A Framework for Production Capacity and Time Utilization of Mono Product Sequential Process Plants

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Abstract- This article addresses the challenges of estimating production capacity and time utilization problem in a sequential process plant. A framework and mathematical model are presented to aid the analysis and understanding of the proposed solution. A set of constraints is provided in order to specify the requirements for production capacity and time utilization planning in a sequential process plant. In order to ascertain the performance of the framework, the mathematical models derived are tested using an existing designed process plant and the results obtained from the evaluation are also presented. The proposed model generates the utilized time for the process plant per batch and also the production capacity of the process plant as well as the production rates of individual machines in the process plant. Application of the model to an existing process plant demonstrates that the addition of buffer storage to store work in progress materials in a mono product sequential process plant will increase the production rate of the plant but the production rate of the machines in the plant remains constant. Also, the addition of buffer storage will increase the time utilized by the process plant to complete its operation per batch.

Keywords Process plants, Production capacity and planning, production framework.

1. Introduction

Sustainable national economic advancement can be attained through longevity of manufacturing firms which can be achieved by effective and continuous production capacity planning and time utilization of process plants in the firms. Production capacity and time utilization planning of process plant is a major task in process engineering. It is an essential stage in the design of a process plant that occurs in vast range of industries in process engineering [1-3]. These industries include chemical, agriculture, food, advanced material, mineral, pharmaceuticals and petrochemical among others. Production capacity and time utilization planning starts from the developmental stage of a process plant. It is usually conceptualized alongside the needs of the customers and it is factored in the design of production facilities that transform raw materials into finish products required by customers [4]. The design of process plants begins with the identification and establishment of process required to accomplish the transformation of raw material or resources. This is usually followed by conceptual and detail design of all the machines required for processes in the plant. Efforts are made by engineers to standardize the output of all the machines in the process plant. However, different machines in a plant may have different capacities due to factors or constraints such as availability of space, environmental impacts, safety precautions, capital involvement, operation and maintenance costs [5].

Furthermore, there is a wide range of technical factors that dictates the sizes and capacities of the machines in a process plant. These factors are the physical dimensions of the machines in comparison with the availability of space and building dimensions, arrangement of the machines in the plant, operating parameters of the prime movers in the process plant and availability of resources such as water and electricity [6]. In order to achieve the development of a safe and effective process plant, the engineer is required to provide a holistic view of the processes involved in the process plant and analyze the operating conditions of the machines in the process plant. This is usually achieved by developing models and simulations. The analysis of processes and machines involved will shed light on the sequence of operation of the machines depending on the type of production process and the stages involved in the transformation of the raw material into finished good [7].

Process plants can be classified based on the type of product it handles and the nature of the processes involved in the plant. Classification based on the products are the type of industries identified above. Sometimes, when the output of the process plant is a continuous stream of a particular type of product as a result of adding of one type of raw material, the plant is called a mono product process plant.

Classification based on the nature can further be grouped into concurrent and sequential process plants. Concurrent process plants are usually encountered when there are two different operations in the processing that must be done simultaneously. In this case two different machines will operate in conjunction with one another and the outputs from the machines are different from each other. The completion time of the two machines may be equal or unequal but, in most cases, it is usually unequal. In some cases, the raw materials in this type of process plants are usually more than one [4]. The sequential process plants are encountered in situations when one operation must be completed before another operations starts. In some cases, the succeeding operations may start when the preceding operation is about to finish. Both categories of process plants usually operate effectively when the system is automated [8].

The production capacity of a process plant can be defined as the maximum amount of product that can be produced per unit time with existing machines and resources used in the plant provided that the availability of variable factors of production is not restricted [9-10]. The time involved in this definition is the utilized time or duration of operation of the process plant. Considering this definition, it is necessary to consider the variable factors that must not be restricted in the production process. These factors are; availability of raw materials for the process plant, product demand by customers, availability of power, availability of workspace for storage of raw material, work in progress and finished goods [3]. These factors play major roles in affecting the operations of the plant. Considering the effect of availability of raw material, process plants that work on seasonal materials will have to stop operation when there is scarcity of the raw material. When there is abundance of raw material the machine will have to produce excessively and it will be difficult to ascertain the capacity of the plant over a period of scarcity and surplus raw material except if it is based on just in time production [11].

Fluctuations in demand of the product also affects the capacity of the plant especially when the product cannot stay for a long time in the processing factory. Most of the time a balance needs to be created between the lead time and quantity of product required from the plant. This is necessary in order to ensure that the production rate of the plant is fully optimized in order to satisfy the fluctuations in demand of the customers [12]. The production rate in this case can be defined as the number of final products that the plant will turn out during a given period of time (which is usually expressed in batch). In practice, it is usually necessary to improvise a buffer store for work in progress along the process plant in order to maximize the high production capacity of some machines in the process plant. The buffer store can be defined as a temporary storage in a process plant where stocks (that are work in progress) can be stored while awaiting further processing. This also assist the process plant to achieve its optimal production capacity [13].

