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Research Paper

Implementation of Control Strategy for Predicting Energy Consumption Management in a Food and Beverage Industry Using Regression Analysis

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Abstract: The philosophy of efficient energy consumption is vitally crucial to profitable production cost in manufacturing industries. This is because the unit production cost is largely determined by the cost of unit energy supply; which is quite higher than the cost of raw materials in Nigeria. It has been established that the Nigerian industrial sector is responsible for 8.7% of the total energy consumption in the nation. Out of this chunk, the food and beverage industry appropriates approximately 2%. Meanwhile, it is observed that the energy consumption trend in most industrial electric motors is always high due to continuous operation even during the idle time/period in production. In this study, data gathered has a coefficient of determination of 99.7%. This is, thus, subjected to regression analysis which assists in predicting the energy consumption trend for a period of one year. Further to this, the capacity of control principles in efficient energy consumption is demonstrated by practical real time implementation of a smart energy saving in the food industries using PLClogicx software. In this sense, the developed programmable logic control (PLC) ladder diagram was further designed and implemented using fuzzy logic control (FLC). This is simulated using MATLAB/Simulink toolbox. By this arrangement; it is observed that there was a significant reduction in energy consumption. This is obviously revealed in the obtained results. In this case, there was an average electrical energy savings of 65.59% in the plant's case sealing section while an energy saving of approximately 0.13% was achieved in reference to the overall energy consumption of the industrial plant's processes. Finally, based on the mathematical calculations obtained from observations of typical production processes in the multinational food and beverage company, the FLC is discovered to provide 99.83% efficiency in optimizing energy consumption.

Keywords: Energy Consumption and Saving, Fuzzy Logic Control (FLC), Programmable Logic Control (PLC) Ladder Diagram, Conveyor Motors, Regression Analysis.

1 Introduction

ENERGY, in its different forms (either electrical or thermal), is required as continuous input to all industrial processes. The total energy consumption of the industrial sectors of developed countries contributes to around 30–40% of total energy demand [1]. In the developed countries, diversion from the generation of more electrical power to more emphasis on optimal utilization of the present available energy using proper monitoring measures and control strategies should be the order of the day. Energy is one of the largest controllable costs in most manufacturing industries with considerable scope for reducing energy consumption and hence, cost [2].

In the food industry, nearly half of all energy consumption is used to change raw materials into finished products, while the remaining is used for the processes required for food preservation and safety [3]. These industrial processes involve frequent and continuous use of energy through electric motors, proximity sensors, control valves, blowers/fans,

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instrument transmitters, heaters and compressors. Majorly in the food industry today, the most highly used and energy consuming device is electric motor with different activities ranging from main driving system, conveyors, blowers, agitator, stirrer, pumps, elevators etc. Hence there is need for advanced and smart motor management solutions that are capable of yielding reliable results.

Ayodele *et al*. [4] evaluated the energy usage in two Nigerian food and beverage industries for a period of four years to develop an index that measures the energy efficiency of producing a finished product. The values obtained for both indices indicated that neither company utilized electrical energy efficiently; one of the reasons attributed to this was the non-compliance to the usage of energy saving equipment. Therefore, power optimization tools such as variable frequency drives, energy-efficient motors, controllers and software can all deliver immediate and measurable desired savings [3].

In line with this, programmable logic control (PLC) has been a powerful tool in modern day industrial applications for control of production machines. It is a solid state user programmable control system with functions to control logic, sequencing, timing, arithmetic data manipulation and counting capabilities. It can be viewed as an industrial computer that has a central processor unit, memory, input / output interface and a programming device [5]. In the past, these functions are accomplished by relays, timers etc. which are bulky systems with chances of errors and if faults occur in these systems, it is more time consuming to find the fault. However, the beauty of the application of PLC is its easy way of fault finding and ability to adjust the program for system modification which makes a great impact on energy savings.

Existing in literature are various methods in which PLC has been used to achieve energy savings. Khule [6] used PLC and supervisory control and data acquisition (SCADA) for monitoring industrial energy. The design proved effective as it provided alerts during unwanted emergency situations caused by excessive power in the plant thereby improving safety. Manivannan [7] developed a prototype to reduce energy consumption in residential buildings using PLC. Mathur [8] established the reliability and ruggedness of the PLC ladder logic for a smart energy saving in a classroom. Although, the PLC can be effective and reliable, it is believed to be much slower when compared with more recent and advanced heuristic techniques. One of such is the fuzzy logic control (FLC).

The FLC is a heuristic procedure for finding optimal solution to a control problem [9]. FLC has equally yielded tremendous results when utilized for energy management. Angalaeswari *et al*. [10] proved the efficiency of the FLC for power management of a grid operated microgrid. Keshtkar and Arzanpour [11] established the adaptive nature of the FLC thus, making it able to respond adequately to new modifications. This was also verified by Prauzek *et al*. [12]. Ghadi, Rasul and Khan [13] highlighted the role of technology in energy savings and its potential by investigating and evaluating the use of FLC in heating, ventilation and air conditioning (HVAC) systems and light controllers for smart buildings. Chekired *et al*. [14] developed a fuzzy home energy management system to save energy during winter and summer in a photovoltaic solar home and results obtained showed significant improvements in energy consumption.

The first objective of this paper is to determine potential energy savings in the food industries by analyzing the predictability of consumption pattern and identify the trend changes in the historical energy consumption. The second objective is to develop a PLC ladder diagram and model a FLC for saving energy consumption. This is to ensure that an effective and efficient control technique is utilized for energy savings. Reductions in consumption of electricity will lead to reductions in demand for electricity and, consequently, reductions in emissions from thermal electric power generating stations [15, 16]. This will, in turn, enhance the fulfillment of the sustainable development goals (SDGs) and consequently, lead to a better and more sustainable future. Basically, the reduction or elimination of energy wastage in the use of industrial electric motors is the focal point of this study. However, it must be clearly stated that the electrical energy consumption would be considered in this study whereby the heat energy, as another major contributor to energy consumption/wastage in production industries would be left out due to lack of specialized and state-of-the-art tools for its data gathering.

The organization of the paper is as follows: Section 2 describes the production operations in a food and beverage industry as well as the breakdown of electrical power requirements in the plant considered. Section 3 contains the investigation of the energy consumption in the plant for potential energy savings; regression analysis is used to predict future energy consumption. It also contains the designs of the PLC and FLC for the conveyor motor control. Section 4 presents the results of the software implementation of the control techniques on energy savings in the plant. The paper is finally concluded in Section 5.

2 Description of Production Process of Plant

A typical production process is depicted in Fig. 1. The processing of the raw materials into finished product involves three major stages which include: paste processing, mixing and pressing and wrapping (packaging). For the paste production process, steamed fermented soya beans are cooked and baked in the oven for a particular period of time before it is being crushed with the milling machine, forming one of the recipe used during the mixing production stage. Meanwhile in the mixing process, where all other raw

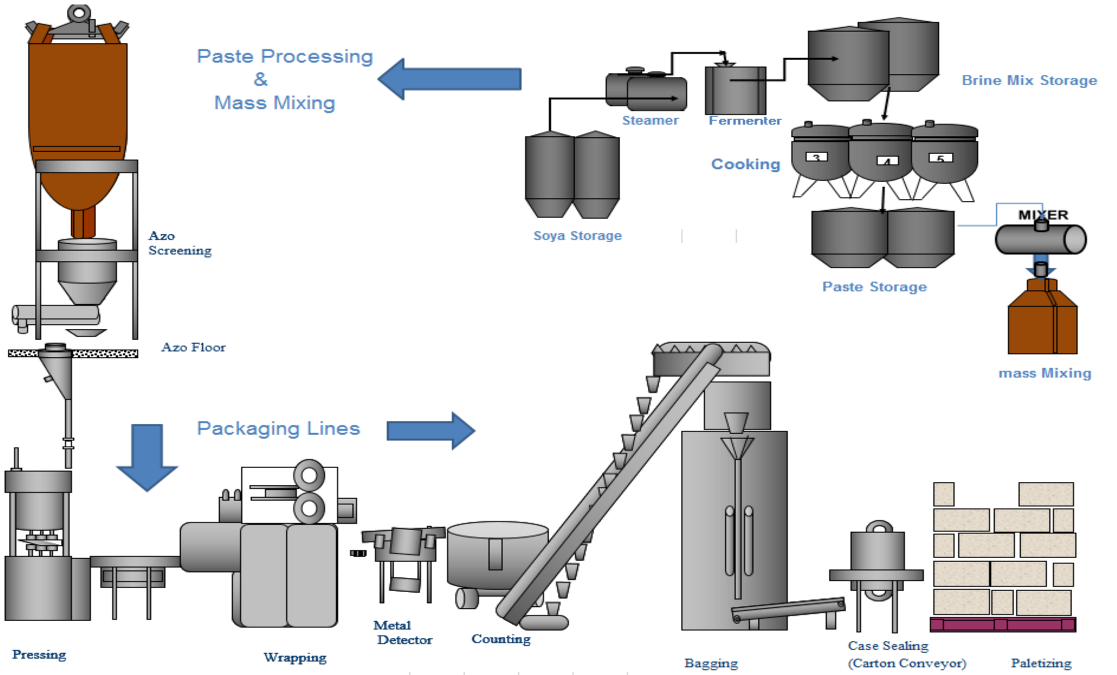


Fig. 1 Complete production process description.

