

MULTIPARAMETRIC SIMULATION OPTIMIZATION OF AN IMPROVED SMALL HOLDING SOAP STAMPING-TABLETING MACHINE

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ABSTRACT

The performance of a Soap Stamping-Tableting was quantified and optimized in this study to response surface methodology. The operational parameters evaluated were conveying speed, stamping and tableting speed, and time of operation while the tableting efficiency, throughput and specific energy consumption of the machine constitutes the responses variables. Response surface analysis was employed and the initial linear models developed augmented to quadratic models when it was established using the analysis of variance (ANOVA) and residual plots to estimate the performance of the soap stamping and tableting machine. The developed quadratic models were used to optimize the performance of the soap stamping and tableting machine using the D-optimality approach to establish the optimal factor settings of the soap stamping and tableting machine rounding up to the nearest whole number values are 351rpm, 21rpm, 55 minutes and an overall D-optimality value of 96 for the conveying speed, stamping and tableting speed and time of operation respectively. This soap stamping and tableting machine plays a crucial role in poverty alleviation and enhancing food security, directly contributing to Sustainable Development Goal (SDG) number 1: Zero Hunger. By efficiently manufacturing and packaging soap, this machine enables the creation of small-scale soap businesses, providing income-generating opportunities for individuals in impoverished communities. The resulting economic empowerment helps lift people out of poverty, addressing the root causes of hunger. Additionally, improved hygiene through widespread access to affordable soap contributes to better health outcomes, further supporting the overarching goal of eradicating hunger and promoting sustainable development.



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1. INTRODUCTION

Soap remains a vital aspect of contemporary life, utilized medically, for laundry, household sanitation, and individual cleanliness (Ajao et al., 2011). As such, it is an

essential item for maintaining good personal hygiene. Soap is a fatty acid salt, produced globally by treating vegetable or animal oils and fats like palm oil, coconut oil, olive oil, and laurel oil with a potent alkaline solution (Aiwizea & Achebob, 2012; Konkol & Rasmussen,

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2019). The soap production process is known as saponification or the basic hydrolysis reaction of fat or oil. Currently, either sodium hydroxide (NaOH) or sodium carbonate is used to make the fatty acid neutral and convert it to salt (Arasaretnam & Venujah, 2019).

Soap is created in three forms, namely bar, powder, and liquid (Ti, 2019; Warra, 2016). In African regions, the process of soap creation involves three different scales namely small, medium, and industrial (large) production (Nwankwojike, 2012). The industrial manufacturing of soap involves a steady process that necessitates a continual input of fat and the extraction of by-products (Chupa et al., 2017). Small to medium scale manufacturing of soap employs conventional manual batch and partial mechanization techniques (Taiwo et al., 2000; Obibuzor et al., 2012).

In countries like Uganda and the rest of Africa, soap is a commonly utilized consumer product, second only to salt and cooking oil (KPMG Africa, 2015). The soap-making business in Nigeria is a profitable venture which has attracted a lot of entrepreneurs due to the easy availability of raw materials, primarily palm oil, across most parts of the country (Akanle & Adewusi, 2023). A significant portion of Ugandan palm oil is located in Lake Victoria's islands (Natawidjaja et al., 2015). More than 20,000 hectares in these regions are dedicated to palm oil tree plantations by Business and Industrial Development Corporations (BIDCO). and an increasing amount of wealthier out-growers (Bigirwa, 2018; Ssemmanda & Opige, 2018). Ideally, bar soap is the most popular form of soap in Uganda (Nakaweesi, 2018). It is a low-cost cleaning detergent that is found in most homes (UNBS, 2011). Mukwano Industries and BIDCO Uganda are the main producers of laundry bar soap supplying over 37 million consumers on daily basis (UBOS, 2016). This is because the majority of the local investors are small and medium-scale processors, employing mostly manual and semi-mechanized production methods.

Soaps are produced in different shapes, sizes, colours and qualities/grades depending on their specific uses and manufacturer (Gatti, et al., 2014). However, soaps created by different manufacturers could have different identical shapes and sizes particularly as each manufacturer has a unique mould representing their trademark. Hence, it is always difficult to differentiate soaps of the same features produced by different manufacturers when there is no brand imprint on them. Oluka et al. (1999), said that trademark is made on products by manufacturers to distinguish the products from that of other manufacturers and that it is useful for companies producing high quality merchandise since shoppers typically patronize their product even while not testing. Registration of trademark uniquely distinguishes manufacturer products from deterrent. Furthermore, large scale soap manufacturers register some unique shape of their products as trademark and print their logo in the body of the products to enable product identification even when it is not packaged or covered with the company's label. Generally, manual process of soap stamping printing of identification marks and

tableting shaping and sizing of factory-made soaps are wiped out by industrial scale machine-controlled producing systems whereas most tiny and a few medium scale soap producers use hand stamps and mould/cutting devices knives for these two operations. A major constraint in soap production for small and medium scale soap manufactures is difficulty in tableting, stamping and shaping for unique product identification. However, in the past, manual method of tableting with a knife edge and stamping with a hand stamp has been developed, but this method is quite laborious, time consuming, lacks precision and consistency and is not commercially viable. On a bid to solve this problem, Eze (2010) developed a manually operated soap tableting and stamping machine (Khurmi & Gupta, 2005). This machine was very tedious to operate, although mechanized, but still faced the same problem confronting the manual method of hand stamping. Consequently, this gave rise to the development of a motorized soap stamping and tableting machine. But none of these machines were able to shape the soap to bring about unique product identification in terms of shape and stamping. Hence this gives rise to the need for the modification and optimization of soap tableting and stamping machine for small and medium scale soap manufactures.

