OPERATIONAL RELIABILITY AND SIGNATURE ANALYSIS OF AN INDIGENOUS PLANTAIN ROTARY DRYING MACHINE

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ABSTRACT

The behavioral mode of machinery is a function of its reliability. Also, machine's reliability is defined by functionality of the various subsystems, devices, and components that make up a machine. Thus, the signature of a locally developed rotary dryer has been understudied in this research to determine its behavioral pattern for its maintainability. The plantain rotary dryer comprises heater, blower, electric motor, and roller and gear drive system. The reliability function is derived from the principle of conditional probability. Also, sensors were attached to the machine components and data logger was used to retrieve temperature, sound, and vibration data at varying operations under both normal and imposed degraded conditions. The regression results from analysis of the retrieved data were compared with the system's network modelling output, a series/parallel reliability network behavioral mode was established as the signature of the plantain rotary dryer. The vibration data modelling of the rotary drying machine output shows that 0.06%, 0.04% and 0.05% of the variation in behavioral signature at: no degradation no loading; no degradation and loaded state; and degradation under loaded state operation conditions are accounted for by a linear, linear and polynomial relationship respectively. In the same vein, the temperature data modelling for the rotary dryer shows that 1.4%, 9.3% and 1.96% characteristic signature at: no degradation no loading; no degradation and loaded state; and degradation under loaded state operation conditions are accounted for by a logarithmic, polynomial and linear relationship respectively. However, these are significantly low due to the aging of the bought out components with an estimated reliability of 0.28. Nevertheless, for commercialization of the machine, newly manufactured components are recommended for development of the rotary drying machine to increase its reliability and maintainability.

Keywords: Reliability, Signature, Plantain, Rotary Dryer

1. | Introduction

Industrial production process efficiency is a function of the reliability and availability of machineries. This efficiency is often interrupted by the intermittent breakdown caused by unsuitable maintenance practices (Adeyeri *et al.*, 2023). A better understanding of the behavioral mode of plant operation at: component level; system level; machine level; all forms of loading capacities; and environmental conditions of machine will be a platform at which an operator could leverage on in obtaining optimal upkeep at reduced or no failures or breakdown.

In the bid to key into the United Nations (UN) Sustainable Development Goals (SDGs), especially the 9th

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SDG goal which is purely on industrial growth and innovative technology, industrial engineers in the developing countries are embracing this with the development of agro allied machineries which will promote industrialization. As a result of poor workmanship and non-availability of state-of-the-art equipment in developing these machines, most of the resulting machines from this process are prone to low performance and productivity and incessant failures. It is therefore needful to establish the machines' characteristics or behavioral trend when in use to address or mitigate this menace and meet up with the 9th goal of SDG. This will thus help in developing a maintenance platform and strategy for a would-be-operator or plant manager in the upkeep of the indigenously developed machine. Once this is established, the availability of the plant, optimal performance and overall equipment efficiency will be guaranteed (Adeyeri *et al.,* 2023).

Thus, this research seeks to establish the signature of the behavioral performance of the drying unit of a plantain flour processing plant developed by Advanced Manufacturing and Applied Ergonomic Research Team (AMAERT) in Federal University of Technology, Akure, Ondo State, Nigeria. The plant (consisting of six machines) was developed in a bid to meet SDGs 1, 2 and 3 as plantain fruit is highly available but encountering preservation challenges as when ripened it becomes spoilt due to its perishable nature (Adeyeri *et al.,* 2022). The plant is an agro-processing plant designed to neatly produce plantain flour from sliced or particulated plantain fingers. The processing plant is essentially an all-in-one plant designed to produce the finished product starting from loading point in a continuous production flow (Olutomilola, 2019). Drying, an integral process in plantain flour production, is effectively actualized through the indigenously developed rotary dryer by extracting moisture from water-embedded materials like plantain chips prior to milling stage (Ayodeji, 2016, Olutomilola, 2019). Meanwhile, every machine component behaves as an individual and prone to failures over time due to wears, which leads to high maintenance cost and unwanted downtime.