Considering these factors, there is a need to establish the production capacity of process plants and time utilization because this will assist in estimating the total amount of the product that the plant can produce and the time required by the plant to produce the estimated capacity per batch of production [14-15]. The aim of this article is to develop a framework and a mathematical model that will assist in evaluating the production capacity and time utilization of a sequential process plant. The novelty of the developed model is the ability to consider the outputs of individual machines alongside their utilized time and selecting the machines with the smallest output as a benchmark. A summation of the time utilized by each machine in the process plant and handling time gives the total utilized time by the process plant. Furthermore, the model also considers the introduction of buffer storage to machines with higher production capacity in order to increase the overall capacity of the process plant. However, this will increase the time utilized by the plant because the time spent to process the work in progress from the buffer storage will be added to the total utilized time.

2. Materials and Methods

2.1. *Framework and Mathematical Model for Capacity Planning and Time Utilization*

In order to create a flow of the proposed model, it is necessary to develop a framework to analyze the basic necessities, operations and requirements of a sequential process plant. Figure 1 shows the developed framework. Considering Fig. 1, it is evident that a production capacity model will be effective when all the capacity of machines in the plant are established and regulated so that the output from the last machine in the plant will be the same as the outputs from other machines in the process plant [16]. It is also clear from the model that capacity of the process plant can also be affected by the presence or absence of buffer store for work in progress depending on whether there is a machine in the plant that can be designed for high capacity without exceeding the available space or affecting other machines in the plant. Also, the time utilization is a function of the time spent by all the machines in the plant and the loading time from the buffer stores in the process plant [17-19].

2.2. *Definitions and Formulations*

In order to simplify the analysis, it is necessary to consider the definitions of the notations and symbols used in the formulation. These symbols and notations are presented as follows;

$M_i =$ Number of Machines in the process plant;

$M_{C_i} =$ The Capacity of machines in the plant that can be transferred from one machine to another (*kg*)

$B_{C_n} =$ Capacity of the buffers that can be loaded on the machines working on buffer (*kg*)

$n =$ Number of times the buffers loads work in progress into the process plant

$M_{B_m} =$ Capacity of the machines working on the work in progress stored in the buffer (*kg*)