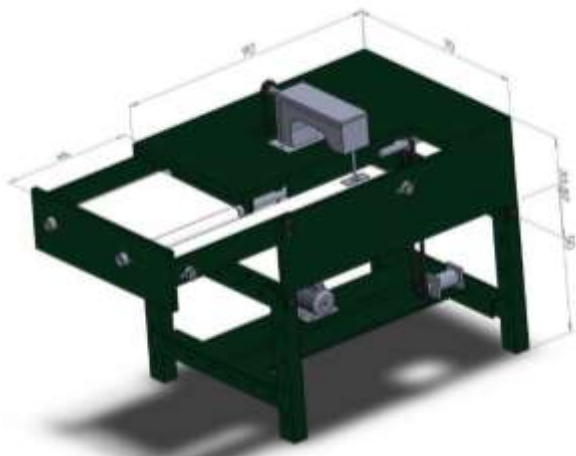
Dunn (2010) customers rate products of small-scale soap producers as inferior even supposing a number of their product are of higher quality than some industrially created ones. In addition, the tedium and drudgery associated with the use of manual devices for soap tableting and stamping by small scale producers make production of soap at this level uneconomical and unattractive to entrepreneurs, despite the huge market prospect of this sector in Nigeria. This soap stamping and tableting machine plays a crucial role in poverty alleviation and enhancing food security, directly contributing to Sustainable Development Goal (SDG) number 1: Zero Hunger. By efficiently manufacturing and packaging soap, this machine enables the creation of small-scale soap businesses, providing income-generating opportunities for individuals in impoverished communities. The resulting economic empowerment helps lift people out of poverty, addressing the root causes of hunger. Additionally, improved hygiene through widespread access to affordable soap contributes to better health outcomes, further supporting the overarching goal of eradicating hunger and promoting sustainable development. Preliminary performance testing of this machine indicates its conveying speed, stamping and tableting speed and time of operation affects its three performance parameters similarly at the same level. In other words, high levels of these three operational parameters results to high values of the three performance indicators. It is desired to operate this machine with maximum efficiency and throughput, and minimum specific energy consumption possible. For this reason, it is of economic sense to apply a multi-response optimization technique that uses small number of experimental runs to evaluate the effect of all these factors simultaneously (instead of one-factor-at-a-time

experimental approach which is time consuming and costly) to determine the optimal settings of these operational parameters that will satisfy these three responses.

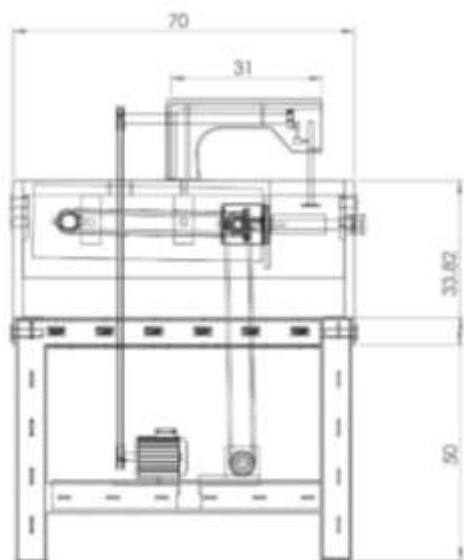
2. MATERIALS AND METHODS

2.1 System Description

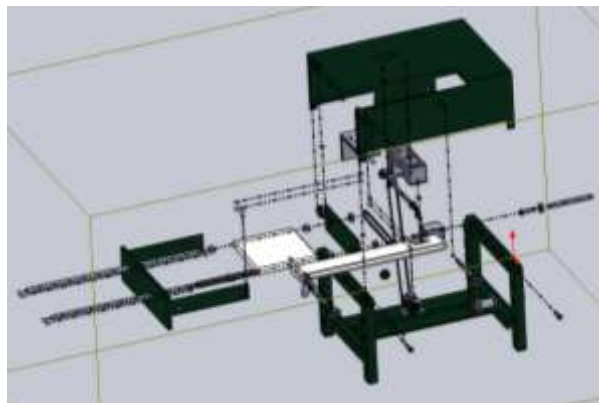
The soap stamping and tableting machine comprises of a frame, loading tray, conveying unit, stamping/tableting unit, sensors, contactors, digital counter, on/off controls, bearing housings, 2 electric motors and collection tray. The frame is the main supporting structure upon which other components of this machine were mounted. The frame is a welded section fabricated from 2.5mm thick angle iron and 1.5mm thick mild steel plate. The conveying unit of this machine comprise of a single-phase electric motor, conveyor shaft, sensors and rollers, conveyor belt, a V-belt and four pulleys. The electric motor installed on a base made from 2.5mm thick angle iron drives the conveyor shaft via a pulley mechanism.