Machine faults are disturbance to the machine systems which are intolerable. Faults are projection from machines' alteration or impairment. In respective of the magnitude of machine's fault, once it is initiated, it disturbs the production plan and target set for each production activities. That is, production processes, man hour time and inventory cost etcetera are being affected; thus, affecting product quality and further leads to customers' dissatisfaction (Adeyeri, 2018). Jayaswal *et al.,* (2008) and Chenxing, *et al.,* 2011), classified machine faults according to the following causes of failure:

i. gradual deterioration of machine parts due to wear, and other similar conditions which could lead to a gradual deterioration of the machine over time;
ii. misuse or application of stress in undesired direction; and
iii. existing weakness in materials, design and manufacturing

The importance of early fault detection cannot be over-emphasized; there is a reduction in the overall repair cost, reduction and possible prevention of down-time and prevention of secondary damages (Behera and Sahoo, 2016).

The reliability of most bought out components for the development of machines in this part of the world cannot be determined by machine fabricators or engineer. The inability in determining reliability of the critical components of the machine most often renders novel and innovative machine design useless, unproductive, moribund, and unreliable. With passage of time, the gradual deterioration in the performance of any machine in use is often unavoidable. Most machine manufacturers perform different tests to ascertain the performance threshold and remaining useful life (RUL) of machines in bid to obtain the machine signature and facilitate performance and use. To ensure optimal functionality of the rotary dryer, there is need to obtain the machine signature based on reliability, and to develop a maintenance culture for the developed plantain rotary drying machine (Moubray, 2000; Barabady, 2005; Zacks, 2012; Okoh, *et al.,* 2014).

Reliability is defined as “likelihood of subsystems or system to implement a required function within the given period, under its operating state” (Zacks, 2012). Reliability finds its application in many fields of research. One of these is in maintenance engineering as industrial assets, equipment and machines conditions call for critical attention for continuous functionality and optimal performance. Hence, Reliability Centered Maintenance (RCM) is one of the potent tools used by maintenance engineers in the maintenance process to determine the most or best suitable and economical maintenance strategy on the basis of equipment condition assessment (Andrena, 2001; Jablonski, 2022).

1.1 | Rotary Dryer Overview

The processing plant consists of the washing, grating or particulating, drying, milling, cooling and packaging sections as shown in Figure 1. The target rotary dryer for this present research is an integral subsystem in the plantain flour processing plant. The rotary dryer, which is the cut out drying section shown in Figure 2, basically consists of a geared motor assembly to facilitate rotary motion, rotary chamber (where drying of grated plantain is done before milling takes place), heating elements and other encased accessories (Olutomilola *et al.,* 2022).

2. | Reliability Modeling of the Rotary Dryer

Considering the rotary dryer and its components as presented in Figure 2. The reliability model formulation will be based on the series or parallel systems determination. To achieve this objectives, the two different scenarios are used to model the arrangement of the components of the rotary drying machine.