$nB =$ Number of buffer in the process plant

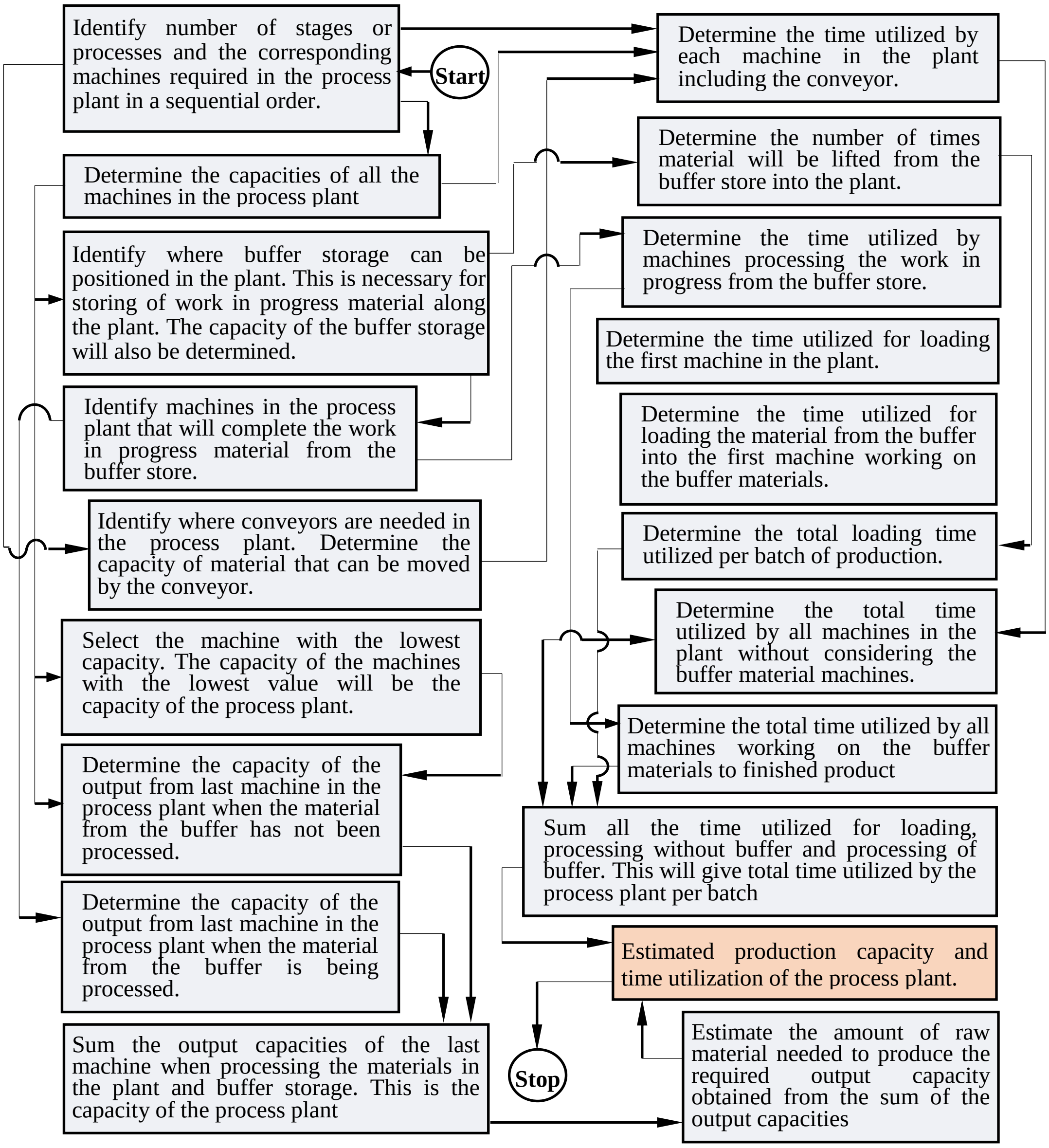

Fig. 1. Framework of the proposed model for estimating production capacity and time utilization sequential process plants.

M_{P1} = Capacity of the process plant excluding the material processed from the buffer (*kg*)

M_{P2} = Capacity of the process plant as a result of materials processed from the buffer (*kg*)

M_P = Total capacity of the process plant per batch (*kg*)

P_R = Production rate of process plant on an hour (*kg/hr*)

M_{t_i} = Time spent by each machine in the process plant including conveyors (*hr*)

M_{tm} = Time spent by machines working on materials from buffer work in progress (*hr*)

M_{P_t} = Time utilized by the plant to produce per batch (*hr*)

M_{Pt_1} = Time required by the process plant to produce per batch excluding the processing of buffer materials (*hr*)

M_{Pt_2} = Time required by the process plant for processing of the buffer materials (*hr*)

T_L = Total loading time (*hr*)

P_{RM_i} = Production rate of each machine in the process plant (*kg/hr*)

T_{m_1} = Time required to load the first machine in the process plant with material (*hr*)

N_{mB} = Number of machines working on buffer stored materials

T_B = Time required to load the work in progress materials from buffer to first machine working on the buffer (*hr*).

In order to simplify the analysis, it is necessary to make the following assumptions;

1. The plant is fully automated and individual machines in the plant are arranged in such a way

that the output of one machine is transferred directly to the next machine as input. Hence, the volume of the inputs for the succeeding machine is equal to the volume of the output of the preceding machine.

2. Minimal material lost in each of the machine is negligible. Hence, the capacity of a machine in the plant will be transferred totally to another machine and this will be taken as the output of the process plant. i.e. $M_{C_i} =$ Constant; $M_{B_m} =$ Constant.
3. The target capacity of the process plant is equal to the output capacity of any of the machine in the process plant that can be transferable to other machines in the plant. Also, the completion time of the process plant is the summation of individual completion time of all the machines because it is expected that all the machines in the process plant would have completed their operation before the final product is obtained.
4. The machines in the plant are arranged to work in a sequential order. However, some may be allowed to work when the preceding machine is about to finish. This implies that, the operation of one machine depends on the successful completion of the previous machine or the desired completion time of the preceding machine.

Firstly, considering assumption three, since the machines in the plant are arranged in a sequential manner, it follows that;

$$M_{P1} = \text{Min}\left\{M_{C_i}\right\} \tag{1}$$

Since the number of times the buffer can load materials into the plant is represented by *n* it follows that;

$$M_{P2} = \sum_{nB=0}^{nB} n\left[\text{Min}\left\{B_{c_n}\right\}\right] \tag{2}$$

Since the capacity of the plant is a function of the output volume or mass of the last machine, it can be deduced that the capacity of the process plant is a summation of the output excluding the material processed from the buffer store and the output of machines obtained by processing the work in progress materials in the buffer. In essence the total capacity of the plant can be expressed as;

$$M_P = M_{P1} + M_{P2} \tag{3}$$

Combining equations (1), (2) and (3) the expression for the total capacity of the process plant can be obtained as;

$$M_P = \text{Min}\left\{M_{C_i}\right\} + \sum_{nB=0}^{nB} n\left[\text{Min}\left\{B_{c_n}\right\}\right] \tag{4}$$

Furthermore, it is evident that the time required by the plant to produce per batch excluding the buffer materials is a function of individual time spent by each machine in the plant and as such this can be represented as;

$$M_{Pt_1} = \sum_{i=1}^{i} M_{t_i} \tag{5}$$

Additionally, depending on the size and number of buffers, the total loading time is a summation of the time required to load the first machine working on buffer stock in the plant, and the first machine in the process plant. The time required to load the first machine working on the buffer is a function of the number of times materials are loaded from the buffer and the number of buffers in the plant. Hence, the total loading time can be expressed as;

$$T_L = T_{m1} + nT_B \tag{6}$$

The time required to process the materials from the buffer is a function of the number of times the buffer supplies the machines and the time spent by the machines handling the work in progress from the buffer. This will be greatly affected by the number of buffers in the process plant. In essence, the time required to completely process the material from the buffer can be obtained from;

$$M_{Pt_2} = n\left[\sum_{N_{mB}=1}^{N_{mB}} M_{tm_n}\right] \tag{7}$$

The total time utilized by the plant is a function of the time spent on loading, time spent by individual machines when processing the actual capacity and time spent to process the work in progress from the buffer store. This can be expressed as presented in equation (8);

$$M_{P_t} = M_{Pt_1} + M_{Pt_2} + T_L \tag{8}$$

Combining equations 5, 6, 7 and 8, the total time utilized by the process plant per batch can be deduced as;

$$M_{P_t} = \sum_{i=1}^{i} M_{t_i} + n\left[\sum_{N_{mB}=1}^{N_{mB}} M_{tm_n}\right] + T_{m\,1} + nT_B \tag{9}$$

