



Cost Effective Maintenance and Machine Reliability for Food Manufacturing Industries using Optimal Maintenance Strategy

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

An optimal maintenance strategy for cost effective maintenance and machine reliability in food manufacturing industries was developed in this study. Maintenance and cost parameters were employed to develop cost-reliability based model in terms of an optimal maintenance using lingo solver. The developed cost-reliabilitybased model considered system's reliability, cost of equipment failure, preventive maintenance, corrective maintenance and downtime cost associated with - equipment maintenance. A case of a food manufacturing company in Nigeria was observed and the data was used to evaluate the model. It is imperative to know that, the developed optimal maintenance strategy provided better cost savings and improved system reliability than the current maintenance cost and machine reliability of the industrial case study.

Keywords: *Lingo solver; cost effective; cost-reliability parameters; maintenance strategy; optimization; maintenance cost; food manufacturing.*

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1. INTRODUCTION

The main focus for food manufacturers is to improve efficiency and profitability through the reduction of total manufacturing costs by optimizing operation processes and maintenance activities achieved through continuously improved machine reliability and an efficient maintenance strategy. Some studies [1-4], have discussed the economic implications of maintenance as it applies to food manufacturing industries showing how and effective maintenance policy affects productivity and profitability of a manufacturing process.

According to [5] the effective maintenance of food manufacturing component is a vital strategic task given the increasing demand on sustained availability of those components used for manufacturing. This is crucial as sudden failures of these components can be prohibitively expensive because they result in immediate lost production outcome, inefficient quality characteristics and poor customer satisfaction.

Overall the importance of maintenance is ever increasing as a result of the widespread automation of manufacturing systems and the capital expenditure allocated to it, thus making maintenance of manufacturing components an investment opportunity to be maximized and not a cost center [6] While the economic downturn continuously drives manufacturing organizations to seek for more efficient strategies to manage

maintenance, globalization has increased the pressure on organizations and companies to operate in the most efficient and economical way. This predisposition promotes that companies concentrate immensely on their core businesses, outsource less profitable departments and services to reduce costs [7]. However, only a few have the internal resources to implement such practical culture [8]. Hence the aim of this study is to develop an optimal maintenance strategy for cost effective maintenance and machine reliability in food manufacturing industries.

1.1 Problem Statement

The organization under study runs a computerized manufacturing process for the manufacturing and processing of noodles for human consumption. This organization adopts corrective maintenance as its preferred maintenance strategy only, which can be described as a reactive, fire fighting strategy. The information obtained from the maintenance team of the organization was that most faults and failures can be fixed manually by the maintenance team in a relatively short period of time. But there have been incidents and occasions where breakdowns resulted in long unavailability of the manufacturing physical assets. Also observed was the effect of faults and failures on the manufacturing process as depicted in Fig. 1.