(a)



(b)



(c)

Figure 1. (a) Isometric View of the modified machine (b) Detailed design drawing of the machine (c) Exploded view

The conveyor shaft is a 25mm diameter mild steel rod and is supported at both ends using ball bearings. The collection tray is a foldable rack attached to the frame for collection of stamped and tableted soaps. The soap conveying belt was installed on the surface of the machine using two rollers with one mounted on the conveyor shaft and the other at a distance in the opposite end of the machine surface (Figure 1).

3. EXPERIMENTAL DESIGN/PROCEDURE

The test performance indicators of the soap stamping and tableting machine are the tableting efficiency, throughput, and specific energy consumption. The tableting efficiency as expressed in Equation 1 by (Nwankwojike, 2012) is the total mass of well stamped/tableted soap by the machine to mass of scrap stamped.

$$\eta(\%) = \frac{N_g}{N_T} \times \frac{100}{1} \quad (1)$$

Where,

N_T = total mass of well stamped/tableted, kg.

N_g = mass of scrap stamped, kg

The throughput is the total mass of well stamped and tablet discharged by the machine per unit time as expressed by Equation 2.

$$TP = \frac{N_T}{t} \quad (2)$$

Where,

TP = throughput capacity, kg/s.

N_T = total mass of well stamped and tablet, kg.

t = time of operation, mins.

The specific energy consumption of the machine is the electric power energy consumed per unit mass of soap fed on it as expressed in Equation 3.

$$SE = \frac{P}{N_T} \quad (3)$$

Where,

SE = Specific Energy, kg/s.

P = power consumed by the electric motor, W.

N_T = total mass of soap, kg.

Equations (1-3) are the mathematical relationship used for computing the performance parameters from experimental results. The choice of the experimental design was based on the study objectives, resource availability and source of data collection. Effects of the operational parameters of the soap stamping and tableting machine on the performance parameters – tableting efficiency ($\eta_{\%}$), throughput (TP) and specific energy consumption (SE) were studied. MINITAB version 19 was used to generate and randomize a two coded level (+1 and -1) factorial design layout in which “+1” and “-1” indicate the high and low level of the factors respectively with “0” as the midpoint of the factors. Thereafter, the actual high and low levels of the operational factors being investigated was determined from experimental tests.

A two-level half factorial design ($nf = 2^{k-1}$) was employed in this study and the choice of this factorial design layout is because of its economic viability, desirable properties, orthogonality and it permits marginally small experimental runs to be analyzed for high factorial points. Experimental study variable number ($K = 3$), for independent variables considered are the conveying speed (CS), stamping and tableting speed (STS), time of operation (T) were used for the design and analysis of the results.

Table 1. Response surface design layout

StdOrde r	RunOrde r	Coded values of factors		
		x1	x2	x3
15	1	0	0	0
18	2	0	0	0
14	3	0	0	1
17	4	0	0	0
8	5	1	1	1
10	6	1	0	0
13	7	0	0	-1
19	8	0	0	0
7	9	-1	1	1
9	10	-1	0	0
2	11	1	-1	-1
6	12	1	-1	1
16	13	0	0	0
11	14	0	-1	0
20	15	0	0	0
12	16	0	1	0
5	17	-1	-1	1
1	18	-1	-1	-1
3	19	-1	1	-1
4	20	1	1	-1

The responses of tableting efficiency (η), throughput (TP) and specific energy consumption (SE) were computed from the results of the factorial runs using the coded factor levels to first fit coded linear functions (main effects) of the performance indicators and the operational variables of the machine using MINITAB.

A central composite design was employed in this study to predict response surface models with quadratic effects and two factor interaction for the tableting efficiency (η), throughput capacity (TP) and specific energy consumption (SE) with respect to the operational parameters. The response design comprises two level factorial points (-1, 1), center points (0) and axial points (- α , α) for each independent variable. The number of experimental runs was determined from

$$n = 2^{k-q} + n_c \tag{4}$$

Where n_c is the number of centre points ($n_c = 2$), k is the number of factors in the design (i.e 3) q is the number of fractions ($q = 1$) and the number of experimental runs is $n = 20$ Hence the response surface design table for the soap stamping and tableting machine study is given in Table 1.