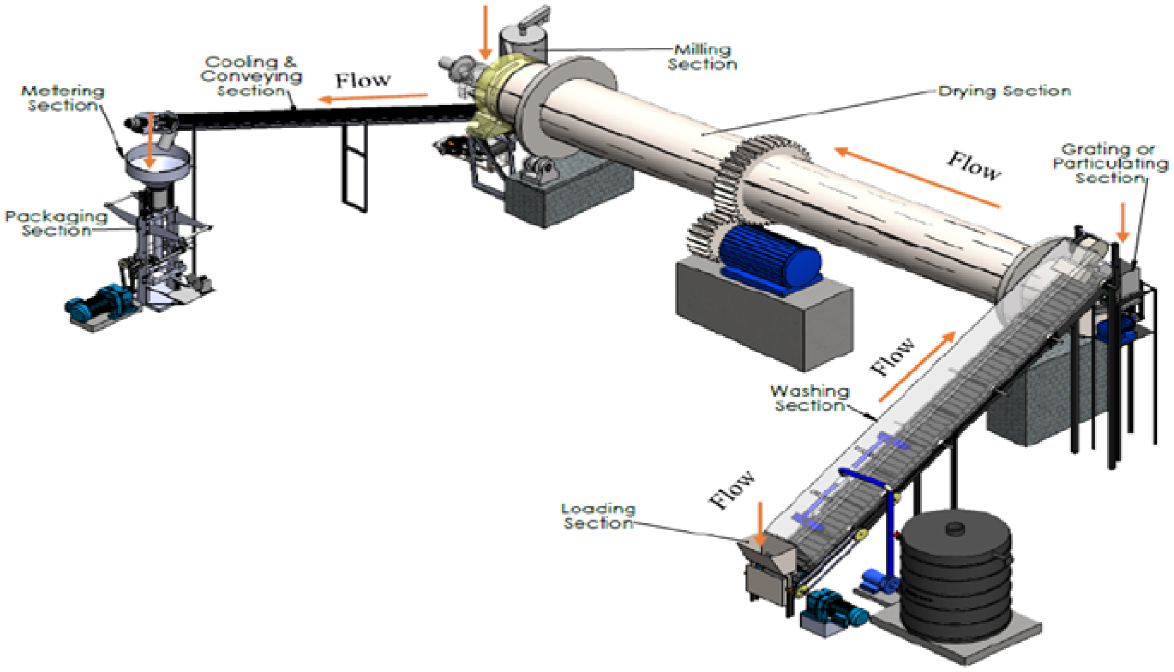


Figure 1 | Plantain Flour Processing Plant (Olutomilola, 2019)

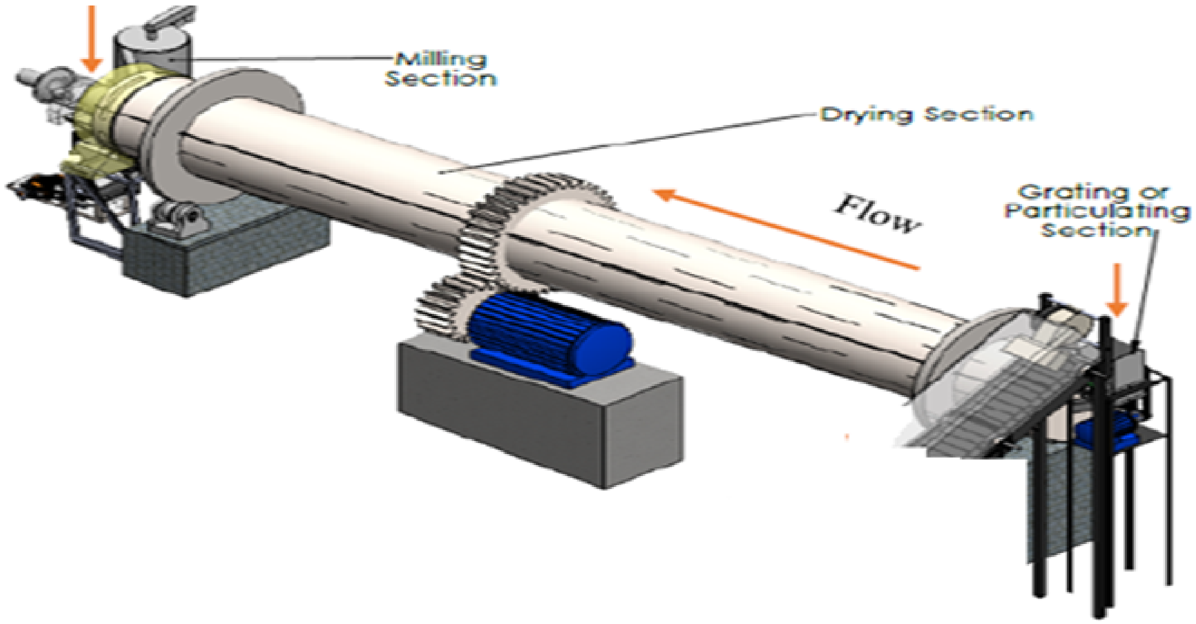


Figure 2 | Rotary Dryer for Plantain Flour Processing Plant (Olutomilola, 2019)

2.1 | Arrangement I: Series Consideration

The uniqueness of series arrangement is that the non-functionality of any one of the components from reliability perspective will lead to the system's failure. The resulting series system of the dryer is as presented in Figure 3.

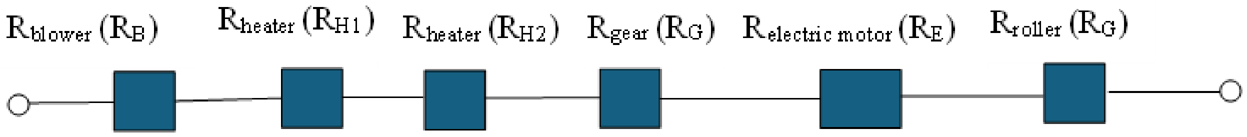


Figure 3 | The series reliability diagram for plantain rotary dryer

2.1 | Arrangement I: Series Consideration

The uniqueness of series arrangement is that the non-functionality of any one of the components from reliability perspective will lead to the system's failure. The resulting series system of the dryer is as presented in Figure 3.