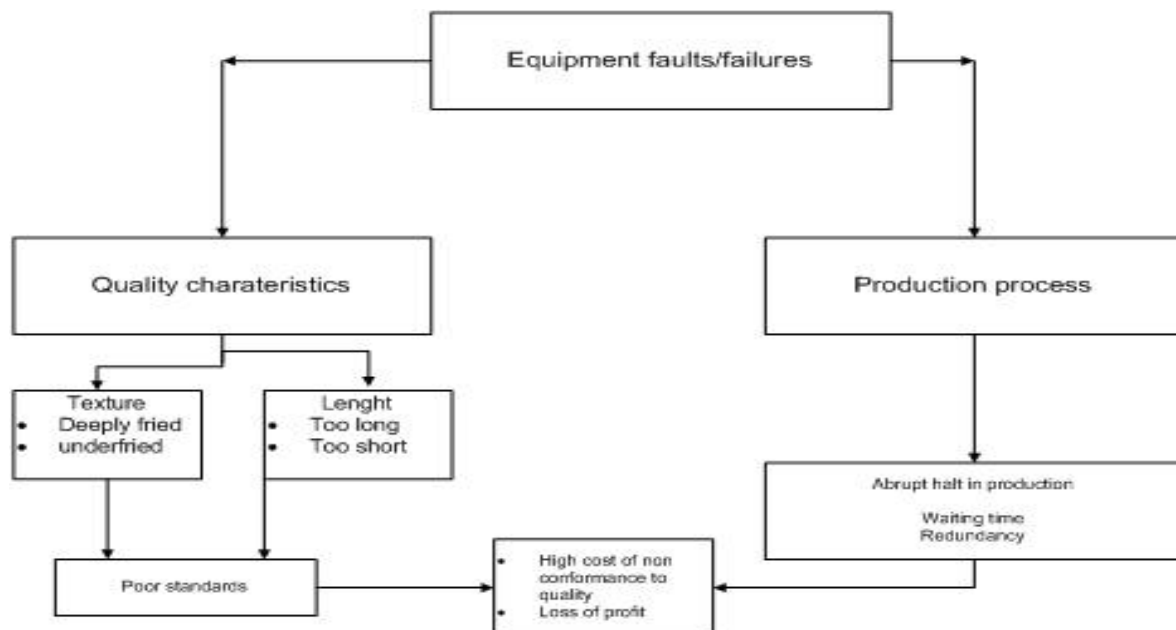


Fig. 1. Faults/failures and implications

The implications observed are in contradiction of the maintenance goals and objectives of the organization which is that in the long run maintenance should ensure equipment availability in order to produce products at the compulsory quantity and quality levels.

2. RESEARCH METHODOLOGY

The relevant data were collected through direct observations of the manufacturing and maintenance processes, for 26,234 hours of equipment faults and failures and equipment cost data for thirty six months. The data were obtained from a food and beverage at Chicason Drive, Umudim, Nnewi, Anambra State, Nigeria.

The optimal method used a cost-based approach to minimize total maintenance cost while assuring the desired improvement of machine reliability. The system was a repairable multi-component system arranged in series with each of the components subject to degradation and follow non-homogeneous Poisson process (NHPP) with an increasing rate of occurrence of failure (t), the following notations of the model are defined:

- N : Number of manufacturing components
- T : Length of planning scope
- J : Number of intervals
- λ : scale parameter (failure function) of component i
- β : shape parameter (improvement/degradation) of component i
- α_{pmi} : Age reduction factor of preventive maintenance on component i
- FC_i : cost of performing maintenance due to failure of component i
- PMC_i : Cost for preventive maintenance for component i

- CRC_i : Cost of corrective replacement for component i
- DC : cost of downtime of the manufacturing system
- RR : Required reliability of the system of components
- $X_{i,j}$: The effective age of component i at the start of period j
- $XX_{i,j}$: The effective age of component i at the end of period j

Assumptions:

- If preventive maintenance is performed on any component, the effective age of the component is reduced by 30% thus the age reduction factor of preventive maintenance on a component i (α_{pmi}) is assigned a fixed value of 0.7.
- The failure of the manufacturing components is characterized by Weibulldistribution
- There is minimum acceptable required reliability of the components
- The skilled and unskilled used for the maintenance are the employees of the company so they are always available.

2.1 Case Study of a Company

The study was carried out in a food and beverage manufacturing company "Tummy Tummy Foods Industries limited" located at Chicason Drive, Umudim, Nnewi, Anambra State, Nigeria. The company majors in the production of edible foods (Tummy Tummy Instant Noodles) for human consumption. The production line is connected in series as illustrated in Fig. 2.

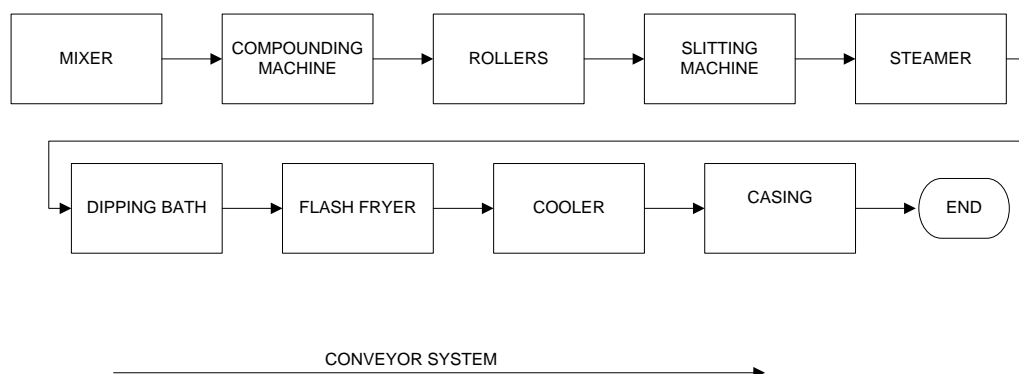


Fig. 2. Illustration of the Production line

2.2 Reliability Parameters

To estimate the shape (λ) and scale (β) parameters in the model, maximum likelihood estimation as illustrated by [9] is applied in this study.

$$\lambda = \frac{\sum_{q=1}^K N_q}{\sum_{q=1}^K T_q^\beta - S_q^\beta} \quad (1)$$

$$\beta = \frac{\sum_{q=1}^K N_q}{\lambda \sum_{q=0}^K (T_q^\beta \ln T_q - S_q^\beta \ln S_q) - \sum_{q=1}^K \sum_{i=1}^{N_q} \ln X_{iq}} \quad (2)$$

Where

K = no of systems,

Sand T = start and end times of observation,

N_q = number of failures on the q th system

X_{iq} is the age of the q th system at the i th failure.