The rate of production of the plant (P_R) in an hour can be deduced as;

$$P_R = \frac{M_P}{M_{P_t}} \tag{10}$$

Combining equations (4), (9) and (10) we obtain;

$$P_R = \frac{M_{C_i} + \sum_{nB=0}^{nB} nB_{c_n}}{\sum_{i=1}^{i} M_{t_i} + n\left[\sum_{N_{mB}=1}^{N_{mB}} M_{tm_n}\right] + T_{m\,1} + nT_B} \tag{11}$$

This expression can be used to determine the capacity of the process plant per day provided that the number of working hours per day is specified for the operators. The production rate of each machine in the process plant $\left(P_{RM_i}\right)$ can also be obtained by dividing the total capacity of the process plant by the time spent by the machines in each operation. This can be expressed as;

$$P_{RM_i} = \frac{M_P}{M_{t_i}} \tag{12}$$

2.3 Application of the framework to a *Poundo* yam process plant

In order to test the developed mathematical model, a process plant for production of *Poundo* yam [6, 20] will be used as a case study in this article. The process plant transforms yam into a flour that can be used to make a doughy food called *Poundo* yam. The plant has seven machines operating sequentially and performing different operations. The operations in the plant are washing, peeling and slicing, parboiling, conveying, drying, milling and sieving.

Since there is no buffer in the process plant, the buffer components of the equations will be neglected. These operations are carried out sequentially with the aid of different machines as presented in Fig. 2 and Fig. 3. The following data are obtained from the operation of the process plant as presented in Table 1.

Considering assumption 3, the transferable output that can be handled by all the machines in the process plant is $0.635\ m^3$ of sliced cubes of yam. Hence the target capacity of the *Poundo* yam process plant (M_{ci}) is $0.635\ m^3$. In order to determine the time utilized by the washing ($M_{t\ washing}$) and peeling/slicing ($M_{t\ peeling}$) machines to produce the target capacity of the process plant, it is necessary to consider the bulk density and average mass of yam that will produce $0.635\ m^3$ of the sliced cubes of yam. The average mass and bulk density of yam are $5\ kg$ and $1104\ kg/m^3$ respectively [21-23].