The response surface design layout generated (Table 1) was used to develop a linear model for the tableting efficiency (η), Throughput (TP) and specific energy consumption (SE) of the form:

$$y_m = f(x_1, x_2 \dots x_k) + \epsilon_m \tag{5}$$

Where y represents the responses in their natural units, m is the number of responses in the design, x represents the factors in their coded forms, k is the number of factors and ϵ is the error (also known as residual). The first order response surface model was subsequently approximated with a regression equation of the form (Myers et al., 2016):

$$Y = \beta_0 + \sum_{j=1}^k \beta_j x_j + \sum_{j < i=2}^k \beta_{ij} x_i x_j \tag{6}$$

Where “ Y ” is the predicted response; β_0 , the constant (intercept); β_i , the linear coefficient and β_{ij} , the cross-product coefficient. X_i and X_j are the coded independent variables.

The coefficient of determination, R^2 and adjusted coefficient of determination, $adj - R^2$ for each of the response models was determined so as to know how properly the models fit the measured data. The values of R^2 lies between the zero and one (i.e $0\% \leq R^2 \leq 100\%$) and the more the value of R^2 approaches one (1), the better the estimated model fits the data. Residual is the difference between the respective observed responses and their model predicted values. If a model is adequate, the points on the normal probability plots of the residuals will form a straight line. The plots of the residuals versus run order and that of residuals versus fitted response should exhibit scatter feature without any obvious pattern (i.e. structureless) while histogram of the residuals is expected to portray dumb-bell shape. The significance of each model term was analyzed using the $t - statistics$. If $|T|_{cal} > T_{tab}$, then the corresponding factor or term is

said to be statistically significant and T_{tab} is obtained using statistical table.

The analysis of variance was employed in testing the adequacy of the fitted models to be true approximations of the measured data. If the calculated value of F – statistic (F_{cal}) for each of the fitted models exceed the tabulated value of F – statistic (F_{tab}) i.e $F_{cal} > F_{tab}$ and $P - val < \alpha$, the fitted models are said to be adequate approximation of the data for the performance parameters of the soap stamping and tableting machine, however if reverse of the above statement is the case; $F_{cal} < F_{tab}$ and $P - val > \alpha$, then the models are inadequate to fit the data. The models lack of fit test will also be conducted to check the goodness of fit of the predicted models for the measured data. If the calculated value of F – statistic (F_{calLOF}) for each of the fitted models exceed the tabulated value of F – statistic (F_{tabLOF}) i.e $F_{calLOF} > F_{tabLOF}$ and $P - val < \alpha$, the fitted models are said to exhibit insignificant lack of fit for the fitted data of the performance parameters of the soap stamping and tableting machine, however if reverse is the case; $F_{calLOF} < F_{tabLOF}$ and $P - val > \alpha$, then the models are said to exhibit significant lack of fit. The residual analysis of the models was conducted, graphically and statistical significance of each model term was tested at 95% significance level. Insignificant terms were eliminated from the models using stepwise model building approach. The confirmation trials were conducted using the same procedure as in the determination of the factor levels. The tableting efficiency (η), Throughput (TP) and Specific energy consumption (SE) of the machine were predicted based on various factor combinations of confirmation experimental plan using point prediction capability of MINITAB. A multiple response optimization model was formulated using Desirability function approach.

The limits of the operational factors investigated were determined from experimental tests of factor variations with performance parameters. The actual high and low levels for each factor was selected based on non-variation of the responses or indicated asymptote behaviour of the responses before or after some combination of the variables. The tableting efficiency, throughput and specific energy consumption of the machine were evaluated at each combination of the variables by feeding a known mass of soap into the machine for stamping and tableting. After each operation, the stamping and tableting time involved was taken using stop watch and weighed using electronic digital balance of 0.01g accuracy, the power consumed by the motor during operation was measured with a clamp wattmeter.

4. RESULTS AND DISCUSSIONS

The result of the experimental runs on the experimental plan for factor combination is given in Table I
The second order model for predicting conveying speed of the machine (CS), stamping and tableting speed (STS), and time of operation (M) with the actual values of the

modified soap stamping and tableting machine responses in their original/natural units are given by equations (1)-(3):

$$\eta = -3661 - 7.5 CS + 390 STS - 47.2 M + 0.0029 CS * CS - 9.95 STS * STS + 0.797M * M + 0.459 CS * STS - 0.2046 CS * M + 1.61 STS * M$$

(7)

$$TP = 79224 + 424 CS - 8135 STS - 1064 M + 0.535 CS * CS + 208.3 STS * S - 0.48 * M - 22.06CS * STS - 2.14CS * M + 58.1STS * M$$

(8)

$$SE = -2930 - 11.53 CS + 319 STS - 5.1 M - 0.01141 CS * CS - 8.49 STS * STS - 0.141 M * M + 0.584 CS * STS + 0.0187 CS * M + 0.37 STS * M$$

(9)

The two-level half factorial design with center points and axial points totaling thirty-two (20) experimental runs with an axial point value of (± 1.68) which allowed analysis of second order (quadratic) interactions of the initial linear designs was used to develop quadratic models for the soap stamping and tableting machine responses. The quadratic models are shown in equations (7 – 9).