Where shape (λ) and scale (β) parameters represents the slope and location of the failure distribution curve

The parameter λ is used to understand the reliability growth of the system under the following conditions:

- If $0 < \lambda < 1$, the failure/repair rate is decreasing. Thus, system is improving over time.
- If $\lambda = 1$, the failure/repair rate is constant. Thus, system is remaining stable over time.
- If $\lambda > 1$, the failure/repair rate is increasing. Thus, system is deteriorating over time.

2.3 System Cost Function

Taking into account that any maintenance or replacement action that is carried out is associated with cost, the cost of maintenance or replacement of component i at the end of period j include the total sum of failure cost, cost of preventive maintenance, cost of replacement of component and downtime cost.

To calculate for failure cost (FC_i), the expected number of failures for component i in period j the expected number of failures for component i in period j is calculated and multiplied by the cost of failure for component i

$$FC_i = F_i \times [N_{i,j}] \text{ for } i = 1, \dots, N; j = 1, \dots, T \quad (3)$$

Where

F_i = cost of failure for component i

$[N_{i,j}]$ = expected number of failures for component i in period j

From equation 3,

$$[N_{i,j}] = \lambda_i [(xx_{i,j})^\beta - (x_{i,j})^\beta] \text{ for } i = 1, \dots, N; j = 1, \dots, T$$

Therefore

$$FC_i = F_i \times \lambda_i [(xx_{i,j})^\beta - (x_{i,j})^\beta] \text{ for } i = 1, \dots, N; j = 1, \dots, T \quad (4)$$

Cost of preventive maintenance PMC_i refers to the cost incurred while component i is maintained. It includes cost of consumables (CCC_{ij}), cost of condition-based maintenance ($CCBM_{ij}$), and cost of time based maintenance ($CTBM_{ij}$). Where cost of consumables includes the cost of consumable material and equipment used while carrying out preventive maintenance activities such as cost of lubricating oil (CLO_{ij}), cost of component wires (CCW_{ij}), cost of replacement vital parts (screw nuts, belts etc) ($CRVP_{ij}$), cost lubricating grease (CLG_{ij}). The cost of condition-based maintenance includes cost of inspections (CI_{ij}), cost of diagnostic actions (CDA_{ij}), travel cost (CT_{ij}), labour cost (CL_{ij}) and cost of delayed production (CDP_{ij}). While cost of time-based maintenance includes the cost of preventive oil change ($CPOC_{ij}$), cost of equipment material change ($CEMC_{ij}$).

$$\text{Thus } PMC_i = CLO_{ij} + CCW_{ij} + CRVP_{ij} + CLG_{ij} + CI_{ij} + CDA_{ij} + CT_{ij} + CL_{ij} + CDP_{ij} + CPOC_{ij} + CEMC_{ij} \text{ for } i = 1 \dots N; j = 1, \dots, T$$

$$\text{Where } CCC_{ij} = CLO_{ij} + CCW_{ij} + CRVP_{ij} + CLG_{ij} \\ CCBM_{ij} = CI_{ij} + CDA_{ij} + CT_{ij} + CL_{ij} + CDP_{ij} \\ CTBM_{ij} = CPOC_{ij} + CEMC_{ij}$$

$$\text{Thus } PMC_i = CCC_{ij} + CCBM_{ij} + CTBM_{ij} \text{ for } i = 1 \dots N; j = 1, \dots, T \quad (5)$$

Cost of corrective maintenance of component CMC_i is the cost CRC_i incurred when component i is replaced at the end of period j with a new component i . It includes cost of diagnostic actions, Cost of repair actions, Cost and equipment hire and travel expenses, labour cost and administrative cost.

Thus $CMC_i = CDA_{ij} + CRA_{ij} + CEH_{ij} + TEC_{ij} + LC_{ij} + AC_{ij}$ for $i = 1 \dots N; j = 1, \dots, T$ (6)

The cost of downtime of the manufacturing system DC is the cost lost when component i is maintained or replaced at period j

$$DC = DT \times PL \quad (8)$$

Where

DT : Average duration for downtime

PL : estimated profit loss per hour by the company due to downtime.