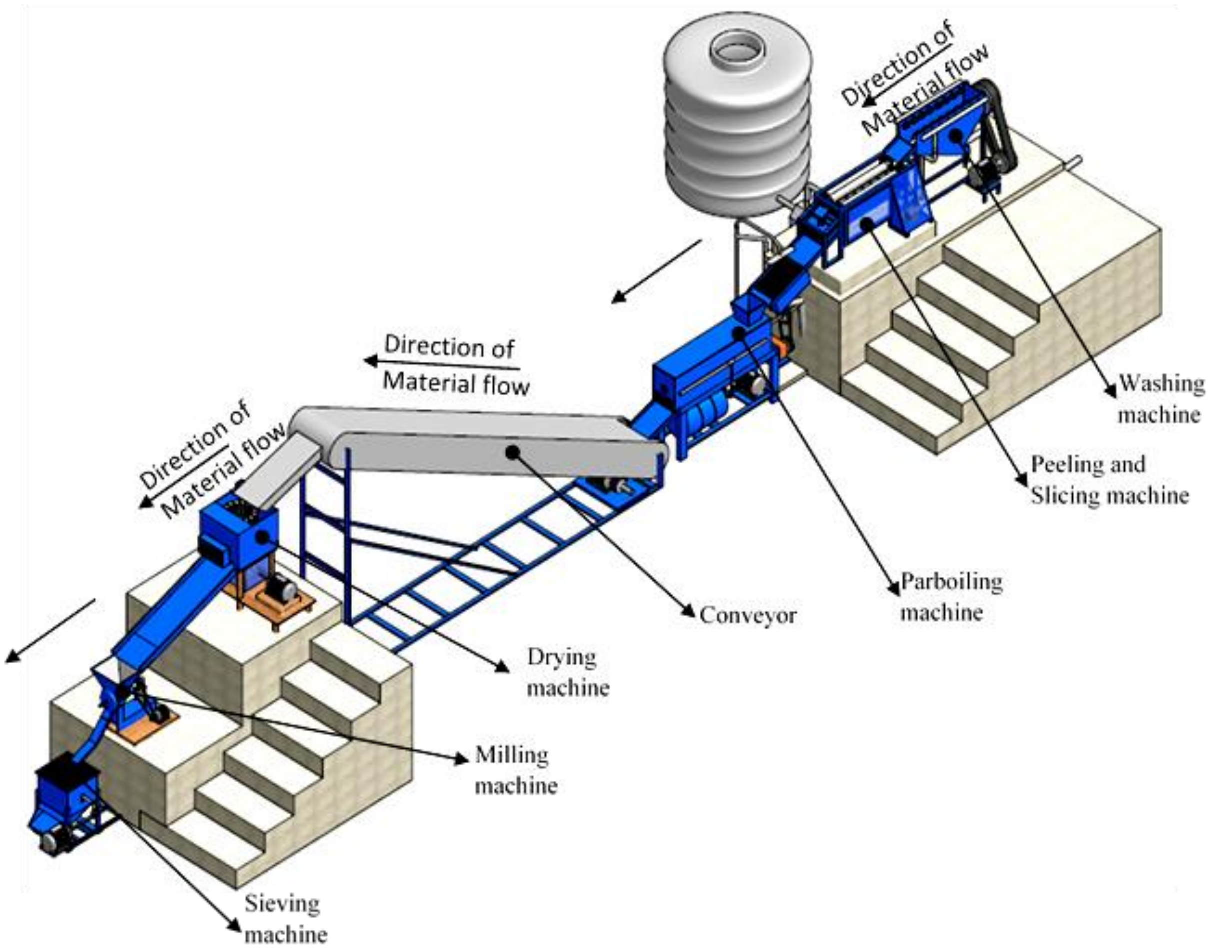

Fig. 2. A pictorial View of the *Poundo* Yam Process Plant [20]

Table 1. Data obtained from the operation of the *Poundo* yam process plant

S/N	Machines	Machine Outputs (MC_i)	Time Utilized (M_{ti})
1	Washing machine	(MC_1): Continuous production	*(1.5 min/tuber)*
2	Peeling and Slicing Machine	(MC_2): Continuous production	*(1.25 min/tuber)*
3	Parboiling Machine	(MC_3): $0.635\ m^3$ of sliced cubes	$M_{t\ parboiling}$: *3 hrs.*
4	Conveyor	(MC_4): Continuous operation (*1.52 tons/hr*.)	$M_{t\ conveying}$: *(25/60) hr.*
5	Drying Machine	(MC_5): $0.771\ m^3$ of sliced cubes	$M_{t\ drying}$: *3 hrs.*
6	Milling Machine	(MC_6): $0.738\ m^3$ of sliced cubes	$M_{t\ milling}$: *(15/60) hr.*
7	Sieving Machine	(MC_7): $0.682\ m^3$ of sliced cubes	$M_{t\ sieving}$: *(22/60) hr.*

Fig. 3. Fabricated *Poundo* Yam Process Plant [20]

Hence;

$$M_{twashing} = \left[\frac{M_{ci} * \rho_{yam}}{M_{yam}}\right] * min/\ tuber|_{washing} \quad (13)$$

$$M_{tpeeling} = \left[\frac{M_{ci} * \rho_{yam}}{M_{yam}}\right] * min/\ tuber|_{peeling} \quad (14)$$

Therefore,

$$M_{twashing} = \left[\frac{0.635*1104}{5}\right] * 1.5 = 3.5\ hrs.$$

$$M_{tpeeling} = \left[\frac{0.635*1104}{5}\right] * 1.25 = 3\ hrs$$

Furthermore, considering assumption 3 and equation 5 we can deduce that;

$$M_{Pt_1} = \sum_{i=1}^{i} M_{t_i} = M_{t_{washing}} + M_{t_{peeling}} + M_{t_{parboiling}} + M_{t_{conveying}} + M_{t_{drying}} + M_{t_{milling}} + M_{t_{sieving}} \quad (15)$$

$$\therefore M_{Pt_1} = 3.5 + 3 + 3 + \left(\frac{25}{60}\right) + 3 + \left(\frac{15}{60}\right) + \left(\frac{22}{60}\right) = 13.53\ hrs$$

Hence the mass of yam the plant can handle per batch (M_P) is $M_{yam/batch}$ can be obtained as described in equation (16) [24]:

$$M_P = M_{yam/batch} = M_{C_i} * \rho_{yam} \quad (16)$$

Where ρ_{yam} is the average density of yam

$$\therefore M_p = M_{yam/batch} = 0.635*1104 = 701.04\ kg$$

The production rate (P_R) of the *Poundo* yam process plant can be obtained from equation (10) as;

$$P_R = \frac{701.04}{13.53} = 51.8 \simeq 52\ kg/hr$$

Since the raw material processed by the plant is yam, it is necessary to express the capacity in the form of tubers. The number of tubers of yam that the plant can handle per batch $\left(N_{tubers/batch}\right)$, can be obtained from equation (17) using the average mass of a yam tuber [22-24];

$$N_{tubers/batch} = \frac{M_{yam/batch}}{M_{yam}} \quad (17)$$

$$\therefore N_{tubers/batch} = \frac{701.04}{5} = 140.2 \simeq 140\ tubers/batch$$

