.46%, and magnetic separator has 63.94% utilization over 46800 seconds of the simulation period.

The throughput per hour of the plant was also measured, and it showed an achievable output over one hour, indicated in *Fig. 11*. As observed in *Fig. 11*, there was an improvement in the overall plant layout output per hour. While the plant was designed to process 500 t/day, the workstation (Source1) served the raw materials entry location with an output of 39.92 t/h, Screener_washer, Magnetic_separator, packaging line, rotary drum dryer had 49.10, 49.30, 24.75 and 24.75 t/h respectively.

The system throughput shown in *Table 3* highlighted the output at the end of the simulation period. The system showed the plant throughput of 67.41% and tailings of 32.59%.

Table 4 compares the old and optimized designs based on workstation utilization and throughput per hour. Workstation utilization improved on the magnetic separator from 50.07 to 63.97% and the packaging line from 48.59 to 63.87%. Meanwhile, the rotary drum dryer was reduced from 32.96% to 18.44% because of the initial model's bottlenecks (queues) before materials were received for drying. This also results in more drying time, more energy, and a longer working period. However, this reduction in the optimized layout would serve as an advantage as it would conserve energy and reduce working hours on the dryer. Throughput per hour was also compared. The result showed that the throughput also increased from 39.97 to 49.20 Kg in the screener_washer, Magnetic Separator from 19.74 to 49.20 Kg, Magnetic Separator from 16.69 to 24.75 Kg while the rotary drum dryer also improved from 19.52 to 24.75 Kg. The improvement was due to the introduction another workstation in the optimized model layout (Magnetic Separator2).

5 | Conclusion

The study was conducted to develop an optimum layout and perform a simulation analysis on a proposed kaolin beneficiation plant with an estimated production capacity of 500 tons/day. The work intended to generate pragmatic data for establishing a beneficiation plant in Nigeria that will allow the country to tap into the global opportunities of refined kaolin products. This will, in turn, create jobs, increase revenue, and improve the standard of living of people around the mining areas. The optimized plant layout proved more effective, had higher throughput, and improved plant efficiency than the initial model layout. The proposed plant design was achieved and implemented through SLP steps such as plant capacity, material flow, activity relationship and layout alternative analyses.

List of Abbreviations

Not applicable.

Declarations

Ethics approval and consent to participate

This does not apply to this research.

Consent for Publication

This does not apply to this manuscript.

Availability of data and material

This does not apply to this manuscript.

Competing interests

There are no competing interests to declare concerning the content of this manuscript.

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Authors' Contribution

AHN was the PhD student who carried out the investigations reported in this manuscript under the supervision of the other three co-authors. This author also made the original manuscript draft. IMD was the Chairman of the Supervisory Committee of the PhD student (the first author). His contribution was in shaping the manufacturing processes that have been modelled and simulated. He helped draft the design concept and provided input on interpreting the results. IBU, a ceramics specialist and a member of the Supervisory Committee, established the unit operations involved and led to the coining of the process flow chart for the beneficiation of Kaolin. He also contributed to interpreting the results obtained from the FLEXSIM software. IDM was also a member of the Supervisory Committee, and his input was in optimizing the designed plant and interpreting the output from the FLEXSIM. All authors read and approved the final manuscript.

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