Table 2. Coefficient of determination and error standard deviation of the quadratic models

Responses	S	R-sq	R-sq(adj)	R-sq(pred)
η	2.80732	82.92%	67.56%	31.04%
TP	32.9540	98.01%	96.22%	81.14%
SE	1.62774	99.31%	98.69%	92.26%

Also, the models for tableting efficiency, throughput and specific energy exhibited significant lack of fit. Hence, these models will be further reduced by eliminating the insignificant factors in the model terms while maintaining hierarchy of the model equation using the stepwise elimination method. Those statistically insignificant terms are eliminated from the model as shown in Equations (7 – 9) while the coefficient of determination and error standard deviation of the quadratic models are shown in Table 2.

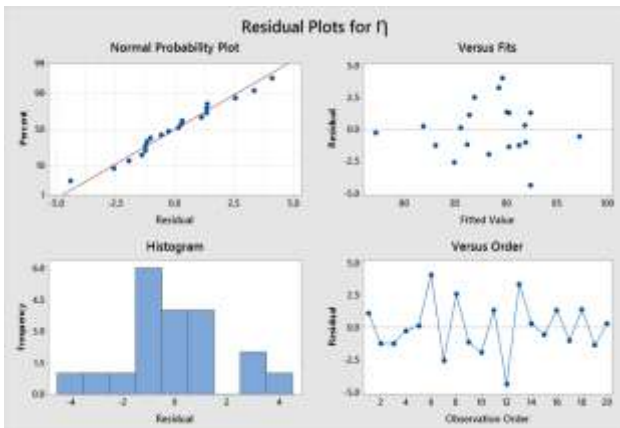


Figure 2: Residual plots for quadratic model of the tableting efficiency

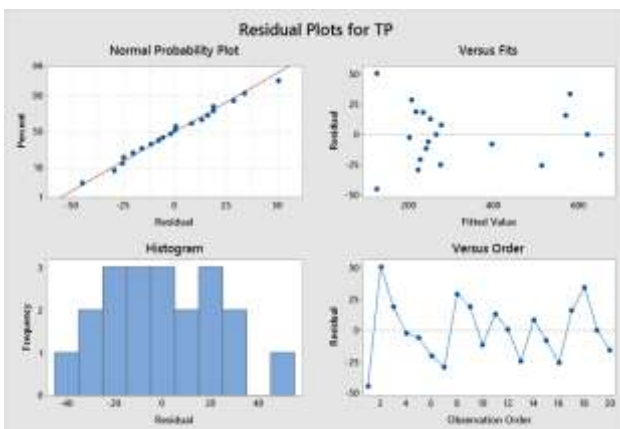


Figure 3: Residual plots for quadratic model of the throughput

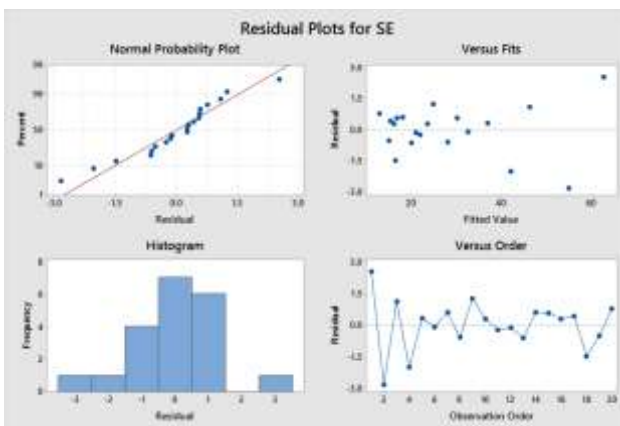


Figure 4: Residual plots for quadratic model of the specific energy

The introduction of the quadratic terms improved the adequacy of the models and the plots of the normal probability tends to fall in a straight line and the histogram gives the required dumb bell shape, hence, the quadratic models are adequate to statistically fit the data with little outliers and reduced skewness.

The table of model confirmatory test shown in the table 3 indicated that the fitted functions were good fits for the soap and tableting machine responses and can be used for the optimization of the machine with the predicted values

having a percentage error of plus and minus five percent ($\pm 5\%$)

Table 3: Model confirmatory test result

Variables	Setting			
CS	350.822			
STS	21			
M	55			
Responses	Fit	SE Fit	95% CI	95% PI
SE	-31.1	37.0	(-109.7,47.4)	(-110.3,48.0)
TP	6365	364	(-137,1409)	(-143,1415)
η	91.3	37.0	(13.0,169.7)	(12.4,170.3)

The response surface plots are used to describe the potential relationship between three variables. The predictors are plotted in the x- axis and y- axis while the response variable is represented in the z- axis. The contour plots can be represented with shaded area or contour lines as shown in the figures 2, 3 and 4. A contour plot provides a two-dimensional view of the surface where the points that have the same response are connected to produce contour lines of constant responses. Contour plots are useful for establishing the response values and operating conditions that are desirable while the surface plots provide a more vivid concept of the response surface than the contour plots.