The production rate of the Poundo yam process plant in an hour in the form of tubers $\left(P_{R(tub)}\right)$ can also be obtained using equation 10 as;

$$P_{R(tub)} = \frac{N_{tubers/batch}}{M_{P_t}} \quad (18)$$

$$\therefore P_{R(tub)} = \frac{140}{13.53} = 10.4 \simeq 10\ tubers\ per\ hour$$

Where;

$P_{R(tub)}$ = The production rate of the *Poundo* yam process plant in form of tubers

$N_{tubers/batch}$ = Number of yam tubers the process plant can handle per batch

$M_{yam/batch}$ = Mass of yam the process plant can handle per batch

M_{yam} = Average mass of a tuber of yam

M_{Pt_1} = Time required by the *Poundo* yam process plant to produce per batch excluding the processing of buffer materials (*hr*)

However, in order to identify and ascertain the effect of buffer storage on how it affects the production capacity and time utilization, let us assume that an imaginary buffer storage which content can be loaded twice is added to the system with a negligible loading time. Since the washing machine, peeling and slicing machine are allowed to work continuously, then the excess materials processed from these machines will be stored in the buffer storage. In view of this the imaginary buffer can be positioned after the peeling and slicing machine. It is worthwhile to know that the maximum amount of work in progress that can be loaded from the buffer storage cannot be greater than the targeted capacity of the process plant.

Also, the washing and peeling/slicing machines will continue to work during the parboiling and drying operation and as such the time for washing and peeling to produce the buffer material will not be considered in the overall time of the process plant when working on buffer but will be considered for the production rate of the machines. The components of the buffer storage in the model equations will be considered in this case and as such, the plant capacity and production rate are expected to change. Hence the machines that will process the materials from the buffer storage are parboiling machine, conveyor, drying machine, milling machine and sieving machine. Furthermore, considering assumption two, the benchmarked or throughput capacity will also be produced from the plant when processing the materials from the buffer. Table 1 can be adjusted to provide details for the imaginary buffer as shown in Table 2.

Hence, the following parameters can be deduced for the imaginary buffer storage.,

$N_{mB} = 5$

$T_B = 0$

$B_{C_n} = M_{B_m} = M_{C_i} = 0.635\ m^3$

$n = 2$

$nB = 1$ (Number of buffer storage in the process plant)

From equation (2); $M_{P2} = 1.270\ m^3$

Table 2. Introduction of Imaginary buffer to the operation of the *Poundo* yam process plant

S/N	Machines	Machine Outputs (MC_i)		Time Utilized (M_{ti})	
		No Buffer	Imaginary Buffer added	No Buffer	Imaginary Buffer added
1	Washing machine	Continuous production		*(1.5 min/tuber)*	
2	Peeling and Slicing Machine	Continuous production		*(1.25 min/tuber)*	
3	Parboiling Machine	$0.635m^3$	$1.270m^3$	*3hrs*	*6hrs*
4	Conveyor	Continuous operation		*(25/60) hr*	*(25/30) hr*
5	Drying Machine	$0.771\ m^3$	$1.542\ m^3$	*3hrs*	*6hrs*
6	Milling Machine	$0.738\ m^3$	$1.467\ m^3$	*(15/60) hr*	*(15/30) hr*
7	Sieving Machine	$0.682\ m^3$	$1.364\ m^3$	*(22/60) hr*	*(22/30) hr*

Hence, the capacity of the process plant when the imaginary buffer is introduced is obtained from equations (3) and (4) as;

$$M_P = \text{Min}\left\{M_{C_i}\right\} + \sum_{nB=0}^{nB} n\left[\text{Min}\left\{B_{c_n}\right\}\right] =$$

$$0.635 + 1.270 = 1.905m^3$$

Hence that volume of *Poundo* yam that the plant will produce per batch in the presence of the imaginary buffer is $1.905m^3$. Similarly, the mass of yam that the plant can handle per batch can also be obtained from the bulk density of yam as 2103*kg*. Also, the total time utilized by the plant can also be obtained using equation (7) to (9) as follows;

$$M_{Pt_2} = n\left[\sum_{N_{mB}=1}^{N_{mB}} M_{tm_n}\right] =$$

$$2\left[3 + \left(\frac{25}{60}\right) + 3 + \left(\frac{15}{60}\right) + \left(\frac{22}{60}\right)\right] = 14.07hrs$$

Since the loading time is negligible the total time utilized by the process plant per batch can be deduced as;

$$M_{P_t} = \sum_{i=1}^{i} M_{t_i} + n\left[\sum_{N_{mB}=1}^{N_{mB}} M_{tm_n}\right] =$$

$$13.53 + 14.07 = 27.6hrs$$

Hence the mass of yam the plant can handle per batch with imaginary buffer (BM_P) is $BM_{yam/batch}$ can be obtained as:

$$BM_P = BM_{yam/batch} = M_P * \rho_{yam} = 1.905 * 1104 = 2103\ kg$$

Similarly, the production rate of the *Poundo* yam process plant $P_{R(buffer)}$ considering the imaginary buffer can also be obtained from equation (11) as;

$$P_{R(buffer)} = \frac{2103}{27.6} = 76.2 \simeq 76\ kg/hr$$

Also, the number of tubers of yam that the plant can handle per batch under the imaginary buffer $\left(BN_{tubers/batch}\right)$, can be obtained from;

$$BN_{tubers/batch} = \frac{BM_{yam/batch}}{M_{yam}} = \frac{2103}{5} \simeq 421\ tubers$$