With reference to Figure 3, the five components of the dryer is as modelled in equation (1).

Let the probability of successful operation of the blower, electric heater, roller, electric motor, and gear be R_{blower} (R_B); $R_{\text{electric motor}}$ (R_E); R_{heater} (R_H); R_{roller} (R_R); and R_{gear} (R_G), respectively. And Q_{blower} (Q_B); $Q_{\text{electric motor}}$ ($_E$); Q_{heater} (Q_H); Q_{roller} (Q_R); and Q_{gear} (Q_G) are the probability of failure for blower, electric heater, roller, electric motor, and gear respectively. Since success and failure are mutually exclusive and complementary,

$$\left.\begin{aligned} R_B + Q_B &= 1\\ R_H + Q_H &= 1\\ R_E + Q_E &= 1\\ R_R + Q_R &= 1\\ R_G + Q_G &= 1 \end{aligned}\right\} \tag{1}$$

$$R_S = R_B \cdot R_{H1} \cdot R_{H2} \cdot R_E \cdot R_R \cdot R_G \tag{2}$$

In general term, equation (2) becomes equation (3) if there are more n components in series.

$$R_s = \prod_{i=1}^{n} R_i \tag{3}$$

Similarly, the unreliability of the rotary dryer is as expressed in equations (4), (5) and (6).

$$Q_S = 1 - (R_B \cdot R_{H1} \cdot R_{H2} \cdot R_E \cdot R_R \cdot R_G) \qquad (4)$$

$$Q_S = 1 - \begin{pmatrix} 1 - Q_B)(1 - Q_{H1})(1 - Q_{H2}) \\ (1 - Q_E)(1 - Q_R)(1 - Q_G \end{pmatrix} \qquad (5)$$

$$Q_s = 1 - \prod_{i=1}^{n} R_i \qquad (6)$$

2.2 | Arrangement II: Series-Parallel Consideration

With reference to Figure 4, for parallel consideration, the six components namely: blower, heater1, heater2, roller, electric motor and gear system has been utilized in this model as contained in Figure 4. In this arrangement, the assumption taken is that only one component need to be working for the success of the rotary dryer.

Combining in series the blower, heater 1 and heater 2 to form an equivalent component A. Also, combining in series, the roller, electric motor and gear system to form an equivalent component C.

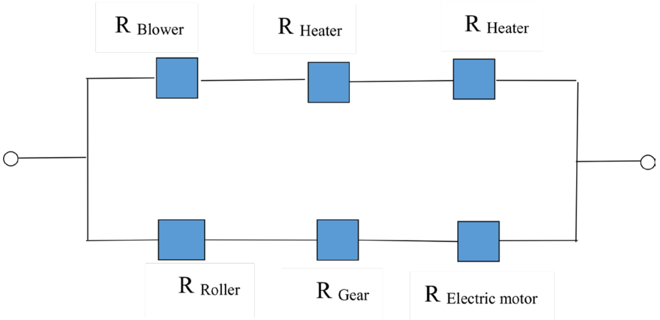


Figure 4 | The series/parallel reliability diagram for rotary dryer

The resulting combination is as presented in Figure 5, and then recombine to give Figure 6.

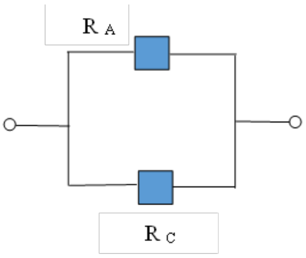


Figure 5 | 1st reduction of the series/parallel reliability diagram for rotary dryer

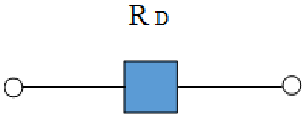


Figure 6 | 2nd reduction of the reduced series/parallel reliability diagram for rotary dryer

With the notations given in section of "Arrangement I", then equations (7) and (8) give the reliability for the first reduction output. While equations (9) and (10) present the model output for the second reduction shown in Figure 6. The simplified reliability for the plantain rotary dryer is as depicted in equation (11).