Optimization using the contour and surface plots can be used to estimate the optimal relationship between each of the responses and any combination of the factors. Only statistically significant terms were considered in the plots and the topography of each plot indicates the effect each factor pair has on the response with other factors kept constant. Generally, it is desired that the soap stamping and tableting machine operates at maximum tableting efficiency and throughput and minimal specify energy consumption. In the following contour and surface plots, it will be established which factor settings will give the desired results.

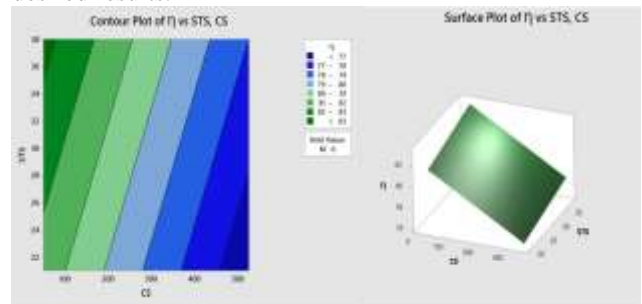


Figure 5: Contour and surface plots of tableting efficiency against STS and CS

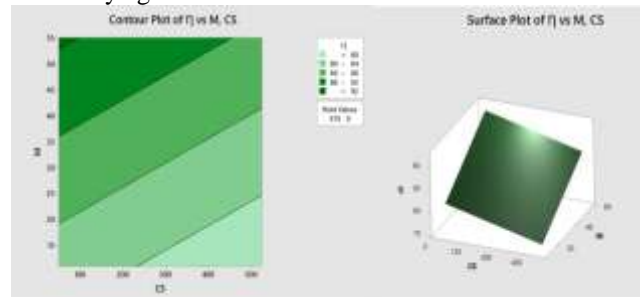


Figure 6: Contour and surface plots of tableting efficiency against M, and CS

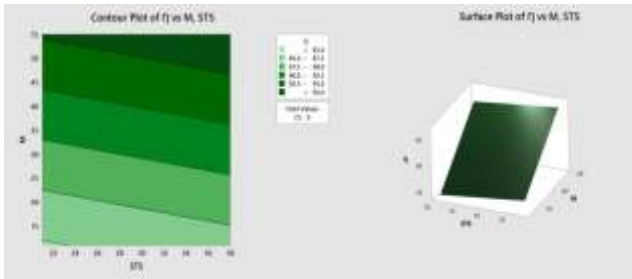


Figure 7: Contour and surface plots of tableting efficiency against M, and STS

Fig. 5, maximum tableting efficiency is obtained at minimum conveying speed of machine (CS) and minimum stamping and tableting efficiency (STS). Figure 6, minimum tableting efficiency occurs at maximum time of operation (M) and a maximum conveying speed. Figure 7, maximum tableting efficiency occurs at minimum time of operation of the machine and stamping and tableting speed. Similar to the tableting efficiency response, it is expected that the machine operates at maximum throughput capacity obtainable.

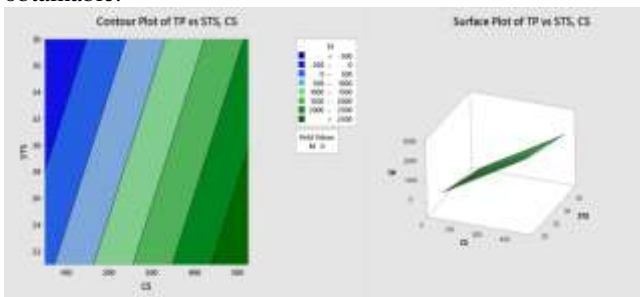


Figure 8: Contour and surface plots of throughput against STS, and CS

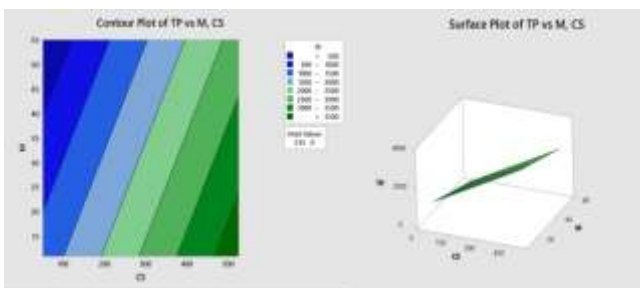


Figure 9: Contour and surface plots of throughput against M, and CS

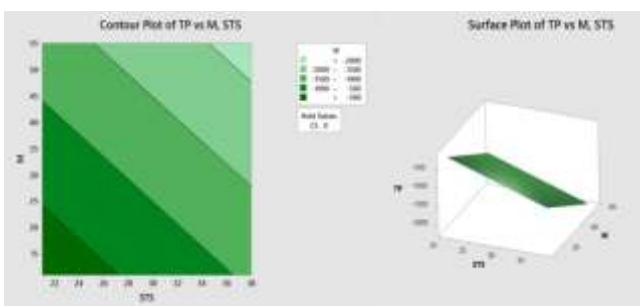


Figure 10: Contour and surface plots of throughput against M, and STS

Figure 8, it was observed that maximum throughput capacity is obtained at minimum stamping and tableting speed of machine (STS) and conveying speed of the machine (CS). Figure 9, maximum TP is obtained at minimum time of operation (M) and minimum conveying speed (CS). Figure 10, maximum throughput is obtained at the low-range of time of operating of the machine (M) and minimum stamping and tableting speed (STS).