Hence, the production rate of the Poundo yam process plant in an hour in the form of tubers when considering the buffer storage can also be obtained as;

$$BP_R = \frac{BN_{tubers/batch}}{M_{P_t}} = \frac{421}{27.6} = 15\ tubers/hr$$

In order to appraise the performance of the model and create a basis for comparison, another mathematical model was used to analyze the *Poundo* yam process plant. The results obtained from the comparison are presented in Table 4. The production rate, production capacity and time utilized by a mono product sequential process plant are obtained as follows [5].

$$R_P = \frac{60}{T_p} \tag{19}$$

Where R_P is the production rate and time utilized by the plant. Also, T_p is the production time per work which can be obtained from equation (20) as;

$$T_p = \frac{T_b}{Q} \tag{20}$$

Where Q is the output of the plant per batch in terms of quantity and T_b is the batch processing time of the plant which can be obtained from equation (21) as;

$$T_b = T_{su} + QT_c \tag{21}$$

Where T_{su} is the set-up time to prepare for batch production of all the machines in the process plant and T_c is the operation cycle time per batch. The production capacity of the process plant can be obtained from equation (22);

$$PC = \frac{nSHR_p}{n_o} \tag{22}$$

Where S and H are numbers of shifts per batch and Hours per batch respectively, while n and n_o are the numbers of plants in the facility and number of machines in the process plant.

3. Results

An estimation of the output capacity per batch, time utilization per batch and production rate per batch for each machine and the process plant as a whole is presented in

Table 3. This estimation is based on the presence and absence of the imaginary buffer storage in the process plant. It is evident from the results of the application of the model that the introduction of buffer into the plant increases the output capacity of the machines, time utilized and production rate of the process plant. The buffer storage did not alter the production rate of individual machines in the process plant because the production rate is a function of the machine output and utilized time. This implies that, as the machines output increases the utilized time increases and as such the production rate remains constant. However, the production rate of the process plant increases (from 51.8 *kg/hr* to 76 *kg/hr*) as the buffer storage is introduced into the plant. The increased production rate can be attributed to an increase in the utilized time. This increase is due to simultaneous operation of the machines when the buffer materials are processed. For instance, during the parboiling process the washing and peeling/slicing machine will continue to produce sliced cubes that will be stored in the buffer storage. In essence, the time utilized by the plant at this stage remains the same because the parboiling machine is still in operation while additional materials are added to the buffer storage. It can be hypothetically stated that buffer storage increases the production rate of the process plants if it will not require additional time to produce the work in progress or if the work in progress will be produced while other machines in the plant are in operation. The same scenario is experienced between the parboiling machine and drying machine because as the drying machine dries the parboiled cubes of yam from the parboiling machine another batch of sliced cubes are loaded into the parboiling machine. This implies that, the increased production rate of the process plant is due to the simultaneous operation of the machines which is contrary to the rest period experienced by the machines when there is no buffer storage in the process plant.The process plant transforms yam into a flour that can be used to make a doughy food called *Poundo* yam. The plant has seven machines operating sequentially and performing different operations. The operations in the plant are washing, peeling and slicing, parboiling, conveying, drying, milling and sieving. Since there is no buffer in the process plant, the buffer components of the equations will be neglected. These operations are carried out sequentially with the aid of different machines as presented in Figures 2 and 3. The following data presented in Table 1 are obtained from the operation of the process plant.

Considering assumption 3, the transferable output that can be handled by all the machines in the process plant is $0.635\ m^3$ of sliced cubes of yam. Hence the target capacity of the *Poundo* yam process plant (M_{ci}) is $0.635\ m^3$. In order to determine the time utilized by the washing ($M_{t\ washing}$) and peeling/slicing ($M_{t\ peeling}$) machines to produce the target capacity of the process plant, it is necessary to consider the bulk density and average mass of yam that will produce $0.635\ m^3$ of the sliced cubes of yam. The average mass and bulk density of yam are $5\ kg$ and $1104\ kg/m^3$ respectively [21-23].