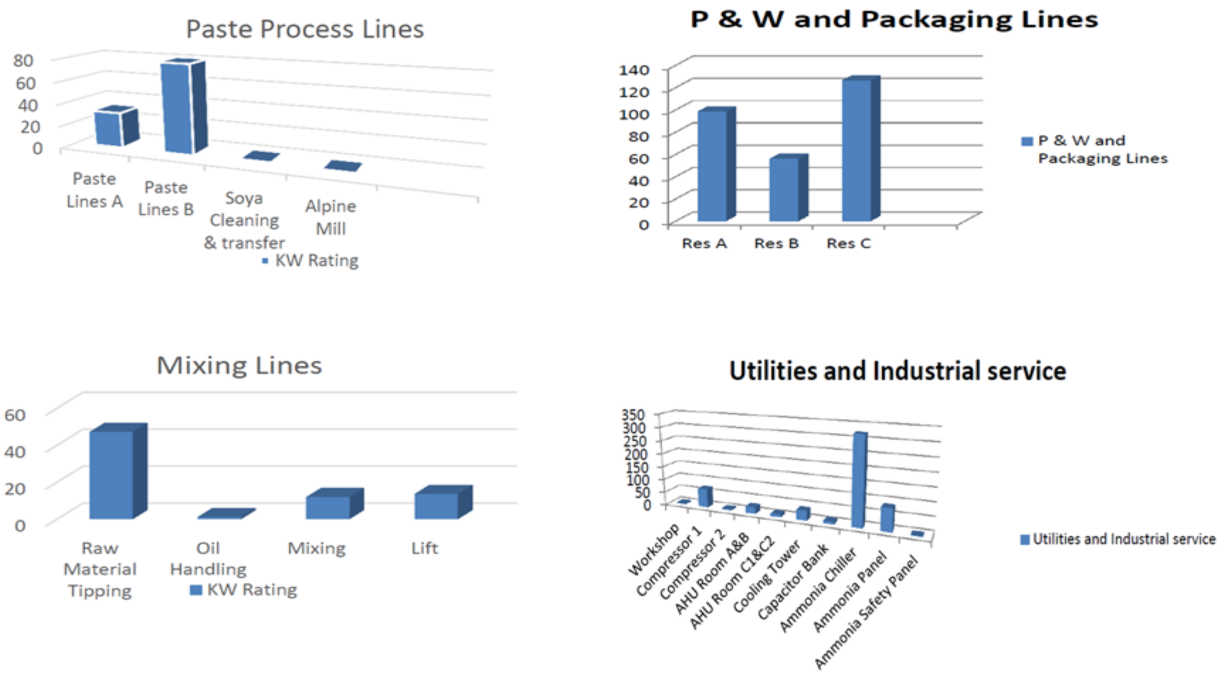


Fig. 2 Power requirements of various sections in the plant.

materials including monosodium glutamate (MSG), salt, sugar, starch, rework are being mixed with the paste prepared during the first stage to produce the mixed powder**.** Finally, in the packaging stage, the mixed powder formed are pressed to form cubes, wrapped, counted in batches with high speed counter machine and finally packaged with a bagging machine for food safety and quality control measures.

2.1 Utilization of Electrical Energy in Plant

Electrical energy is being utilized in all the sections of the plant. Fig. 2 shows the charts of power requirements (kW) of different sections within the plant indicating total power requirements of 113.6kW, 74.2kW and 281kW for the paste processing lines, mixing lines, and packaging lines respectively.

The plant under study receives electrical power supply from the factory power plant, distributed accordingly to different equipment and various sections within the plant. An installed energy meter on a feeder incomer records import and export values of power to the grid. The total working days in a year was also noted for the plant which was estimated to be on the average of 363 days (8712 hours). Using the factory power plant's SCADA system parameters and the excel sheet for capturing daily energy data, data for a period of one year was collected as shown in Table 1. The values presented in Table 1 represent the energy audit carried out within the factory.

3 Methodology

In order to determine the standard for the energy consumption for upcoming years, a plot of energy consumption (kWh) against production (Ton) is obtained as shown in Fig. 3. When a scatter diagram shows a low degree of scatter, it is indicative of a good fit. If data fit is poor, there should be a relationship which indicates a poor level of control and hence a potential for energy savings.

In order to achieve a straight line from the scatter plot, the general form, Eq. (1), as in [17] is used:

$$y = mx + c \tag{1}$$

where,

y = Energy Consumption [kWh]

m = Slope

x = Production [Tons]

c = Intercept

The indication of Fig. 3 is that the energy consumption/production points fall into a roughly linear pattern. However, using the least square regression analysis with regards to the data captured from Table 1, the regression equation [18] with 12 months number of given historical data (N=12) is given as:

$$y = \beta_1 x + \beta_0 \tag{2}$$

where, β_1 is the regression coefficient and β_0 is the regression constant

$$\beta_1 = \frac{N\sum xy - \left(\sum x\right)\left(\sum y\right)}{N\sum x^2 - \left(\sum x\right)^2} \tag{3}$$

$$\beta_0 = \frac{\sum y - \beta_1 \sum x}{N} \tag{4}$$

Using (2)-(4), a regression analysis table is created as shown Table 2.

Table 1 Production and electrical energy consumption in the plant for year 2017.

Month	Total production, x [Ton]	Electrical energy consumption, y [kWh]	Specific energy consumption [kWh/Ton]
January	7743	163241	21.08
February	7743	170173	22.76
March	8277	170797	20.64
April	8010	164836	20.58
May	8010	172849	21.58
June	8010	186547	23.29
July	8277	197901	23.91
August	8277	202348	24.45
September	8010	170914	21.34
October	8010	185489	23.16
November	8010	189648	23.68
December	8277	182028	21.99
Total	96654	2156771	268.46
Average	8032.25	179731	22.37

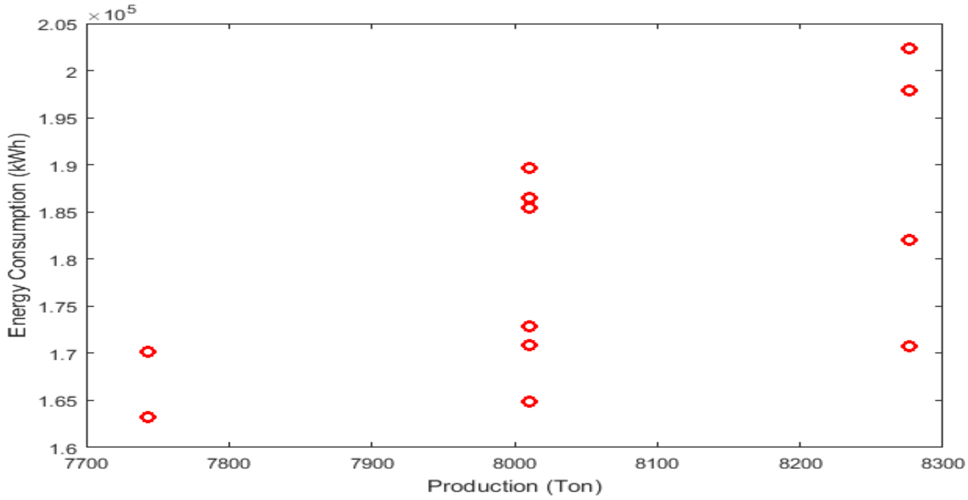


Fig. 3 Scatter plot of energy consumption against production.

