Modelling and Simulation of a Bakery Production Line Using Hierarchical Timed Coloured Petri Nets

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Abstract: Numerous efforts are being made yearly by researchers to improve the production flow, planning and scheduling of food manufacturing systems through the use of modelling to meet both current and future market demands. In this paper, a Hierarchical Timed Coloured Petri Nets (HTCPN) model was developed for bakery production system using Ladoke Akintola University of Technology (LAUTECH) Bakery, Ogbomoso, Nigeria, as a case study. The HTCPN model was developed consisting of main module and five sub modules. The sub-modules named *mixing*, *fermenting*, *rolling*, *cutting* and *baking* modules modelled the sequential processes of converting flour into bread. The model was simulated using Coloured Petri Nets Tools to determine the average production processing times for processing of 50, 100, 150 and 200 kg of flour into bread. The simulation was also extended to determine the utilization rates required at varying units (manual mixing process, the rolling machine, manual cutting process and baking) for processing of 50 and 100kg bags of flour. The model was validated by comparing the simulated and the actual processing times at 5% significance level using statistical t-Test. The simulation results revealed that the production processing times for processing of 50, 100, 150 and 200 kg of flour starting from the mixing process till baking process were 217, 314, 411 and 508 minutes respectively. The utilization rates required at the mixing process unit, the rolling machine unit, the cutting process unit and baking unit were 0.138; 0.115; 0.046; 0.147 respectively for processing of 50kg bags of flour and 0.191; 0.159; 0.064; 0.203 respectively for processing of 100kg bags of flour. Statistically, there were no significant differences between the simulated and the real processing times. This model could be employed to study worker and machine utilization rates as well as production time required to produce bread from a given quantity of flour in the considered bakery production system or other related ones.

Keywords: Scheduling, Hierarchical Timed Coloured Petri Nets, Utilization Rate, Bakery, Production Flow

1. INTRODUCTION

One of the manufacturing sectors that contribute to the enormous development of any nation is the Food production industry. Food industry plays a vital role in satisfying the needs of the community with respect to availability, distribution and quality of food. The food processing sector in West Africa is widely dominated by Small and Medium Enterprises (SMEs) one of which is the bakery production line like processed Garri and bread loaves which are of high demand [1] in the domestic market as well as for exporting. The contributions of SMEs have been recognized as main sustenance of the economy because of their capacity in enhancing the economy output and human welfare. [2] emphasized that SMEs are the backbone of the contemporary economic development due to the significant role they play in the sustainability of the world economic development. In Nigeria, bakery products industries create a lot of jobs; those directly employed by the industry, armies of bread distributors, sellers and hawkers all over the streets. The impact of economic downturn and challenging market condition on SMEs calls for an urgent demand to implement the effective resource utilization and processing system that will improve productivity [3]. In order to meet both the current and future market demands, concerted efforts are being made to improve food manufacturing systems through modelling [1].

Modelling techniques have been widely applied to studying food manufacturing systems. These include bakery production line, bread loaves production and pasta production. Modelling is the process of constructing a model where a model is an abstraction of a real system and the working of some interested parts of the system. In order to understand and improve the behavior and bottleneck of any complex system it is important to construct the model of such system [17]. A model can thus be experimented to understand, identify the bottleneck restraining optimal productions and improve the system. Experimenting with a model is a process called simulation. It is used before an existing system is altered or a new one is built in order to meet specification. Simulation enables possible modification of system model without disturbing the actual system [4]. In addition to this, the experiment environment can be controlled and repeated multiple times to get an accurate result while experimenting with the system models. [5] presented the concepts and methods of simulation using ARENA as a carrier to help the modeller reach the ability to carry out effective simulation modelling. Banks [6] and Balci [7] focused on verification and validation of the model as the most important element.

Besides, Petri Nets (PN) as a discrete event simulation modelling language is better suited for modelling multi-process systems which include food manufacturing systems. PN is a graphical and mathematical tool for describing and studying systems which are characterized as being synchronous, asynchronous, concurrent, parallel, distributed, deterministic, non-deterministic and or stochastic [8, 9]. PN approach can be extended by colour, hierarchy and time concepts [10]. The inclusion of colour and hierarchy to the classical PN results in a high-level PN called the Hierarchical Timed Coloured Petri Nets (HTCPN) [11, 12], which combines the strength of PN with the strength of functional programming language Standard ML [10, 9].

2. REVIEW OF RELATED WORKS

Most existing works [13, 14, 15, 16] on food manufacturing systems, especially in bakery production line, are based on non-modular model. For example, [13] modelled the optimization of bakery production using methods of scheduling theory. However, such a model could not absolutely represent a multi-process food manufacturing system such as bakery production line. Furthermore, [20] employed an HTCPN to model a Product Development (PD) system with emphasis on dynamics of engineering processes. Precisely, the author created an HTCPN model that conceptualized the PD system with associated engineering processes, and further analyzed the model to verify dynamic properties of the modelled PD system using structural analysis methods. Albeit, in this paper, the goal is to develop a modularized HTCPN model for a food production system (bakery production line) which significantly differs from engineering oriented PD process in terms of system entities and attributes, and to carry out a simulation based analysis on the developed HTCPN model in order to gain insight into best production scenarios which could be hardly verified through the structural analysis methods proposed by [20]. The HTCPN model can be adapted through its associated modules to suite other related food production systems, and can be utilized as well to evaluate the performance of the considered bakery production line based on the flow time (processing time) and utilization rate of resources and worker.