4. Discussions

The results obtained from application of the model to the *Poundo* yam process plant shows that the mathematical model will function as intended. The model was able to obtain the production capacity of the process plant, as well as the time utilization. Furthermore, the model also obtained the production rate of individual machines in the process plant. The production rate of each machine obtained can be used to optimize the plant because it shows the machine with the highest and lowest production rate. It will also assist in positioning of buffers in the plant in order to increase the production capacity of the process plant. Considering the results presented in Table 3, a high production rate of 3259 *kg/hr* from the milling machine indicates that a buffer can be placed between the milling and sieving machine since the milling has high production rate. However, the drying machine preceding the milling machine has a low production rate and as such it can be increased or designed to be three or four drying machines in order to meet up with the high demand of the milling machine. This will also ensure that the high delivery rate of the conveyor is also utilized because the drying machine will demand for more materials when increased. Similarly, the capacities of the washing, peeling and slicing and parboiling machines can also be increased in order to meet the higher demands of machines in the system. The introduction of buffer storage in the process plant provides a significant increase in the output capacity of the process plant. However, this significant increase is reduced in the production rate of the plant as a result of time involvement. Considering this time involvement, the process plant can be optimized by introducing more machines to processes taking more time in the process plant or by improving the performance of the machines taking more time to complete their task. As stated earlier, in order to compare the performance of the developed model, another model was used to analyze the *Poundo* yam process plant. The other model used was able to estimate the production capacity, production rate and time utilization but the values obtained are different from the present study as presented in Table 4. The present study shows that the production rate of the machines in the process plant remain constant when operating the process plant with either no buffer storage or with buffer storage. Though, there is a difference in the production rate of the whole process plant when operating with buffer storage. On the other hand, the other model used for comparison shows significant difference in the production rate of the machines in the plant as well as the whole process plant. However, the production rates of the machines are expected to be constant either operating with buffer or with no buffer. This is necessary because the production rate is a function of time and output capacity. In view of this, when the buffer storage is added the time utilized increases as well as the output capacity and as such the production rate remains constant. As expected, the two models provide substantial differences in the production capacities of the machines in the plant when operating with no buffer and when operating with buffer. It is expected that the production capacity of the machines and the whole process plant should be high when operating with buffer storage. This expectation was clearly demonstrated by the two models except for the milling and sieving machine which appears otherwise in the other model used for comparison. Similarly, the time utilized by the machines in the process plant and by the process plant as a whole is expected to increase when operating with buffer storage. The two models demonstrated this fact by showing a significant difference in the utilization time obtained from the evaluation process.

Table 3. Results for production rates and capacities of machines in the *Poundo* yam process plant

S/N	Machines	Production Rate (*kg/hr*)		Machine's output Capacity (*kg*)		Time Utilized per batch (*hr*)	
		No Buffer	Imaginary Buffer added	No Buffer	Imaginary Buffer added	No Buffer	Imaginary Buffer added
1	Washing machine	200	200	700.00	2100	3.50	10.50
2	Peeling and Slicing Machine	240	240	720.00	2160	3.00	9.00
3	Parboiling Machine	234	234	701.00	2103	3.00	9.00
4	Conveyor	1665	1664	699.20	2097	0.42	1.26
5	Drying Machine	284	284	851.18	2553	3.00	9.00
6	Milling Machine	3259	3259	814.75	2444	0.25	0.75
7	Sieving Machine	2035	2035	752.93	2259	0.37	1.11
	Process Plant	51.8	76	701.04	2103	13.53	27.6

Table 4. Comparison of the present study with another model using the *Poundo* yam process plant as a case study

S/N	Machines	Models for Comparison	Production Rate (*kg/hr*)		Machine's output Capacity (*kg*)		Time Utilized per batch (*hr*)	
			No Buffer	Imaginary Buffer added	No Buffer	Imaginary Buffer added	No Buffer	Imaginary Buffer added
1	Washing machine	Present Study	200	200	700.00	2100	3.50	10.50
		Another model	76.10	130.60	214.06	1880.64	2.63	16.10
2	Peeling and Slicing Machine	Present Study	240	240	720.00	2160	3.00	9.00
		Another model	86.36	127.00	242.92	1828.80	2.71	16.56
3	Parboiling Machine	Present Study	234	234	701.00	2103	3.00	9.00
		Another model	88.69	128.78	249.47	1854.43	2.63	16.12
4	Conveyor	Present Study	1665	1664	699.20	2097	0.42	1.26
		Another model	635.18	130.81	1786.67	1883.66	2.63	16.08
5	Drying Machine	Present Study	284	284	851.18	2553	3.00	9.00
		Another model	73.05	107.44	205.48	1547.14	3.20	19.57
6	Milling Machine	Present Study	3259	3259	814.75	2444	0.25	0.75
		Another model	915.76	112.24	2575.90	1616.26	3.06	18.74
7	Sieving Machine	Present Study	2035	2035	752.93	2259	0.37	1.11
		Another model	669.56	121.4	1883.38	1748.16	2.83	17.32
	Process Plant	Present Study	51.8	76	701.04	2103	13.53	27.6
		Another model	19.67	121.43	1022.55	1748.59	19.69	100.80

5. Conclusion

The development of process plants for achieving conversion of raw materials to finished goods plays a critical role in national development and technological sustainability. It is important to consider the capacity planning and time utilization alongside the development of these process plants from the conceptual stage of individual machines in the system. This is necessary because it will assist in optimizing the production from the process plant in order to meet the demand of the consumers. Capacity planning and time utilization of process plants will provide adequate information on the amount of raw material needed for production and the quantity of finished goods that can be moved into the system at a particular time. In order to achieve effective production capacity planning and time utilization of process plants, mathematical models are required. The mathematical model and framework presented in this article have been able to provide results by its application to a *Poundo* yam process plant. However, future work is still possible in the area of developing the framework into a model with user interface using the mathematical model and creating a computer aided process planning software that can be adopted by industries in order to know the capacities of their plants. Further work is still necessary towards developing similar model for concurrent process plants since all process plants cannot be sequential in nature.

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