Table 2 Regression analysis table for saved energy consumption of conveyor motors.

x	y	xy	$\|x^2\|$	$\|y^2\|$	$\|\hat{y}\|$	$\|\bar{y}\|$	$\|(y-\hat{y})^2\|$	$\|(y-\bar{y})^2\|$
7743	163241	1263975063	59954049	26647624081	167337.2698	179730.9167	16779426.27	271917352.8
7743	170173	1317649539	59954049	28958849929	167337.2698	179730.9167	8041365.767	91353771.64
8277	170797	1413686769	68508729	29171615209	188583.688	179730.9167	316366270.0	79814867.60
8010	164836	1320336360	64160100	27170906896	177960.4789	179730.9167	172251946.4	221858543.5
8010	172849	1384520490	64160100	29876776801	177960.4789	179730.9167	26127216.55	47360777.47
8010	186547	1494241470	64160100	34799783209	177960.4789	179730.9167	73728344.60	46458991.55
8277	197901	1638026577	68508729	39164805801	188583.688	179730.9167	86812302.91	330151927.1
8277	202348	1674834396	68508729	409447133104	188583.688	179730.9167	189456284.8	511532457.0
8010	170914	1369021140	64160100	292115955396	177960.4789	179730.9167	49652864.89	77738020.09
8010	185489	1485766890	64160100	34406169121	177960.4789	179730.9167	56678629.95	33155523.29
8010	189648	1519080480	64160100	35966363904	177960.4789	179730.9167	136598149.5	98348541.18
8277	182028	1506645756	68508729	33134192784	188583.688	179730.9167	42977045.15	5276591.687
96654	2156771	17387784930	778903614	3.89453E+11			1175469847	1814967365

Using Table 2, the regression coefficient becomes:

$$\beta_1 = \frac{12(17387784930)-(96654)(2156771)}{12(778903614)-(96654)^2} = 39.7873 \quad (5)$$

And the regression constant becomes:

$$\beta_0 = \frac{2156771-39.7873(96654)}{12} = -140735.7941 \quad (6)$$

After substituting the values of the regression constant and regression coefficient, the predicted energy consumption equation becomes:

$$\hat{Y} = 39.7873x - 140735.7941 \quad (7)$$

Equation (7) shows that the intercept of the regression line is on the negative y-axis as seen on Fig. 4. Note that $\hat{Y}$ is predicted energy consumption.

The coefficient of determination, for determining the portion of the total variation in energy consumption (y), is obtained by using the production tons (x) information in a regression; it is always between 0 and 1. A value of 0 means that x provides no information about y; a value of 1 means that the use of x information allows perfect prediction of y with every point of the scatterplot exactly on the regression line. However, any value in between represents different levels of closeness of the scattered points around the regression line [19].

Therefore, the coefficient of determination according to [20] is:

$$R^2 = 1 - \frac{SSE}{SS_{yy}} \quad (8)$$

where,

$$SSE = \sum (y-\hat{y})^2 \quad (9)$$

This is the sum square of error (SSE) between the actual demand value and the forecasted value.

$$SS_{yy} = \sum (y-\bar{y})^2 \quad (10)$$

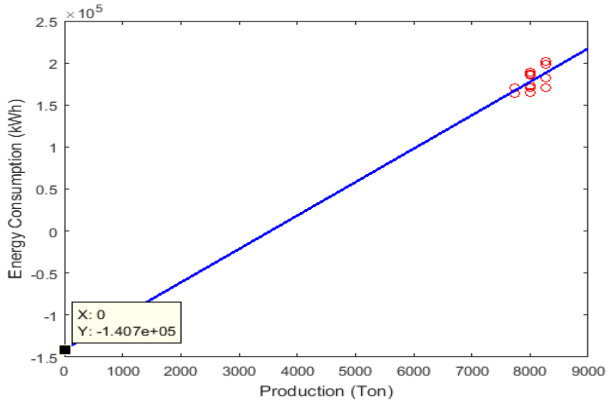


Fig. 4 Regression line showing energy consumption against production.

This is the SSE between the actual demand value and the mean value.

$$R^2 = 1 - \frac{1175469847}{1814967365} = 0.35 \text{ or } 35\% \quad (11)$$

This means that 35% of the variance in energy consumption is predictable from the production, in tons, which indicates that the operational practice was scarcely controlled.

3.1 Control Implementation to the Conveyor System

The case sealing section involves the use of three electric motors which include inlet conveyor motor of 0.12kW, case sealer conveyor motor of 0.25kW and outlet conveyor motor of 0.12kW. The speed of these motors is being controlled by frequency drives which ensure they are not being run on full-load. In the course of carrying out the energy consumption analysis of this section, before the implementation of the control strategy, the circuit breaker for one of the 10 case sealing process lines was identified and connected directly to an energy analyzer as seen in Fig. 5. Afterwards, the captured data saved in the SD Card (Secure Digital Card) were retrieved through the fluke power log software.

The process shown in Fig. 1 was analyzed for energy saving potential. It was observed that most of the

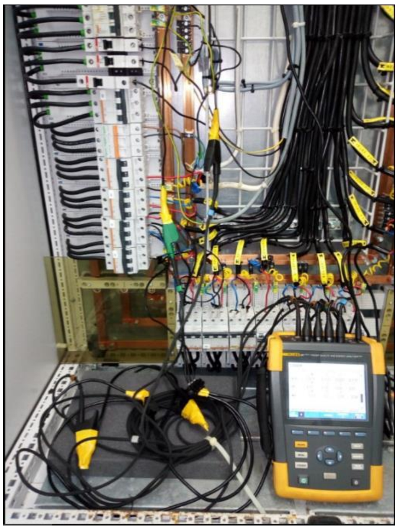


Fig. 5 Energy analyzer connected to the 3-phase circuit breaker.

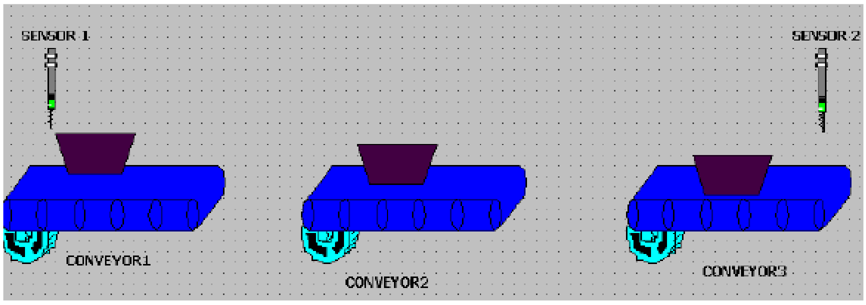


Fig. 6 Case sealer section.

Table 3 Maximum savable time from production operational activities based on observation.

Reference time	Running time [s]	Idle time [s]	Saved time [s]
1 min (60 sec)	20	40	40
2 min (120 sec)	40	80	80
3 min (180 sec)	60	120	120

Table 4 Summary of the time saved in every 8 hour interval.

Reference time [Minutes]	Reference time [Hours]	Saved time [Seconds]	Saved time [Hours]
480	8	19200	5.3333
960	16	38400	10.6667
1440	24	57600	16.0000

electrical induction motors for the end-use carton sealing systems with 10 lines across the plant under study are continuously in use for 24 hours on operation even when there is any form of delay from processing, mixing, pressing, wrapping and packaging line machines. Usually, this delay is as a result of carton case being made ready to pass through the case sealing section. During this delayed period, all the electric motors are running on no-load and energy is being wasted, hence there is need for energy control measures.

The case sealing section is shown in Fig. 6 and it is seen that three electric motors are in use within this section; one for the inlet conveyor which is used for transfer of unsealed carton, the second for the case sealer conveyor which is used for sealing the carton and the third for the outlet conveyor which is used for actualizing injection.

As a means of reducing energy consumption in the process line, a proximity sensor is used for detecting the presence of the movement of carton on the conveyor motor. The process line under study produces 60 bags of sachet per minute while each carton accommodates 20 sachets. After several observations, each carton was observed to be filled within 20 seconds meaning that the conveyor motors would be idle for 20 seconds waiting for the next batch of carton to be sealed. From the observation of production operational activities, Table 3 shows the maximum time of operation of the conveyor motors that can be saved in respect to the reference time.

Hence, the mathematical sequence of the saved time is: 40, 80, 120, 160, 200, 240… If the first term is ‘*a*’ and common difference is ‘*d*’, then the *n*-th term of the arithmetic progression (AP) according to [17] is given by (12).

$$n\text{-th term} = a + (n-1)d \tag{12}$$

Therefore, using (12), Table 4 shows the time saved in every 8 hours interval.

The saved times from Table 4 form the AP, 5.3333, 10.6667, 16.0000, 21.3333… Thus, the conveyor motors’ running and saved times, energy consumed based on running and saved times and the saved energy in every 8 hour interval is seen on Table 5.

From Table 5, energy consumed when idle time is eliminated therefore shows that the active period of the conveyor motors with respect to the reference time which yields saving at an average of 66.7% using (13).

$$\text{Saving} = \frac{\text{Actual} - \text{Ideal}}{\text{Actual}} \times 100\% \tag{13}$$

The regression analysis table is then generated.