3. RESEARCH METHODOLOGY

The research methodology in this study aptly captures the overview of the modelling approach (HTCPN) being employed; description of the case study (bakery production line); data collection from the system under study; development of an HTCPN model for the bakery production line; description of the developed HTCPN model as well as simulation and validation of the developed HTCPN model.

A Overview of the Modelling Approach

The following basic definition of Hierarchical Timed Coloured Petri Nets (HTCPN) was used in modelling the production processes in this paper. The HTCPN are tuples defined as: HTCPN = (S, SN, SA, PN, PT, PA, FS, FT, PP, R, r_0) [10, 19, 20] where:

(i) S is a finite set is a finite set of pages,
(a) $\forall s \in S$: s is a non-hierarchical coloured Petri net.
(b) $\forall s1, s2 \in S: s1 \neq s2 \Longrightarrow (Ps1 \cup Ts1 \cup As1) \cap (Ps2 \cup Ts2 \cup As2) = \phi$

(ii) $SN \subseteq T$ is a set of substitution nodes.

(iii) SA is a page assignment function. No page is a subpage of itself.

(iv) $PN \subseteq P$ is a set of port nodes.

(v) PT is a port type function. PT: $PN \rightarrow \{in, out, i/o, general\}$.

(vi) PA is a port assignment function. It is defined from SN into binary relations.
(a) $\forall t \in S$: $(t) \subseteq (t)\text{x}PNSA(t)$
(b) $\forall t \in SN, \forall(p1, p2) \in PA(t)$: $PT(p2) \neq$ general $\Rightarrow ST(p1, t) = PT(p2)$
(c) $\forall t \in SN, \forall(p1, p2) \in PA(t)$: $C(p1) = C(p2) \wedge I(p1) = I(p2)$

(vii) $FS \subseteq PS$ is a set of fusion sets.
$\forall fs \in FS, \forall(p1, p2) \in fs$: $C(p1) = C(p2) \wedge I(p1) = I(p2)$

(viii) FT is a fusion type function. FT: $FS \rightarrow \{global, page, instance\}$.

(ix) $PP \in SMS$ is a multi-set of prime pages.

(x) R is a set of time values, also called time stamps.

(xi) r_0 is an element of R called the start time

B Description of the Case Study

In this paper, the production process of converting flour into bread at Ladoke Akintola University of Technology (LAUTECH) Bakery, Ogbomoso, Nigeria, was used as a case study. Fig. 1 depicts the flowchart representing the bread production process employed at LAUTECH Bakery. The overall bread production process involves mixing, fermentation, rolling, cutting and baking processes.

(a) Mixing process

The first step in production is the mixing process, which is done manually. This process involves the mixing of flour with other ingredients such as sugar, yeast and baking powder.

(b) Fermentation process

The second step is the fermentation process which involves leaving the dough for some hours to ferment (yeast growth), production of CO_2, ethanol and organic acids. At this stage, the fermentation times were monitored as it varied with temperature.

(c) Rolling Process

In this process, the fermented dough is curled and rolled. The rolled dough can assume different shapes such as long and short tins.

(d) Cutting process

The third process is also called the make-up process which involves rolling, dividing (cutting) of the dough and placing them into the backing pan.

(e) Baking process

The final stage is the baking process which is the process of heating the dough placed in a pan at a specific temperature. The baking period is determined by the oven temperature but ranges between 10-20 minutes.