Thus the total cost of maintenance is the sum of all the cost defined for component i at period j and is expressed as follows:

Total Maintenance cost =

$$\sum_{i=1}^N \sum_{j=1}^T \{F_i \times \lambda_i [(xx_{i,j})^\beta - (x_{i,j})^\beta] + CLO_{ij} + CCW_{ij} + CRVP_{ij} + CLG_{ij} + Cl_{ij} + CDA_{ij} + CT_{ij} + CL_{ij} + CDP_{ij} + CPOC_{ij} + CEMC_{ij} + CDA_{ij} + CRA_{ij} + CEH_{ij} + TEC_{ij} + LC_{ij} + AC_{ij}\} + \sum_{j=1}^T [DC] \quad (9)$$

2.4 System Reliability Function

The reliability of the system at the interval $X_{i,j}$ and $XX_{i,j}$ is given as:

$$R_j = e^{-\lambda t^\beta}$$

Where $t = ((xx_{i,j}) - (x_{i,j}))$

$$\text{Thus } R_j = e^{-[\lambda_i ((xx_{i,j})^\beta - (x_{i,j})^\beta)]} \quad (10)$$

The reliability of the system is measured at an instant. Case in point, the reliability of the system would be the reliability at the end of every period.

2.5 Formulation of Optimization Model for an Optimal Maintenance Strategy Based on Cost and Reliability

The parameters, cost functions and reliability equation have been defined, the optimal strategy is presented as a mixed integer non-linear programming optimization problem to minimize cost and maximize reliability as shown in equation 11:

Minimize Total cost

$$\begin{aligned} &= \sum_{i=1}^N \sum_{j=1}^T \{F_i \times \lambda_i [(xx_{i,j})^\beta - (x_{i,j})^\beta] + CLO_{ij} + \\ &CCW_{ij} + CRVP_{ij} + CLG_{ij} + Cl_{ij} + CDA_{ij} + CT_{ij} + CL_{ij} + \\ &CDP_{ij} + CPOC_{ij} + CEMC_{ij} + CDA_{ij} + CRA_{ij} + CEH_{ij} \\ &+ TEC_{ij} + LC_{ij} + AC_{ij}\} + \sum_{j=1}^T [DC] \end{aligned}$$

Maximize Reliability

$$= e^{-[\lambda_i ((xx_{i,j})^\beta - (x_{i,j})^\beta)]}$$

Subject to

$$\begin{aligned} &X_{i,j} = 0 \text{ For } i = 1, \dots, N; j = 1, \dots, T \\ &XX_{i,j} = X_{i,j} + \frac{T}{j} \text{ For } i = 1, \dots, N; j = 1, \dots, T \\ &X_{i,j+1} = 0 \text{ For } i = 1, \dots, N; j = 1, \dots, T \\ &PMC_{ij}, CRC_{ij} = 0 \text{ or } 1 \text{ For } i = 1, \dots, N; j = 1, \dots, T \end{aligned} \quad (11)$$

The first constraint indicated that the initial age of each component is zero.

The second constraint accounts for the changes in age thus representing the effective age of component i at the end of period j .

The third constraint specifies that if a component is replaced with another new component then $X_{i,j} = 0$, $CRC_{ij} = 1$, $PMC_{ij} = 0$. If a component is maintained then $CRC_{ij} = 0$, $PMC_{ij} = 1$.

3. RESULTS AND DISCUSSION

An analysis of the total cost of maintenance by the company was carried out using time series analysis. The main goal of this analysis is to determine the future cost of maintenance at a given time parameter with the current maintenance strategy of the company and then compare with the optimal cost obtained using the model in equation 11. The result showed an increasing trend line of total maintenance cost as seen in Fig. 3.

From the analysis it was found that in the year 2021, if the current maintenance strategy is still maintained, the total cost is expected to be about ₦9,201,979. Table 1 shows the yearly forecast from 2018 to 2021.

Data from the manufacturing firms shown in table 2 was applied to the optimization model developed in equation 11 and was programmed into lingo 17.0 software for an optimal solution. The cost results obtained were benchmarked with the future maintenance cost forecast.