In order to show that the variance in the energy consumption (when the idle time is eliminated) of the motor system is predictable from the time interval of the analysis, the regression analysis of Table 4 generated is used to determine the coefficient of determination, R^2. The least square regression analysis is again used with regards to the data generated. Applying (2)-(4), where $N = 21$ and other variables from Table 6 are substituted, then,

Table 5 Actual consumed energy and energy consumed when idle time is eliminated.

Reference time [h]	Saved time [h]	Running time [h]	Actual energy consumed [Wh]	Energy consumed based on saved time [Wh]	Saved energy [kWh]
8	5.3333	2.6667	410	136.6684	0.2733316
16	10.6667	5.3333	834	278.0035	0.5559965
24	16.0000	8.0000	1177	392.3333	0.7846667
32	21.3333	10.6667	1541	513.6683	1.027332
40	26.6667	13.3333	1941	647.0032	1.293997
48	32.0000	16.0000	2331	777.0049	1.553995
56	37.3333	18.6667	2755	918.3399	1.836660
64	42.6667	21.3333	3185	1061.675	2.123325
72	48.0000	24.0000	3605	1201.677	2.403323
80	53.3333	26.6667	4002	1334.012	2.667988
88	58.6667	29.3333	4429	1476.347	2.952653
96	64.0000	32.0000	4848	1616.015	3.231985
104	69.3333	34.6667	5265	1755.017	3.509983
112	74.6667	37.3337	5684	1894.685	3.789315
120	80.0000	40.0000	6095	2031.687	4.063313
128	85.3333	42.6667	6528	2176.022	4.351978
136	90.6667	45.3333	6960	2320.024	4.639976
144	96.0000	48.0000	7383	2461.015	4.921985
152	101.3333	50.6667	7799	2599.694	5.199306
160	106.6667	53.3333	8203	2734.362	5.468638
168	120.0000	56.0000	8631	2877.031	5.753969

Table 6 Regression analysis table for saved energy consumption of conveyor motors.

x	y	xy	$\|x^2\|$	$\|y^2\|$	$\|\hat{y}\|$	$\|\bar{y}\|$	$\|(y-\hat{y})^2\|$	$\|(y-\bar{y})^2\|$
8	273.3316	2186.653	64	74710.16	352.2320	2971.606	6225.273	7280682.117
16	555.9965	8895.944	256	309132.1	614.1696	2971.606	3384.110	5835166.841
24	784.6667	18832.00	576	615701.8	876.1072	2971.606	8361.365	4782701.315
32	1027.332	32874.62	1024	1055411	1138.045	2971.606	12257.32	3780199.443
40	1293.997	51759.88	1600	1674428	1399.982	2971.606	11232.91	2814370.279
48	1553.995	74591.76	2304	2414900	1661.920	2971.606	11647.81	2009619.530
56	1836.660	102853.0	3136	3373320	1923.858	2971.606	7603.421	1288101.288
64	2123.325	135892.8	4096	4508509	2185.795	2971.606	3902.526	719579.8067
72	2403.323	173039.3	5184	5775961	2447.733	2971.606	1972.230	322944.9998
80	2667.988	213439.0	6400	7118160	2709.670	2971.606	1737.422	92183.58631
88	2952.653	259833.5	7744	8718160	2971.608	2971.606	359.2920	359.1972563
96	3231.985	310270.6	9216	10445727	3233.546	2971.606	2.435472	67797.48402
104	3509.983	365038.2	10816	12319981	3495.483	2971.606	210.2442	289850.3325
112	3789.315	424403.3	12544	14358908	3757.421	2971.606	1017.240	668648.8264
120	4063.313	487597.6	14400	16510513	4019.358	2971.606	1932.007	1191825.266
128	4351.978	557053.2	16384	18939713	4281.296	2971.606	4995.945	1905428.239
136	4639.976	631036.7	18496	21529377	4543.234	2971.606	9359.092	2783460.125
144	4921.985	708765.8	20736	24225936	4805.171	2971.606	13645.46	3803980.194
152	5199.306	748141.7	23104	24225936	5067.109	2971.606	21060.92	3803980.194
160	5468.638	831889	25600	27032783	5329.046	2971.606	16832.57	4962649.518
168	5753.969	966666.8	28224	33108159	5590.984	2971.606	26564.11	7741546.646
1848	62403.7158	7105061.2	211904	2.4E+08			164303.7	56145075.23

$$\beta_1 = \frac{21(7105061.2)-(1848)(62403.7158)}{21(211904)-(1848)^2} = 32.7422 \quad (14)$$

$$\beta_0 = \frac{62403.7158-32.7422(1848)}{21} = 90.2944 \quad (15)$$

After substituting the values of the regression constant and regression coefficient, the predicted energy consumption equation becomes:

$$\hat{Y} = 32.7422x + 90.2944 \quad (16)$$

where $\hat{Y}$ is the forecasted value of the saved energy consumption of the conveyor motors. Thus, (8)-(10) can be used to estimate the coefficient of determination, R^2, therefore,

$$SSE = \sum (y-\hat{y})^2 = 164303.7 \quad (17)$$

$$SS_{yy} = \sum (y-\bar{y})^2 = 56145075.23 \quad (18)$$

$$R^2 = 1 - \frac{164303.7}{56145075.23} = 0.997 = 99.7\% \quad (19)$$

Hence, the cumulative saved energy consumption of conveyor motors ($\hat{Y}_c$) for the first one month (720 hours), next two months (1416 hours), next three months (2160 hours) etc. can be calculated using Equation (16) of the forecasted saved energy consumed where 'x' represents the time in which there is production process (hours) which is also correlated to monthly representation as shown on Table 7.

However, $\hat{Y}$ (kWh) is the saved energy consumption per month. Since $\hat{Y}_c$ is in (Watt-hour) and there are 10 case sealing section lines in the plant under study, then:

$$\hat{Y}_c\left[\text{kWh}\right] = \left\{\frac{\hat{Y}_c\left[\text{Wh}\right]}{1000}\right\}\times 10 \quad (20)$$

$$\hat{Y}\left[\text{kWh}\right] \text{ per month} = \hat{Y}_n - \hat{Y}_{n-1} \quad (21)$$

where, n is the number of month as it increases from January to December. The overall savings of the motor system with respect to the packaging section of the plant is thus calculated through (22) below.

$$\text{Percentage Savings} = \frac{\hat{Y}\left[\text{kWh}\right]}{\text{Actual}\left[\text{kWh}\right]}\times 100\% \quad (22)$$

3.1.1 Conveyor Motor Control With PLC

Based on observations of the operations of the production process, a ladder diagram program using PLCLogix software was written. The program was implemented using a 6-step procedure as shown in Fig. 7.

The ladder diagram program was written to indicate the time saved from the reference time (a minute of production process). By implementing the steps above using the PLCLogix software, the outcome is shown in Fig. 8.

3.1.2 **Conveyor** Motor Control With **FLC**

The fuzzy logic control is an alternative to the PLC and it basically involves three stages: fuzzification, fuzzy inference process and defuzzification. These stages are discussed in [21]. Using MATLAB/Simulink, a system for the conveyor motor is shown in Fig. 9.

The system in Fig. 9 depicts the procedure for control of 6 cartons. The cartons are represented with step inputs; the initial output is 0 and it changes to 1 at a particular step time. The sensor block, shown in Fig. 10, determines the presence of a carton on the conveyor (when the output is 1) and thus makes the FLC to keep the conveyor motors active until the presence of the carton is no longer detected (when the output is 0).

The fuzzy logic controller requires a single input variable and three output variables for the three different motors as shown in Fig. 11.

The input variable is designed using a single membership function that forms a single line on input value 1 which is labeled as {Movement}. This means that for any input value other than 1, no carton movement is assumed. The output variables require two membership functions labeled as {Idle, Active}, also forming a single line on outputs, 0 and 1 respectively. The inference process is done using two rules as in Table 8. Thus, indicating that the conveyor motor should be idle for an output of 0 and should be active for an output of 1.