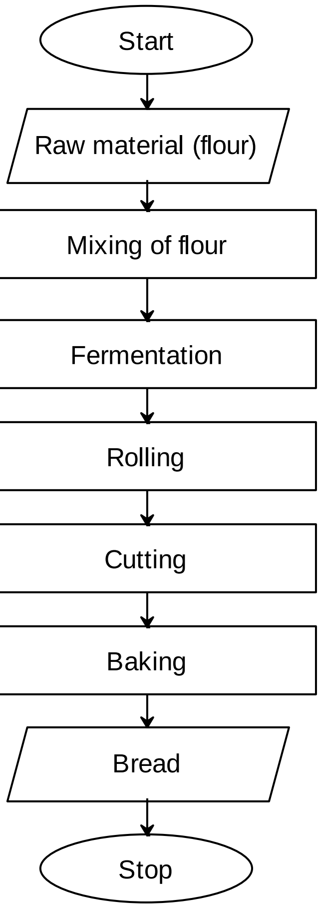

Figure 1: Flowchart of Bread Production Processes

C Data Collection

Data acquisition is crucial because the results and findings of a simulation study in the best cases are as good as the input information. The data obtained from the case study (LAUTECH Bakery) include the bakery working time, amount of raw material (flour), number of resources (labour or machine) and the process time for all resources needed to process flour into bread. These data were collected during one shift period with associated working time which ranged between 11:00am and 4:30pm (5 hours, 30 minutes). Up to 100kg (2 bags) of flour can be processed into bread during the working time. Also, on average, 50kg of flour can be processed into 150 loafs of bread. This shows that the ratio of production of bread (loaf) from flour (in kg) is one to three. That is, 1 kg of flour can produce 3 loafs of bread. The bakery uses manual (labour) mixing and cutting operations; a rolling machine is used to roll the dough before cutting and a traditional oven is used for baking. The average input parameters used in the development of the HTCPN model were derived by selecting days in which the processing time of the same quantity of flour (e.g. 50kg) differs and dividing the total sum by the number of days. The average mixing time, rolling process time, cutting time and baking time for a 50kg bag of flour were 0.6, 0.5, 0.486 and 0.64 machine/labour minutes per kg, respectively. Table 1 depicts different sessions and resources being utilized at LAUTECH Bakery; this also includes the type, number and process time of resources needed to process flour into bread.

Table 1: Type, Number and Process Time of resources in the bakery production line

Section	**Resource Name**	**Resources Number**	**Resource process Time/Work Efficiency (WE)**
Mixing	Mixer	1	30 minutes per 50kg of flour; WE = $\frac{1\,worker*30\,minutes}{50kg}$ = 0.6 worker min/kg
Fermentation		Fixed	2hours = 120 minutes.
Rolling	Rolling machine	1	25 minutes per 50kg of flour; WE = $\frac{1\,machine*25\,minutes}{50kg}$ = 0.50 machine min/kg
Cutting	Manual	2	24.3 minutes per 50kg of flour; WE = $\frac{1\,operator*24.3\,minutes}{50kg}$ =0.486 machine min/kg
Baking	Oven	1	32 minutes per 50kg of flour; WE = $\frac{1\,machine*32\,minutes}{50kg}$ = 0.64 machine min/kg

D Development of the HTCPN Model

The Hierarchical Timed Coloured Petri Nets (HTCPN) model for the bakery production flow under consideration was developed in hierarchal form. It has a main module/top layer as depicted in Fig. 2, and five sub-modules representing each operation (mixing, fermentation, rolling, cutting, baking) which are shown in Fig. 3 to Fig. 7. In the model, system entities are tokens while the states of entities are represented by *places* namely flour, mixer, mixing, dough, fermenting, rolling machine, rolling, worker, cutting, baking process and ready. Also, the model comprises *transitions* which include create order, start mixing process, end mixing process, start fermentation, start rolling process, end rolling process, start cutting process, end cutting process, start baking, end baking and measure flow time. Based on HTCPN formalism, the definition and interpretation of variables and colors being employed in developing the model are as enumerated in Tables 2 and 3, respectively. Also, the definitions and interpretations of the major places being utilized in the model are as enumerated in Table 4 while that of major transitions are as tabulated in Table 5.