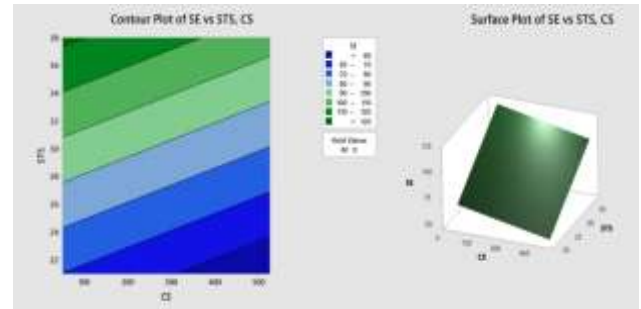


Figure 11: Contour and surface plots of specific energy against STS and CS

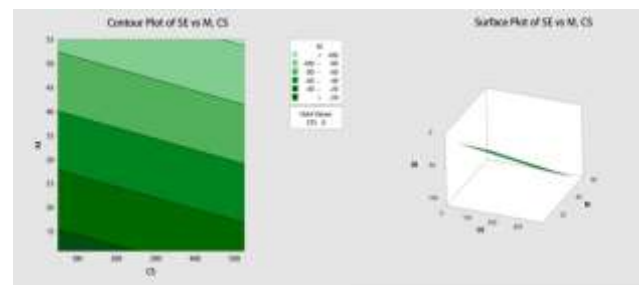


Figure 12: Contour and surface plots of specific energy against M and CS

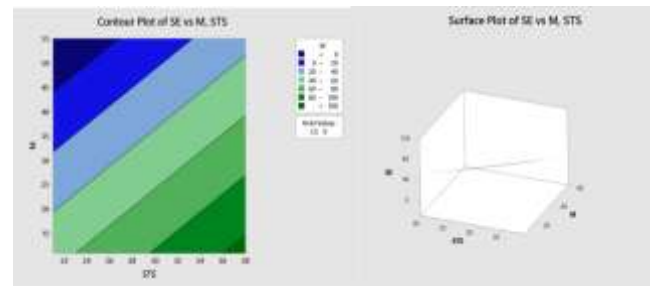


Figure 13: Contour and surface plots of specific energy against M, and STS

In Figure 11, it was observed that the factor combination of stamping and tableting speed and conveying speed required for minimum energy consumption is low-range stamping and tableting speed of the machine (STS) and conveying speed (CS). Figure 12, it was observed that there was a minimum conveying speed (CS) and maximum time of operation (M) as shown in. In Figure 13, minimum specific energy consumption is obtained at minimum stamping and tableting speed of the machine (STS) and minimum time of operation (M). The multiplicity of optimal factor pairs obtained from this technique makes it unreliable because it has led to multiplicity of optimal settings established for one

response. Inspection of the contour plots revealed that for a particular performance parameter, some factor pairs are in the maximum region while others indicate minimum optimal region. The indeterminate tendency of this approach gave rise to the need to adopt a more suitable optimization approach which can define the optimal settings of the operational parameters for all the responses known as the desirability function. Desirability function approach established by Derringer Harrington eliminates the rigor associated with other optimization techniques such as the contour plot

optimization through the application of a multi -response multi -factor optimization technique. It optimizes a set of responses and defines the best factor settings for a solution of a multivariate objective function. The objective of this study is to determine the optimum factor settings of the soap stamping and tableting machine required to obtain maximum tableting efficiency, throughput and minimum specific energy consumption. The response optimizer capability of MINITAB 19 was employed for this purpose and the optimization graph shown in Figure 14.