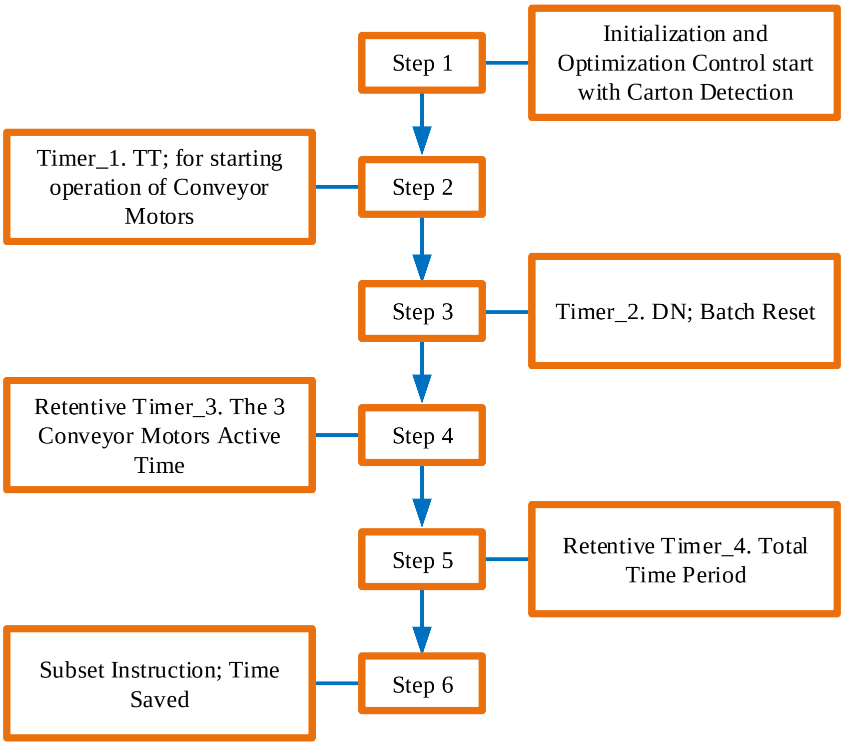
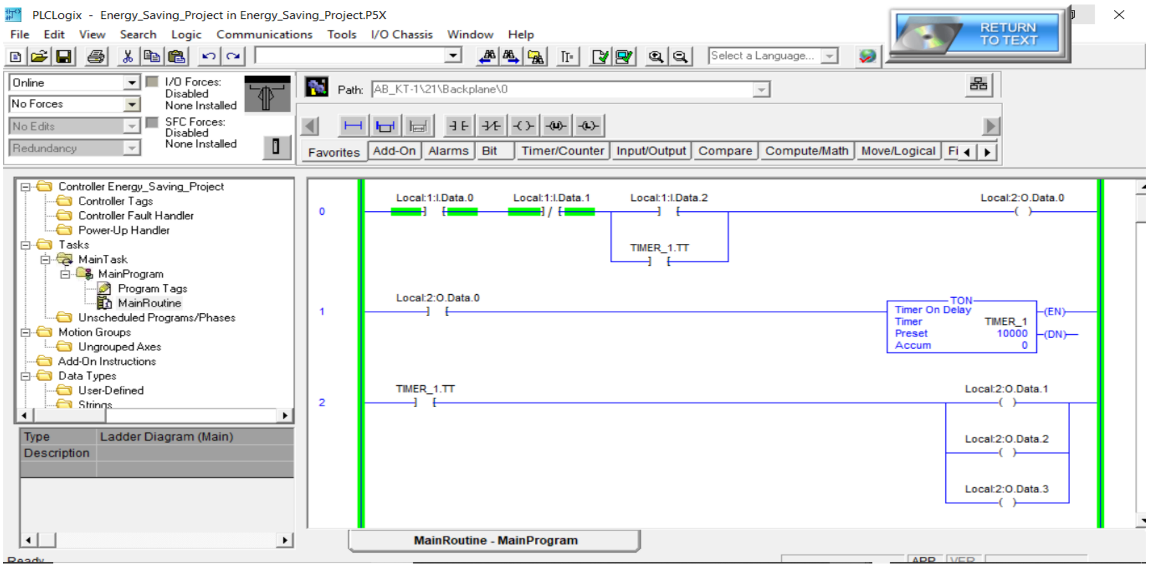
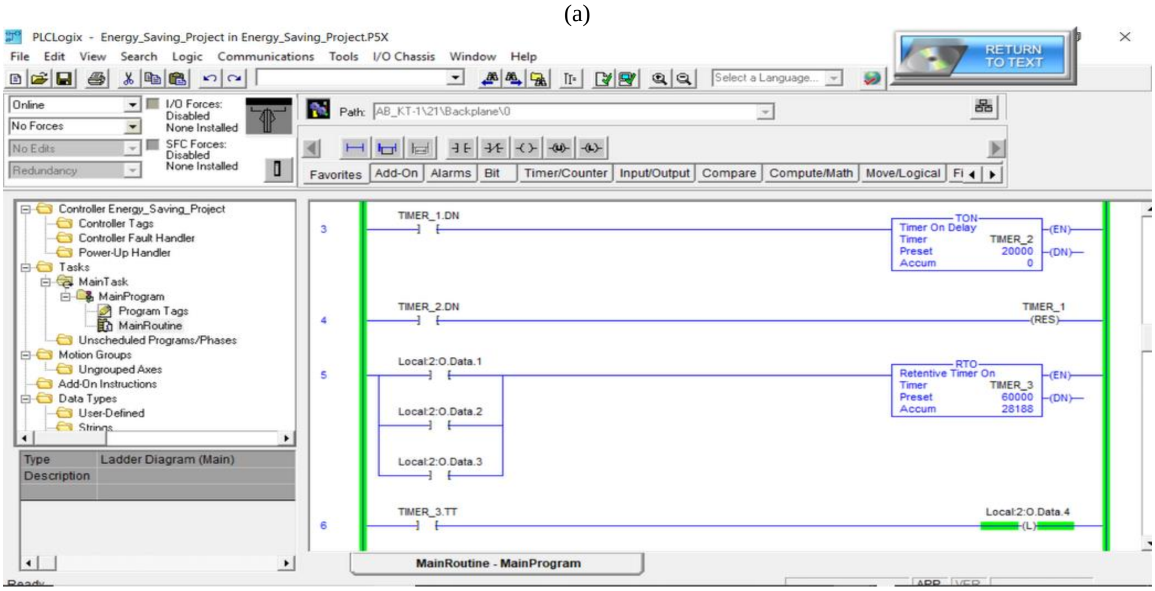


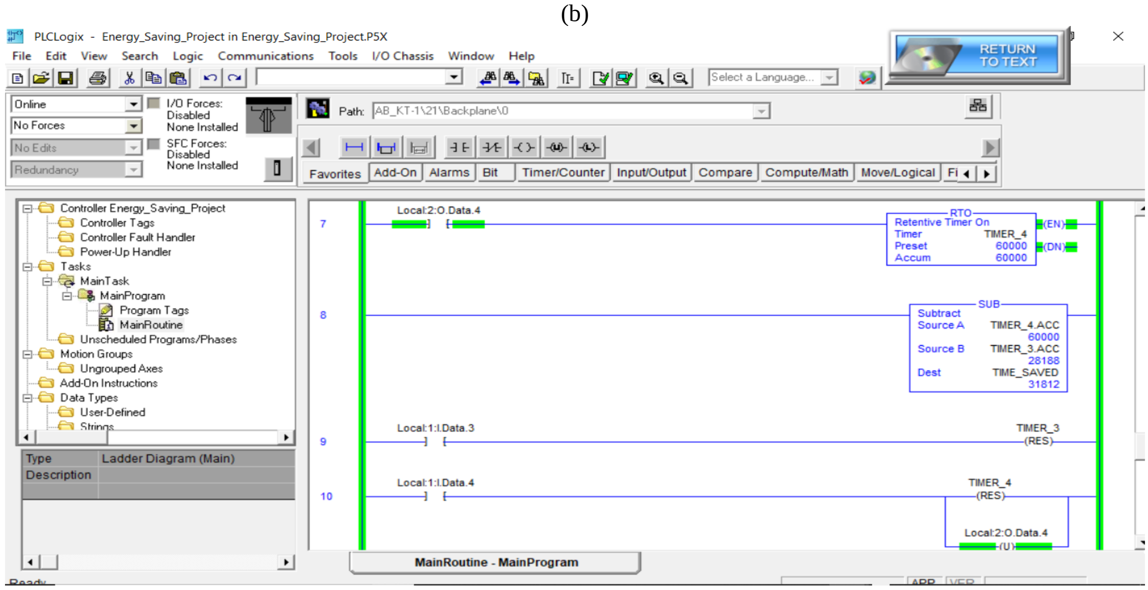
Fig. 7 Six-step ladder diagram procedure for conveyor motors.



(a)



(b)



(c)

Fig. 8 PLC ladder diagram for conveyor motor control.