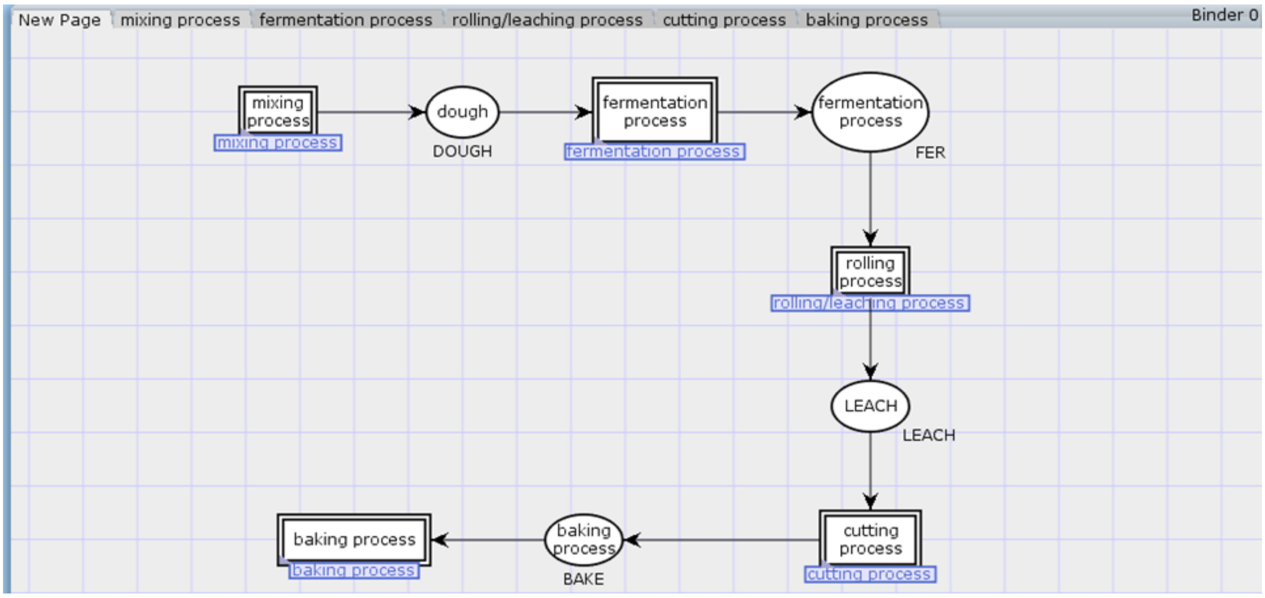

Figure 2: Developed HTCPN Model for Bakery Production Processes

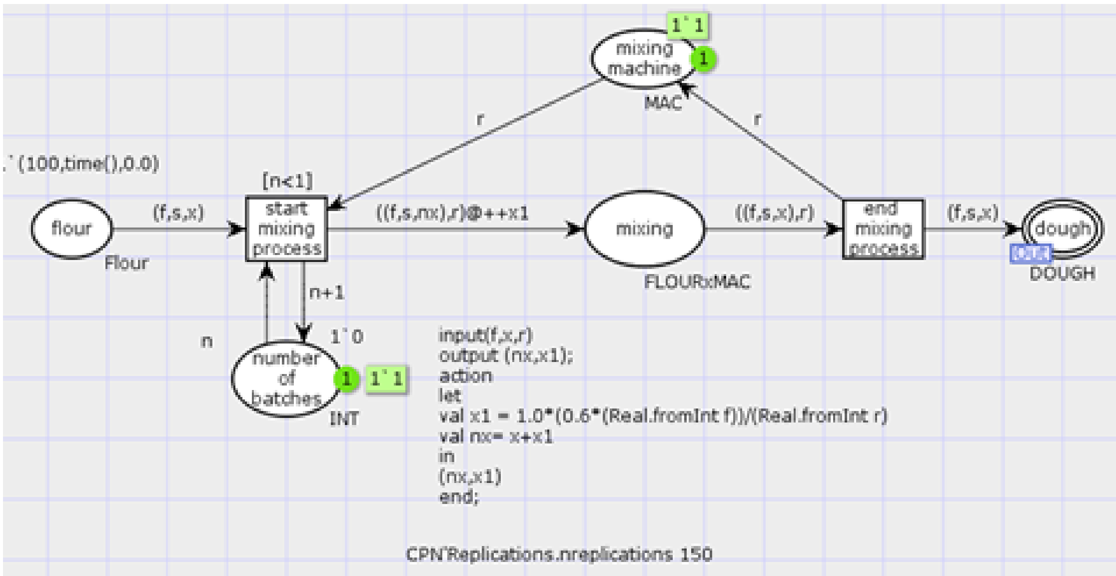

Figure 3: The Mixing Process Module of the Developed HTCPN Model

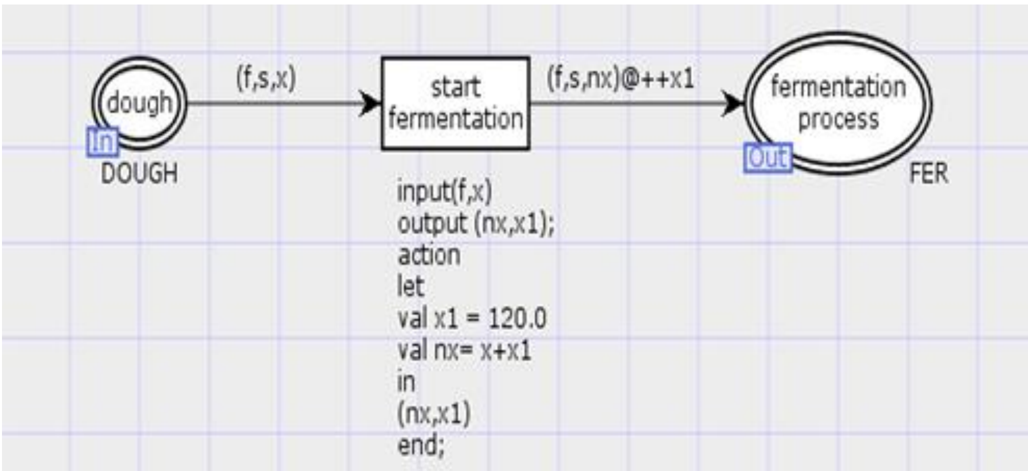

Figure 4: The Fermenting Process Module of the Developed HTCPN Model

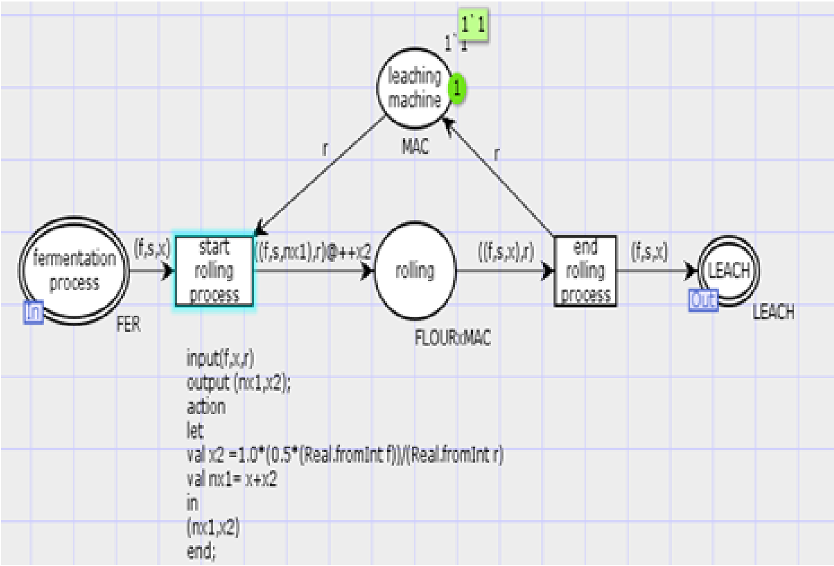

Figure 5: The Rolling Process Module of the Developed HTCPN Model

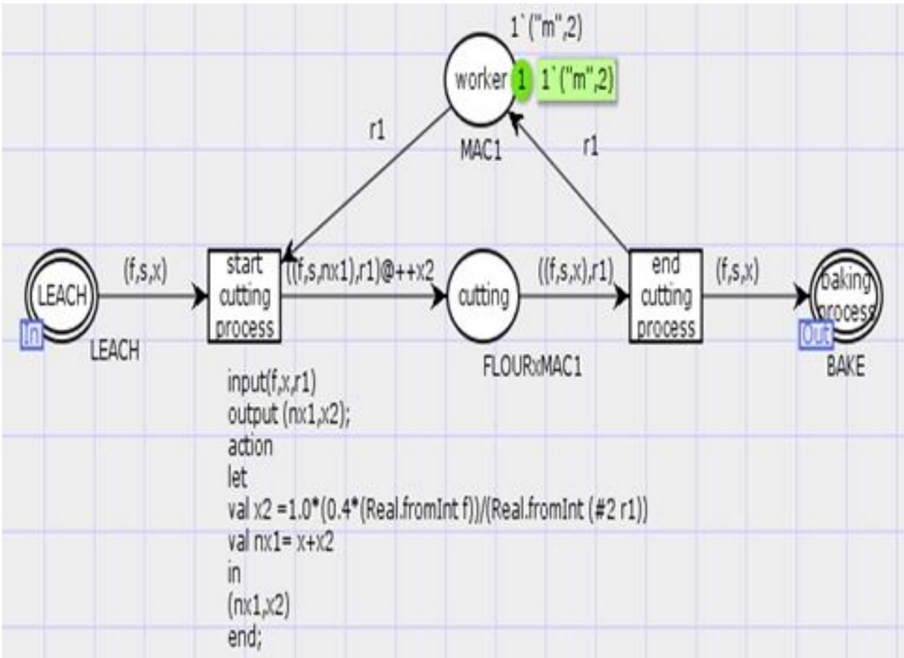

Figure 6: The Cutting Process Module of the Developed HTCPN Model