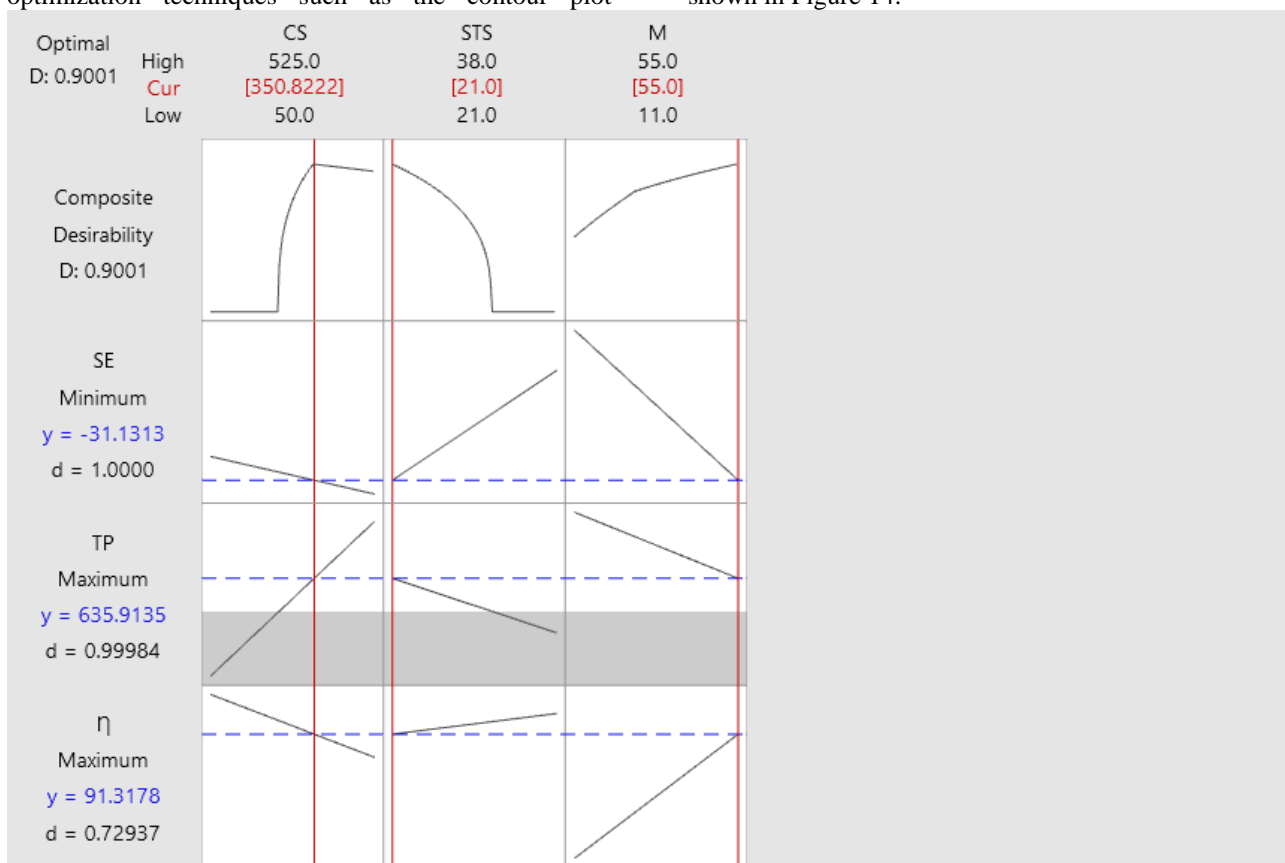


Figure 14: Optimization plot of the soap stamping and tableting machine

The optimization plot of the soap stamping and tableting machine (Figure 14) shows that the optimal factor settings required to obtain maximum tableting efficiency and throughput at minimum specific energy consumption is 351, 21, and 55 for the conveying speed, stamping and tableting speed and time of operation respectively. The optimal response at these factor settings is 91.3%, 6365kg/hr and 31.1kJ/kg at an optimality rate of 73%, 99.9% and 100% for the tableting efficiency, throughput and specific energy consumption respectively with an overall D-optimality value of 96%. This soap stamping and tableting machine plays a crucial role in poverty alleviation and enhancing food security, directly contributing to Sustainable Development Goal (SDG) number 1: Zero Hunger. By efficiently manufacturing and packaging soap, this machine enables the creation of small-scale soap businesses, providing income-generating opportunities for individuals in impoverished communities. The resulting economic empowerment

helps lift people out of poverty, addressing the root causes of hunger. Additionally, improved hygiene through widespread access to affordable soap contributes to better health outcomes, further supporting the overarching goal of eradicating hunger and promoting sustainable development.

5. CONCLUSIONS

Soap stamping and tableting machine was evaluated and optimized with a modified function; to tablet, stamp and shape the soap was designed and developed. The observed improvement in this machine have reasonably reduced improper and faint stamping and completely eliminated the inability to shape the soap for small scale soap producers. Furthermore, the operational parameters evaluated were conveying speed, stamping and tableting speed, and time of operation while the tableting

efficiency, throughput and specific energy consumption of the machine constituted the responses or performance parameters. The optimal response at these factor settings was 91.3%, 6365kg/hr and 31.1kJ/kg at an optimality rate of 73%, 99.9% and 100% for the tableting efficiency, throughput and specific energy consumption respectively with an overall D-optimality value of 96%. This soap stamping and tableting machine plays a crucial role in poverty alleviation and enhancing food security, directly contributing to Sustainable Development Goal (SDG) number 1: Zero Hunger. By efficiently manufacturing and packaging soap, this machine enables the creation of small-scale soap businesses, providing income-generating opportunities for individuals in impoverished communities. The resulting economic empowerment helps lift people out of poverty, addressing the root causes of hunger. Additionally, improved hygiene through widespread access to affordable soap contributes to better health outcomes, further supporting the overarching goal of eradicating hunger and promoting sustainable development.

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