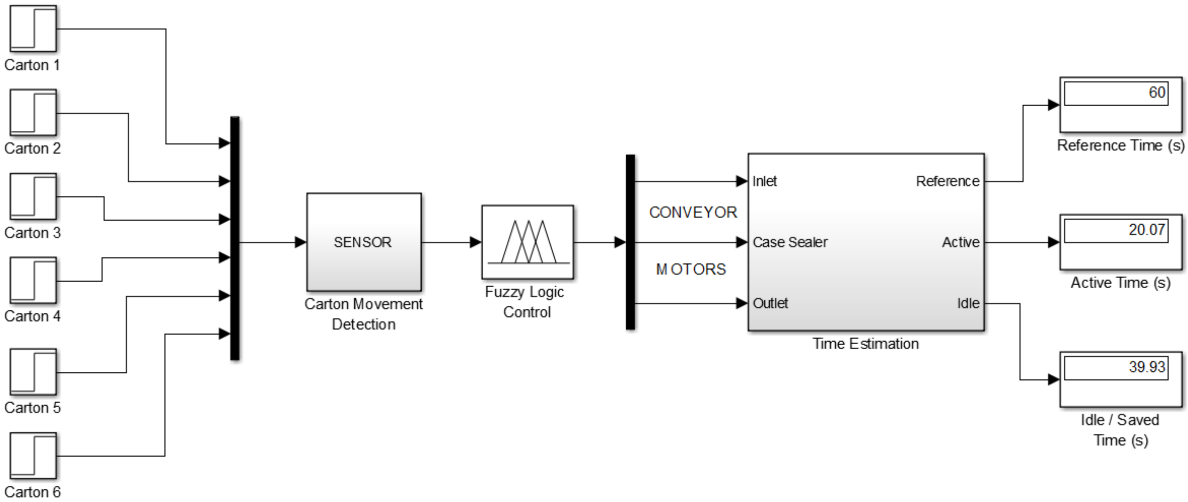


Fig. 9 Smart motor control system using FLC.

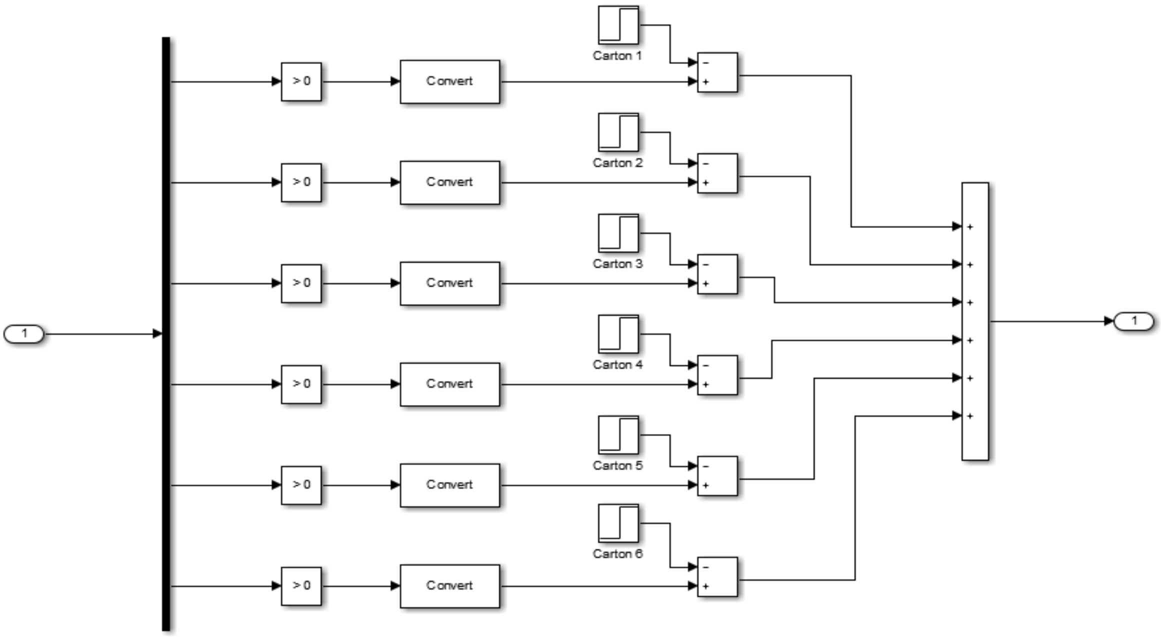
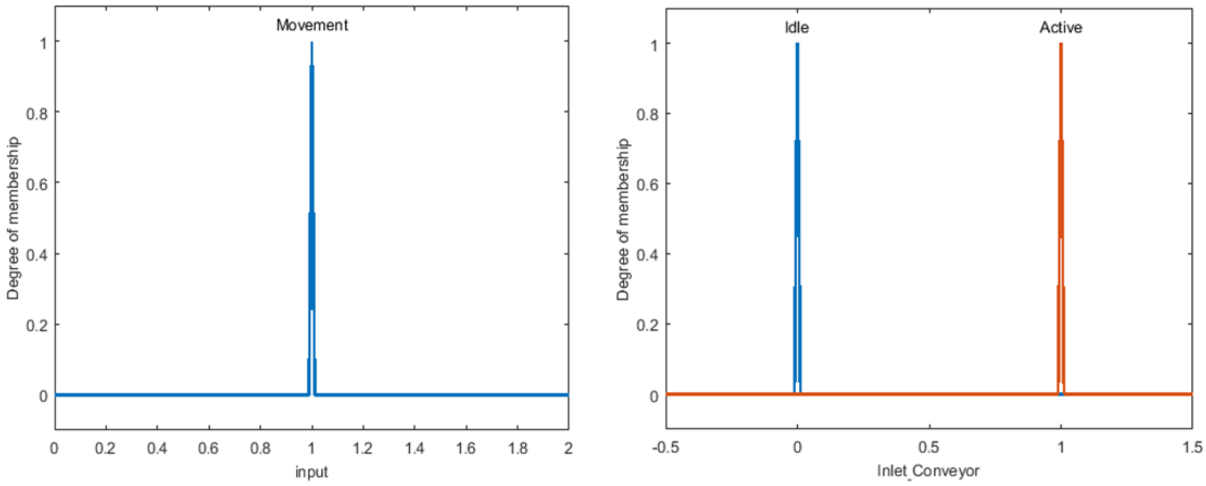


Fig. 10 Sensor block of the smart motor control system for the FLC.



(a) input (b) output

Fig. 11 Fuzzification of input and output variables.

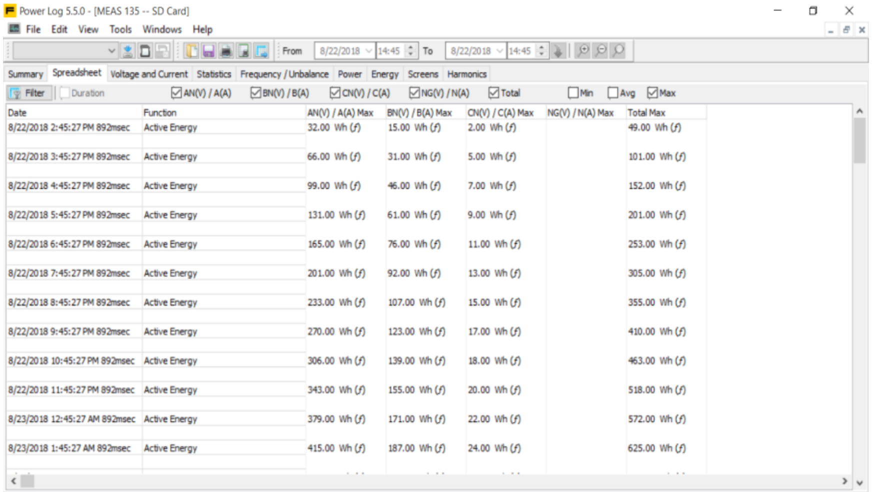
Table 8 Rules relating the input and output variables.

Input \ Output	Conveyor motors
No movement	Idle
Movement	Active

4 Results and Discussion

The captured data, from the energy analyzer setup, saved in the secure digital card (SD card) were retrieved through the fluke power log software and the results can be seen on Fig. 12 which shows the energy consumption (kWh) with respect to time.

The daily consumption profile chart for phases 1-3 of the packaging line's case sealing section of the plant and the sum of all three phases of power supply are shown in Figs 13-16, respectively.