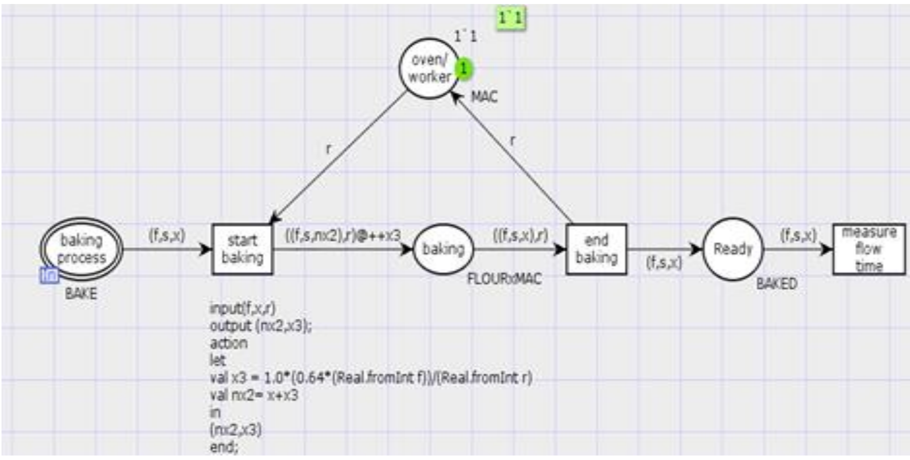

Figure 7: The Baking Process Module of the Developed HTCPN Model

Table 2: Definitions and Interpretations of the variables used in the HTCPN Model

Variable	Variable type	Variable declaration	Interpretation
p, t	string	var p, t :STRING;	They describe information such as weight of size of bread.
i, r	Int	Var i, r :INT;	They describe information such as weight of count.
x,s,nx,x1,x2,x3,nx1,nx2;	Real	var x,s,nx,x1,x2,x3,nx1,nx2:REAL;	They describe timing in the model.