Table 1. Future maintenance cost forecast

Period	Forecast
2018	₦ 6,616,432
2019	₦ 7,478,281
2020	₦ 8,340,130
2021	₦ 9,201,979

Fig. 4 Show the optimal pareto fronts from lingo 17 with associated cost. Each front presents an optimal maintenance schedule and at 50% the

objective function is achieved at ₦7,593,578 with system reliability in between the range of 94% and 99.7% over the defined planning period of 36 month.

The optimal maintenance strategy obtained at the objective function is presented in table 3.

The system reliability as presented in Fig. 5 shows that the reliability of the system lies between 94% and 99.7% over the defined planning period of 36 months with average reliability over the planning period being 97.2%.

The purpose of the optimal maintenance strategy is to ascertain the optimal combination of maintenance actions that meets the objectives of

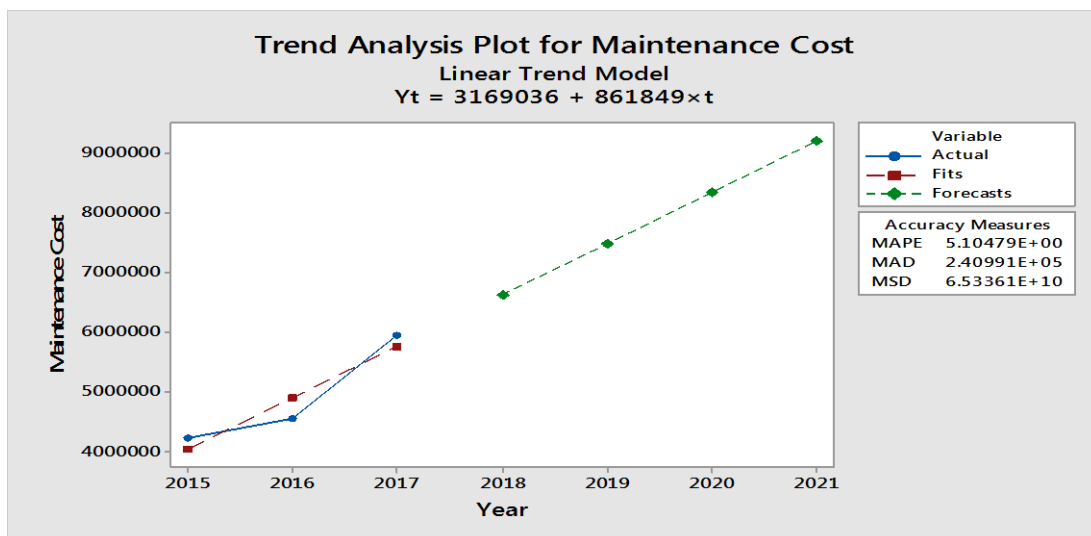


Fig. 3. Trend plot of total maintenance cost with future forecast

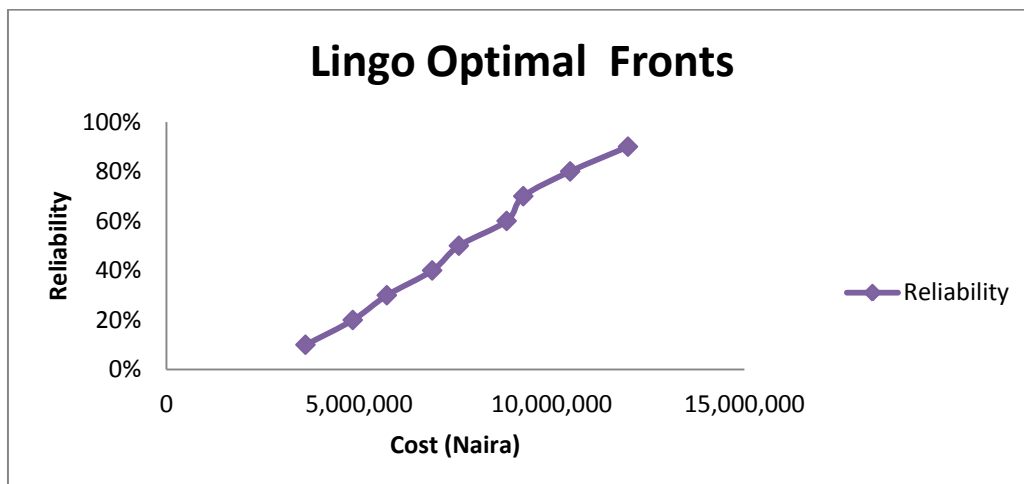


Fig. 4. Lingo optimal fronts for reliability

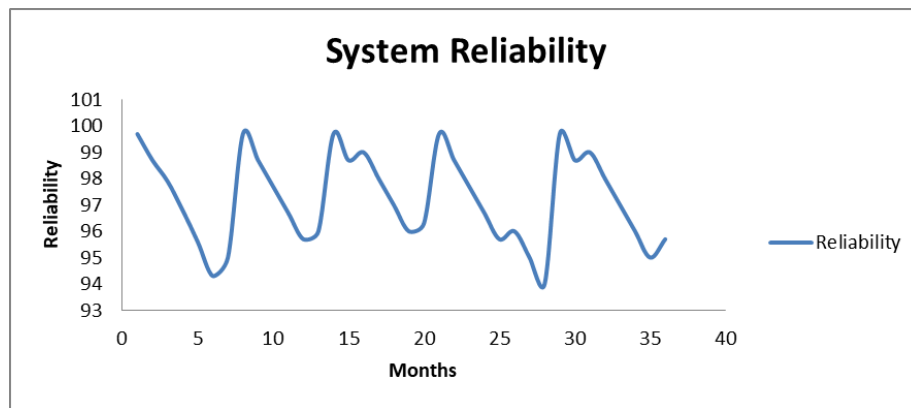


Fig. 5. System reliability (Cost = ₦7, 593,578, Reliability = 99.7%)

Table 2. Parameters of manufacturing firm used

Time Period		36 months					
DC		₦197,561					
N	Component	Shape (β)	Scale (λ)	α_{pmi}	Failure Cost	Preventive Maintenance Cost	Corrective Maintenance Cost
1	Conveyor System	1.5855	3396.50	0.7	₦ 884,210	₦387,450	₦ 496,760
2	Mixer system	1.7610	3375.42	0.7	₦ 366,415	₦93,855	₦ 272,560
3	Roller system	1.7397	3254.14	0.7	₦ 430,680	₦ 92,680	₦ 338,000
4	Slitter	1.7123	3252.65	0.7	₦ 513,322	₦ 99,500	₦ 413,822
5	Compounding machine	1.6852	3170.13	0.7	₦ 618,685	₦ 231,685	₦ 387,000

Table 3. Cost saving and reliability improvement

Categories	Reliability	Cost	Cost Savings
Case Study	93.82%	₦9,201,979	
Solution Method			
Lingo Optimal Solution	99.7%	₦7,593,578	61.7%

Table 4. Optimal Maintenance strategy