Power Log 5.5.0 - [MEAS 135 -- SD Card]

Date	Function	AN(V) / A(A) Max	BN(V) / B(A) Max	CN(V) / C(A) Max	NG(V) / N(A) Max	Total Max
8/22/2018 2:45:27 PM 892msec	Active Energy	32.00 Wh (ƒ)	15.00 Wh (ƒ)	2.00 Wh (ƒ)		49.00 Wh (ƒ)
8/22/2018 3:45:27 PM 892msec	Active Energy	66.00 Wh (ƒ)	31.00 Wh (ƒ)	5.00 Wh (ƒ)		101.00 Wh (ƒ)
8/22/2018 4:45:27 PM 892msec	Active Energy	99.00 Wh (ƒ)	46.00 Wh (ƒ)	7.00 Wh (ƒ)		152.00 Wh (ƒ)
8/22/2018 5:45:27 PM 892msec	Active Energy	131.00 Wh (ƒ)	61.00 Wh (ƒ)	9.00 Wh (ƒ)		201.00 Wh (ƒ)
8/22/2018 6:45:27 PM 892msec	Active Energy	165.00 Wh (ƒ)	76.00 Wh (ƒ)	11.00 Wh (ƒ)		253.00 Wh (ƒ)
8/22/2018 7:45:27 PM 892msec	Active Energy	201.00 Wh (ƒ)	92.00 Wh (ƒ)	13.00 Wh (ƒ)		305.00 Wh (ƒ)
8/22/2018 8:45:27 PM 892msec	Active Energy	233.00 Wh (ƒ)	107.00 Wh (ƒ)	15.00 Wh (ƒ)		355.00 Wh (ƒ)
8/22/2018 9:45:27 PM 892msec	Active Energy	270.00 Wh (ƒ)	123.00 Wh (ƒ)	17.00 Wh (ƒ)		410.00 Wh (ƒ)
8/22/2018 10:45:27 PM 892msec	Active Energy	306.00 Wh (ƒ)	139.00 Wh (ƒ)	18.00 Wh (ƒ)		463.00 Wh (ƒ)
8/22/2018 11:45:27 PM 892msec	Active Energy	343.00 Wh (ƒ)	155.00 Wh (ƒ)	20.00 Wh (ƒ)		518.00 Wh (ƒ)
8/23/2018 12:45:27 AM 892msec	Active Energy	379.00 Wh (ƒ)	171.00 Wh (ƒ)	22.00 Wh (ƒ)		572.00 Wh (ƒ)
8/23/2018 1:45:27 AM 892msec	Active Energy	415.00 Wh (ƒ)	187.00 Wh (ƒ)	24.00 Wh (ƒ)		625.00 Wh (ƒ)

Fig. 12 Energy consumption data retrieved from power log software.

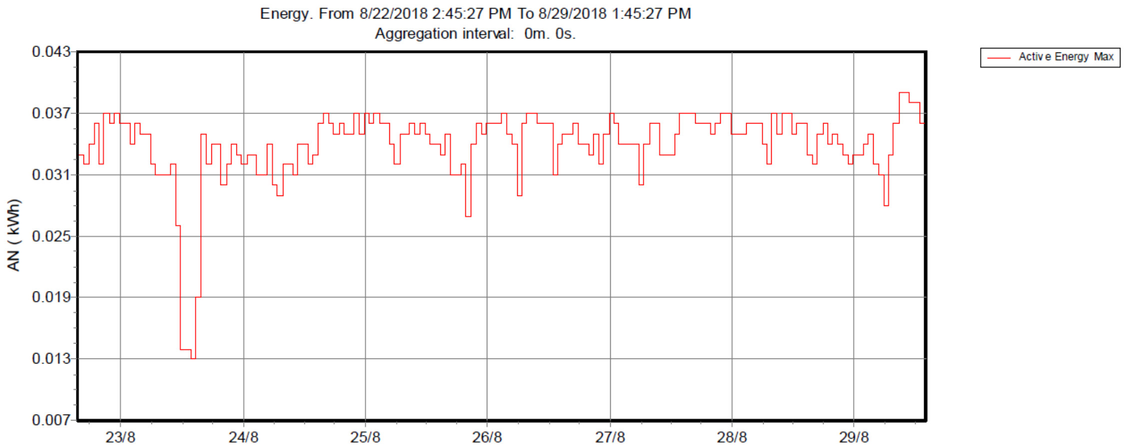


Fig. 13 Daily energy consumption chart for phase 1.

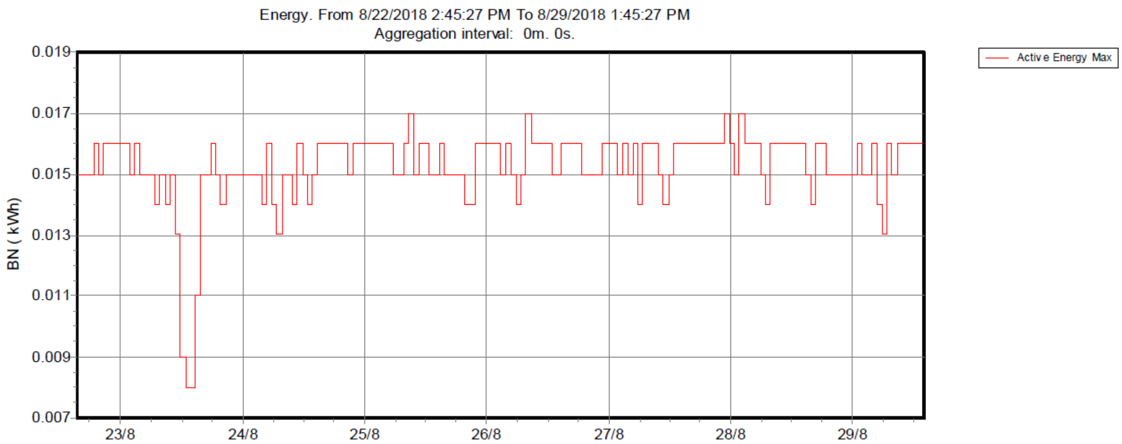


Fig. 14 Daily energy consumption chart for phase 2.

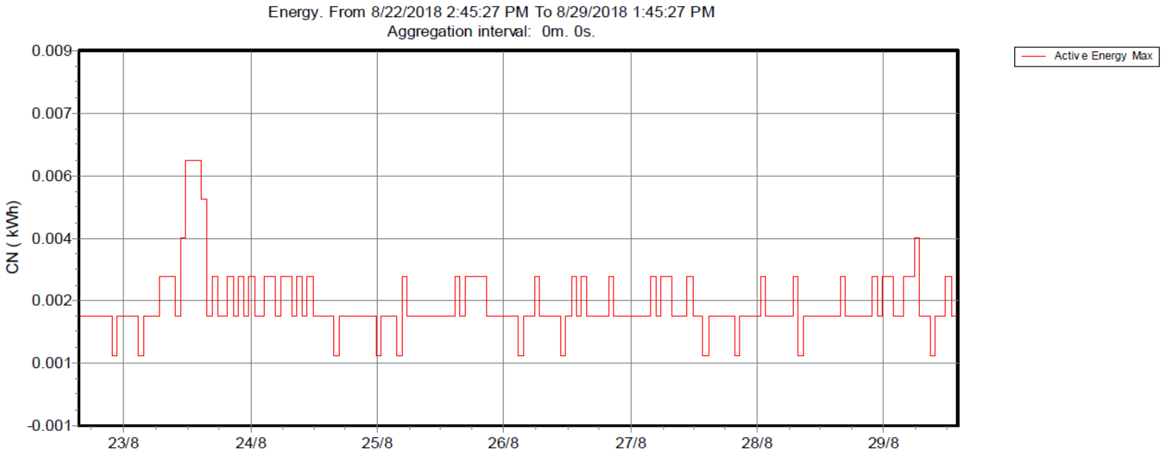


Fig. 15 Daily energy consumption chart for phase 3.

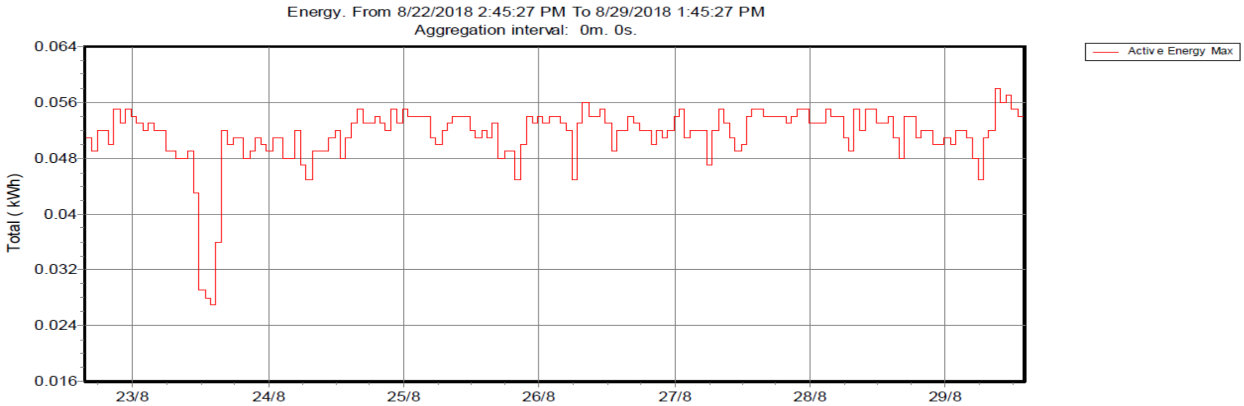


Fig. 16 Daily energy consumption chart for the sum of the three phases.