Table 3: Definitions and Interpretations of the colours used in the HTCPN Model

Colour	Colour Data Type	Colset Declaration	Interpretation
INT	Integer	colset INT = int;	It describes an integer value.
REAL	Real	colset REAL= real;	It describes a real value e.g. time.
STRING	String	colset STRING = string;	It describes a string value.
Flour	Compound (product)	colset Flour = product INT * REAL*REAL timed;	It describes the weight of flour, work start time and total process time.
MAC	Integer	Colset MAC = int;	It describes the list of bread size
FLOURxMAC	Compound (product)	Colset FLOURxMAC = product Flour*MAC timed;	It describes the weight of flour, work start time and total process time.
DOUGH	Compound (product)	colset DOUGH = product INT*REAL*REAL timed;	It describes the weight of dough.
FER	Compound (product)	colset FER= product INT*REAL*REAL timed;	It describes the fermentation process.
MAC1	Compound (product)	colset MAC1 =product STRING*INT;	It describes notation for workers and the number of available workers for production
FLOURxMAC1	Compound (product)	colset FLOURxMAC1=product Flour*MAC1 timed;	It describes the weight of flour, work start time and total process time.

Table 4: Definitions and Interpretations of the places used in the HTCPN Model

Place	Description
Flour	Models the amount of flour to be processed into bread.
Bread size	Models the number of batches of flour to be processed into bread.
Mixer	Models a state in which the operator is idle.
Mixing	Models a state in which the operator is busy.
Fermenting	Models the time the machine and workers are free.
Leaching machine	Models a state in which the leaching machine is idle.
Rolling	Models a state in which the rolling machine is busy.
Leach	Models a state in which the dough has been rolled.
Worker	Models a state in which the worker is idle.
Cutting	Models a state in which the worker is busy.
Baking process	Models a state in which the dough is ready to be bake.
Oven	Models a state in which the oven is idle.
Baking	Models a state in which the oven is busy.
Ready	Model a state in which the bread is ready.

Table 5: Definitions and Interpretations of the Transitions used in the HTCPN Model

Transition	Description
Mixing process	This is a substitution transition. Execution of this transition models process of mixing the dough.
Fermenting	This is a substitution transition. Execution of this transition models process of fermenting the dough.
Rolling process	This is a substitution transition. Execution of this transition models process of rolling the dough.
Cutting process	This is a substitution transition. Execution of this transition models process of cutting the dough.
Baking process	This is a substitution transition. Execution of this transition models process of baking the bread.

E Description of the Developed HTCPN model

The developed HTCPN model is characterized by the following features:

i. A top page (bread production processes) which provide an overview of the entire production processes.
ii. Five modules (mixing, fermenting, rolling, cutting, baking) that modelled the sequential processes of converting flour into bread.
iii. Place 'flour' is a timed colour set with a single token that describe the weight of flour, work start time and total process time.
iv. Place 'counter' is an integer colour set which determine the weight of the next flour to be processed.
v. Transition 'start mixing process' is enabled when a token is available in place 'flour' and place 'counter'. On enablement, it fires the tokens from place 'mixing machine' and place 'flour' to place 'mixing'.
vi. Place 'mixing' models the state at which the mixing machine is busy.
vii. Timestamps denoted by @++x1, @++x2, @++x3 (where x1, x2, x3 are the delays) attached to transitions or added to arc expressions in the model represents the time it took the process to complete as a result of occurrence of an activity (that is execution of transition).
viii. Guard ([n<=1]) attached to transition 'start mixing process' in the mixing process module is a Boolean expression and which must be true to enable the transition means that the number of batches (denoted by variable i) of flour to be processed into bread should not be more than one.
ix. Place 'dough' is a timed colour set which describe the weight of flour, work time of mixing process and total process time.
x. The code segments attached to the transitions. The code segment is divided into three parts: input, output and action. The action part of the code segment contains the CPN ML code to perform some activities that process the input (input) and returns a value (output). For example, the code segment represented below was added to transition 'start mixing process' in the mixing process module to perform mixing process and returns the time (variable nx1) used to mix the flour depending on the number of resources (variable r), the quantity of flour (variable f) and the rate of mixing (0.6 min/kg). The code segment also returns the computed job flow time (x1) which is equal to the job old process time (x) plus the job new process time (x1).

```
input(f,s,r)
output (nx,x1);
action
let
val x1 = 1.0*(0.6*(Real.fromInt f))/(Real.fromInt
(r))
val nx = x+x1
in
(nx,x1)
end;
```

F Assumptions Made in the Developed HTCPN Model

The assumptions made in developing the model are:

i. One time stamp unit represents one minute in the HTCPN Model.
ii. Non contaminated flour is being used for production of bread.