MONTHLY SCHEDULE																																					
N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
1	-	-	P	-	-	-	P	C	-	-	-	-	P	C	-	-	-	-	-	P	-	-	C	-	-	P	-	-	-	-	-	P	-	-	-	-	P
2	-	-	P	-	-	-	-	-	-	-	-	-	P	C	-	-	P	-	-	-	-	-	C	-	-	-	-	-	C	-	-	-	-	-	-	-	P
3	-	-	P	-	-	-	P	C	-	-	-	-	P	-	-	-	P	-	-	P	-	-	C	-	-	-	-	-	-	-	-	P	-	-	-	-	P
4	-	-	P	-	-	-	P	C	-	-	-	-	P	-	-	-	-	-	-	-	-	-	C	-	-	-	-	-	C	-	-	P	-	-	-	-	P
5	-	-	P	-	-	-	-	-	-	-	-	-	P	C	-	-	-	-	-	P	-	-	C	-	-	P	-	-	P	-	-	-	-	-	-	-	P

KEY: N = Number of Components; 1 = Conveyor System; 2 = Mixer System; 3 = Roller System; 4 = Slitter System; 5 = Compounding Machine;

P: Preventive Maintenance; C: Corrective Maintenance

the manufacturing firm. These can either be to maximize reliability or minimize cost. At 50% pareto front, the optimal fronts provided a better cost objective and improved reliability (Cost = ₦7,593,578, Reliability = 99.7%) than that the current maintenance scenario at the food manufacturing company at cost ₦9,201,979.

4. CONCLUSION

An optimal maintenance strategy for effective maintenance cost and machine reliability for food manufacturing industries was presented in this study. The optimal strategy was obtained through the optimization of a mixed integer nonlinear multi-objective programming model presented in the study which was validated using an industrial case study. It was found that the strategy obtained provides a better cost savings and improved reliability thus Maintenance of manufacturing components can be improved using reliability parameters and cost of those components. For the strategy to be effective, input data needs to be as exact as possible. Therefore, there is a need for manufacturing companies to ensure that failure history and cost of maintenance/ replacement of every component are properly documented to ensure accurate reliability prediction and cost forecasting.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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