Table 9 Active and idle time based on the implementation of PLC and FLC on conveyor motors

Reference time [s]	Programmable Logic Control		Fuzzy Logic Control	
	Running time [s]	Idle/Saved time [s]	Running time [s]	Idle/Saved time [s]
60	28.72	31.28	20.07	39.93

The charts depict inconsistency in energy consumption which is why control strategy must be implemented. The estimation of the energy consumed, when idle time has been eliminated, shows that up to an average of 66.7% of electrical energy savings in the case sealing section can be achieved. This percentage value is obtained by using any of the rows of Table 5 with (22) which results in (23).

$$\text{Savings}\,[\%] = \frac{273.3316}{410} \times 100\% = 66.7\% \tag{23}$$

The ultimate goal is to make sure the controller maximizes energy savings as much as possible. Therefore, Table 9 shows the time saved based on simulations of the ladder program by the PLC using the PLCxlogic software and the FLC using the MATLAB/Simulink software.

Table 9 presents the time saved by each control strategy when implemented with the conveyor motors. Controller efficiency is obtained using (24).

$$\text{Efficiency} = \frac{\text{Controller Output}}{\text{Expected Output}} \times 100\% \tag{24}$$

The expected output in this case is the saved time obtained based on observations in production plant (Table 3). For a reference time of 60 seconds, the saved times by the controllers, as seen in Table 9, indicate that the PLC ladder diagram is 78.2% efficient while the FLC is 99.83% efficient. As a result of this, the real time implementation of either controller will yield significant improvements in energy optimization. Babatunde *et al.* [22] established that energy efficiency reduces the cost of energy. Taking into perspective the production plant’s energy consumption in the year 2017, the implementation of the controllers would have resulted in the monthly savings shown in Fig. 17.

As already established, the FLC yields more energy savings than the PLC which is further confirmed in Fig. 17. Using (22), the PLC saved 52.16% energy in the packaging line’s case sealing section while the FLC saved 65.59%. This, thus, results in energy savings in

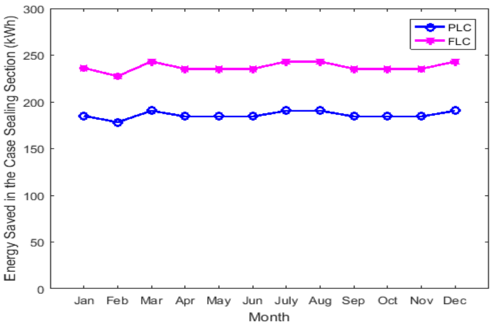


Fig. 17 Controllers' saved energy for 10-line packaging section.

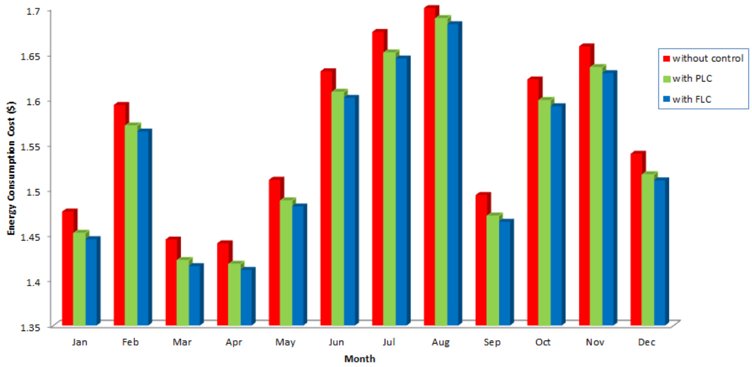


Fig. 18 Monthly energy consumption cost per ton of production without and with control.

the plant's overall energy consumption; 0.103% and 0.132% for the PLC and FLC respectively. Reduction in energy consumption reduces cost of production. Fig. 18 shows the monthly cost (in US Dollar) of energy consumed per ton of production without control and by introducing the PLC and FLC.

From Fig. 18, the implementation of the controllers results in improvement of the overall energy savings and reduction in cost of energy consumption in the plant. As of March, 2019, the price of electricity in Nigeria is 0.07 US Dollar (25.38 Nigerian Naira) per kWh. An electrical energy saving of 2804 kWh from a total of 2156771kWh results in saving 196.28 US Dollar (71,151.50 Nigerian Naira). It should be noted that the conversion rate used is 362.50 Nigerian Naira for every US Dollar (valid on 13th September, 2019).

The process of implementing these changes should take a maximum of 12 hours per packaging line, in which one line must be completed before moving to the next line. With this, the downtime in the system is reduced. As earlier outlined, the total number of packaging lines is 10 and the needed devices/components for the changes per packaging lines are: proximity sensors, compact PLC, AL220 integrated circuit chips, 24V DC supply, 24V DC electrical control relay, cables and other accessories for electrical connections. During the implementation stage, production process is only affected at the packaging case sealing section for one out of the 10 lines at a time. Thus, any unsealed case can be mopped up at the remaining nine packaging lines during their idle time.

Based on the required devices/components, the budget for the implementation of the proposed control procedure for the 10 packaging lines is estimated to not exceed 150 US Dollar (54,375 Nigerian Naira). In order to establish that the control procedure would deliver a positive net present value to the industry, the benefit-cost ratio (BCR) is calculated using (25).

$$BCR = \frac{PV_{benefits}}{PV_{cost}} \tag{25}$$

where $PV_{benefits}$ is the present value of benefits and PV_{cost} is the present value of cost.

As seen in Fig. 18, the electrical energy savings for a period of one year translates to a saving of 192.26 US Dollar; this is taken as the present value of benefit. On the other hand, the present value of cost is the value of the cost for implementation of the control procedure which, as earlier mentioned, is estimated to be at 150 US Dollar. Therefore, all things beings equal, for a period of one year, the BCR is 1.33. Since the BCR is greater than one, it indicates that the implementation of the control procedure will yield a positive net value to the industry. From this, it is evident that reduction in energy consumption will lead to an overall reduction in costs of production.

In summary, the low-cost and without-cost energy efficiency suggestions that could be implemented to reduce the total cost of production include:

- The use of proximity sensors for the detection of the presence of carton casing. This would prevent continuous operation of the motors during idle time.
- The use of control relays to prevent and protect the controllers from being damaged through any form of excessive current in cases where the conveyor motors become faulty. This reduces maintenance cost and hence, overall production cost is reduced.
- Operators should pay attention to stand-alone conveyor motors; they should be stopped during production shutdown to further reduce production costs.
- Immediate engineering intervention by technicians to correct any form of friction and mechanical overload to avoid further damage to other devices.

5 Conclusion

Control strategy for energy consumption has been proposed for the food and beverage industry in this study. In the course of implementing the control strategies, the following findings were discovered:

1. With the application of regression analysis, the

analyzed data of the plant under study was estimated to be reasonably predicted with a coefficient of determination of R^2 = 35%. This indicates that 35% of variance in energy consumption was predicted from production, in tons. Also, the regression analysis of the observed optimal energy consumption was forecasted for a period of one year and the coefficient of determination was deduced to be R^2 = 99%.

2. An average electrical energy savings of 66.7% was calculated possible based on observation in the packaging line's case sealing section of the plant. Upon implementing the FLC and PLC, the packaging line's case sealing section resulted in 52.16% and 65.59% energy saving for the PLC and FLC respectively. Taking the overall production plant into perspective, electrical energy savings of 0.103% and 0.132% were achieved.

Though the PLC resulted in lower energy savings when compared with the FLC, its use nonetheless, will reduce production costs [23, 24]. On the other hand, the FLC, with an efficiency of 99.83%, guarantees a yearly savings of approximately 2804 kWh from a total of 2156771 kWh. Considering the gathered results from the plant under study, it is necessary to implement control strategy in order to achieve great energy savings in the food and beverage industry. Also, it should be noted that heat is another major energy-consuming part in industries; future research efforts will be dedicated to exploring the effects of heat losses on the manufacturing activities and how this can be minimized to save energy.

Acknowledgments

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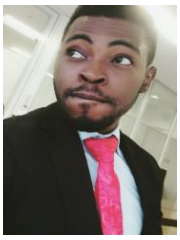

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