G Simulation and Validation of the Developed HTCPN Model

The developed HTCPN model of bread production processes was simulated on Intel(R) Pentium(R) CPU 2020M @2.40GHz 64 BIT Operating System using CPN Tools (version 4.0.1). The idea of simulation is to take an executable model such HTCPN model and run several times [19]. Each simulation run is an experiment, which corresponds to a random work in the state space of the model. Due to the fact that the HTCPN model is stochastic, 50 simulations were run on the model, and in each simulation, the average time (processing time) utilized to process 50kg (one bag of flour) and 100kg (two bags of flour) into bread were obtained. In order to carryout sensitivity analysis of the developed HTCPN model, two cases (A and B) were investigated. Case A was carried out in order to determine the effect of the currently available resources on the daily working time, resource utilization rates and production time of bread if the quantity of flour to be processed increases up to 150 kg(3 bags) and 200kg (4 bags). In case B, the parameters under study were studied by varying the number of critical resources (labour doing the mixing, baking oven and rolling machine) used for production.

The HTCPN model was validated by carrying out a statistical analysis (t-Test) between the output of the simulation model (flow time, utilization rate of resources) with the actual flow rate and utilization rate of resources at 5% significance level. The average flow time and the utilization rate of resources were obtained during the simulation.

In order to improve the performance of production flow time and resource utilization rate in the case study under consideration, the HTCPN model was simulated for conditions when more quantity of flour is to be processed within the current time and with the current resources. Flow time (processing time) is the time from when the production starts to when the production finishes while the utilization rate (labour or machine) represents the total busy time of resources or labour.

H Monitors used in the HTCPN model

The developed model has monitors attached to its places and transitions that are responsible for the collection of data during the simulation run. In the developed HTCPN model, on the places 'mixing', 'rolling', 'cutting' and 'baking' which modelled the states at which the resources (labour or machine) were busy, the marking size monitor was added to determine their respective average utilization rate. On the transition 'measure flow time', data collector monitor was added to determine the flow time for the whole process.

4. RESULTS AND DISCUSSION

A Simulation Results of Developed HTCPN Model

The simulation results of the developed HTCPN model, as shown in the third column of Table 6, revealed that the average times (processing time) utilized to process 50kg (one bag of flour) and 100kg (two bags of flour) into bread were 217 and 314 minutes, respectively. In addition, Table 6 (columns 4, 5, 6 and 7), revealed that the utilization rates required at the mixing process unit, the rolling machine unit, the cutting process unit and baking unit were 0.138; 0.115; 0.046; 0.147 respectively for processing of 50kg bags of flour and 0.191; 0.159; 0.064; 0.203 respectively for processing of 100kg bags of flour. From the simulation results, it was observed that in all cases of production in the bakery line, baking unit had the highest utilization rate followed by mixer as against utilization rates of other resources. Hence, mixing operator and baking unit are one of the critical resources in the production process.

Table 6: Actual and Simulated Values of Flow Time (Processing Time) and Utilization Rate (UR) of Resources

Size	Actual Processing Time (minutes)	Simulated Processing Time (minutes)	Mixing (operator) UR	Rolling machine UR	Cutting (operator) UR	Baking unit UR
50kg	223	217	0.138	0.115	0.046	0.147
100kg	312	314	0.191	0.159	0.064	0.203

Fig. 8 shows the simulation results of scenario A. It depicts the cumulative process time obtained when the quantity of flour to be processed increases up to 150 and 200kg using the currently available resources. From the simulation results, the production times for processing of 50, 100, 150 and 200 kg of flour starting from the mixing process till the end of baking process were 217 minutes (3 hours, 37 minutes), 314 minutes (5 hours, 14 minutes), 411 minutes (6 hours, 51 minutes) and 508 minutes (8 hours 28 minutes), respectively. This implied that as the quantity of flour to be processed increases beyond 100kg, production time tends to be higher than the daily working time by 182 minutes.

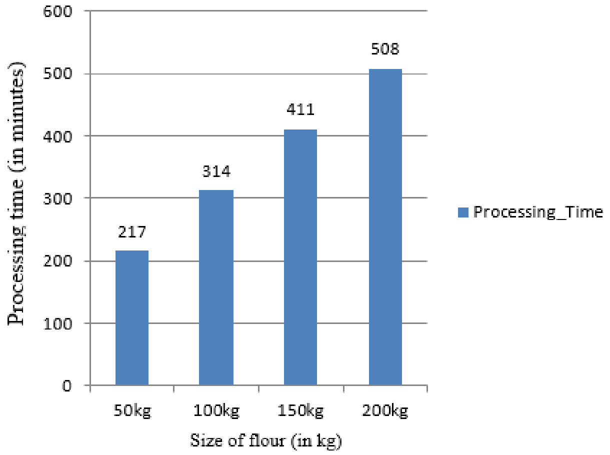

Figure 8: Simulation Result of processing time of flour up to 200kg Quantity

Fig. 9 also reveals the simulated utilization rates of resources when the quantity of flour to be processed increases up to 150 and 200kg within the current working period and the current resources. This implies that the critical resources identified at this stage were the labour mixing the flour, the rolling machine and the baking oven.

The simulation results as depicted in both Fig. 9 and Fig. 10 revealed that the production times and the utilization rates of resources for processing flour increases as the quantity of flour to be process increases. Thus, there is need for improvement on these two performance metrics (utilization rates of resources and production times). In doing so, Case B was examined by varying the number of critical resources (labour doing the mixing, baking oven and rolling machine) used for production. Fig. 10 shows the comparison between Case A and Case B. The result revealed that by increasing the number of worker doing the mixing, the rolling machine and the baking oven each by one, the processing time of 50, 100, 150 and 200kg bags of flour decreases. Thus, from the simulation results of the two cases experimented, if the management of the considered bakery system wants to maximize their production, the only scenario that would not have adverse effect on the daily working time of the production process is the case of increasing the number of identified critical resources by one (Case B).

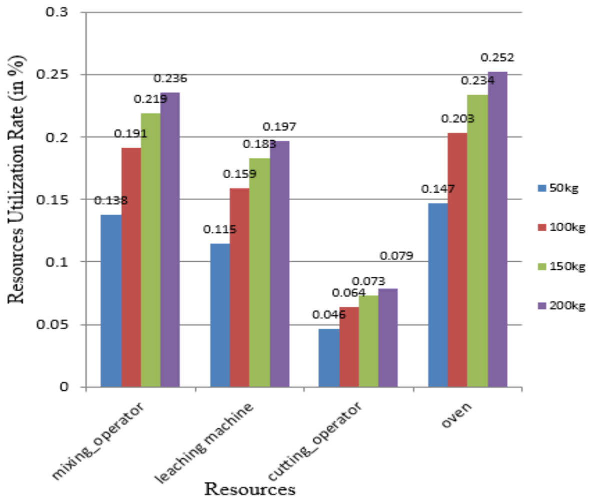

Figure 9: Simulation Results of Utilization Rates of Resources for the processing of Higher Quantity of Flour.

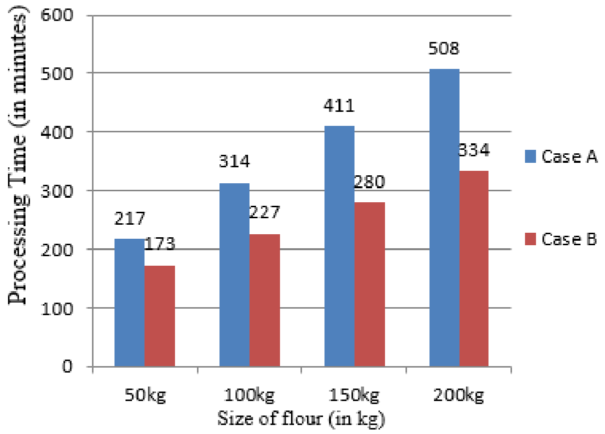

Figure 10: Comparison between Simulation Results of Processing Time of Higher Quantity of Flour under Currently Available Resources (Case A) and Increase in Number of Resources (Case B).

B Validation Results of the Developed HTCPN Model

Statistical analysis was carried out on the simulation results and the actual processing time using the Statistical Package for the Social Science software (SPSS version 17.0). Table 6, for validation of the developed HTCPN model, compares the simulated average processing time with the actual processing time to process 50kg and 100kg flour into bread as observed from the case study. Table 7 depicts the validation results which showed that statistically there were no significant differences between the simulated and real average values since their p-values ≥ 0.05. This implies that the developed HTCPN model is valid, and it accurately represents the considered bakery system.

Table 7: Summary of t-Test for the Simulation Result and Actual Average Processing Time

Variable	t-value	p-value	Remark
Processing Time	0.500	0.705	Since p-value is greater than 0.05, then there is no significant difference between the real data and simulated data (production time of bread) at 5% significant level.

5. Conclusion and Future Work

In this paper, the HTCPN model abstracting the production process of bread at LAUTECH Bakery has been developed, simulated and validated based on the production time and utilization rate of resources. From the results obtained, the following conclusions were arrived at:

i. The simulation result was adequately compared with the real production time and average utilization rate of resources using t-test; there were no significant differences between the simulated and actual production time and average utilization rate at $p \geq 0.05$.

ii. The developed HTCPN model is a representation of the bakery performance consisting of the state of the system and the events or transitions that cause the system to change its state.

iii. The result shows that the mixing process and bakery process have the highest utilization rate of resources.

iv. The validity of the developed model shows that the model is useful for the management of bakery production line to enhance the production process.

This research has been able to develop a HTCPN model which could serve as a reference model for analyzing and improving the utilization rate of resources and production time in a named bakery production line. However, it is recommended that future research may be geared towards the development of a model for a bakery production system which takes into cognizance demands as one of significant factors in any production system.

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