$$R_A = R_B \cdot R_{H1} \cdot R_{H2} \qquad (7)$$

$$R_C = R_E \cdot R_R \cdot R_G \qquad (8)$$

$$R_D = 1 - (1 - R_A)(1 - R_C) \qquad (9)$$

$$R_D = R_A + R_C - R_A R_C \qquad (10)$$

$$R_D = R_B \cdot R_{H1} \cdot R_{H2} + R_E \cdot R_R \cdot R_G - R_B \cdot R_{H1} \cdot R_{H2} \cdot R_E \cdot R_R \cdot R_G \qquad (11)$$

It is worth noting that these equations derived in this section were used to develop a reliability computation table for the rotary dryer. The results are presented in subsequent section.

3. | Establishment of the Rotary Drying Machine Behavioral Signature

Degradation model tab in excel package and python programme were used to establish the signature of rotary dryer. The retrieved rotary dryer condition dataset was divided into three sets of which its algorithm experimental procedures are as shown in the flowchart of Figure 7.

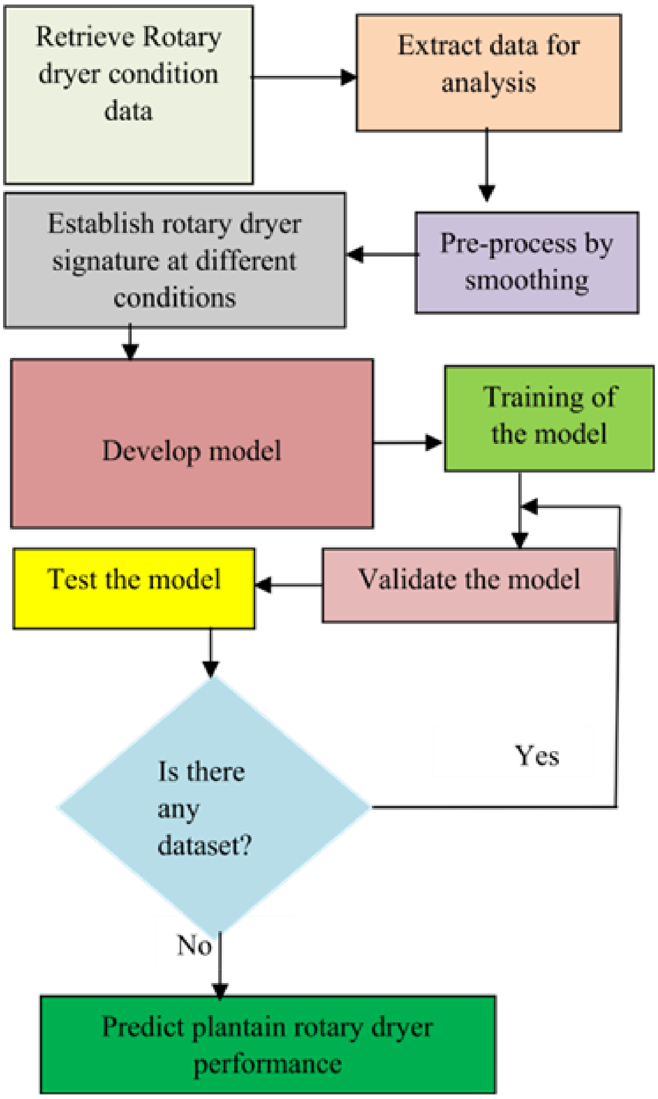


Figure 7 | Analytical flow chart on the retrieved machine data

Reference to Figure 7, the data sets were retrieved with the aid of the data logger and after which they were preprocessed in a bid to establish the behavioral pattern of the plantain rotary drying machine. The model development was achieved using Microsoft Excel package in which the data set was trended in order to know the mathematical equation that gives the best fit line through regression analysis. However, with the volume of data set and for ease of graphics visualizing the behavioral trend of the machine, the data sets were imported into python software package. The steps involved in the processing of the data set are as stated:

i. importing comma separated values (csv) file to pandas;
ii. cleaning of data and ensuring data integrity;
iii. since data required time series analysis, visualization for temperature, sound and vibration was done for only the first 1 hour under various machine conditions due to data volume;
iv. visualization was also done to understand the various machine conditions; and
v. regression analysis was carried out to aid the trend and make future predictions.

4. | Results and Discussion

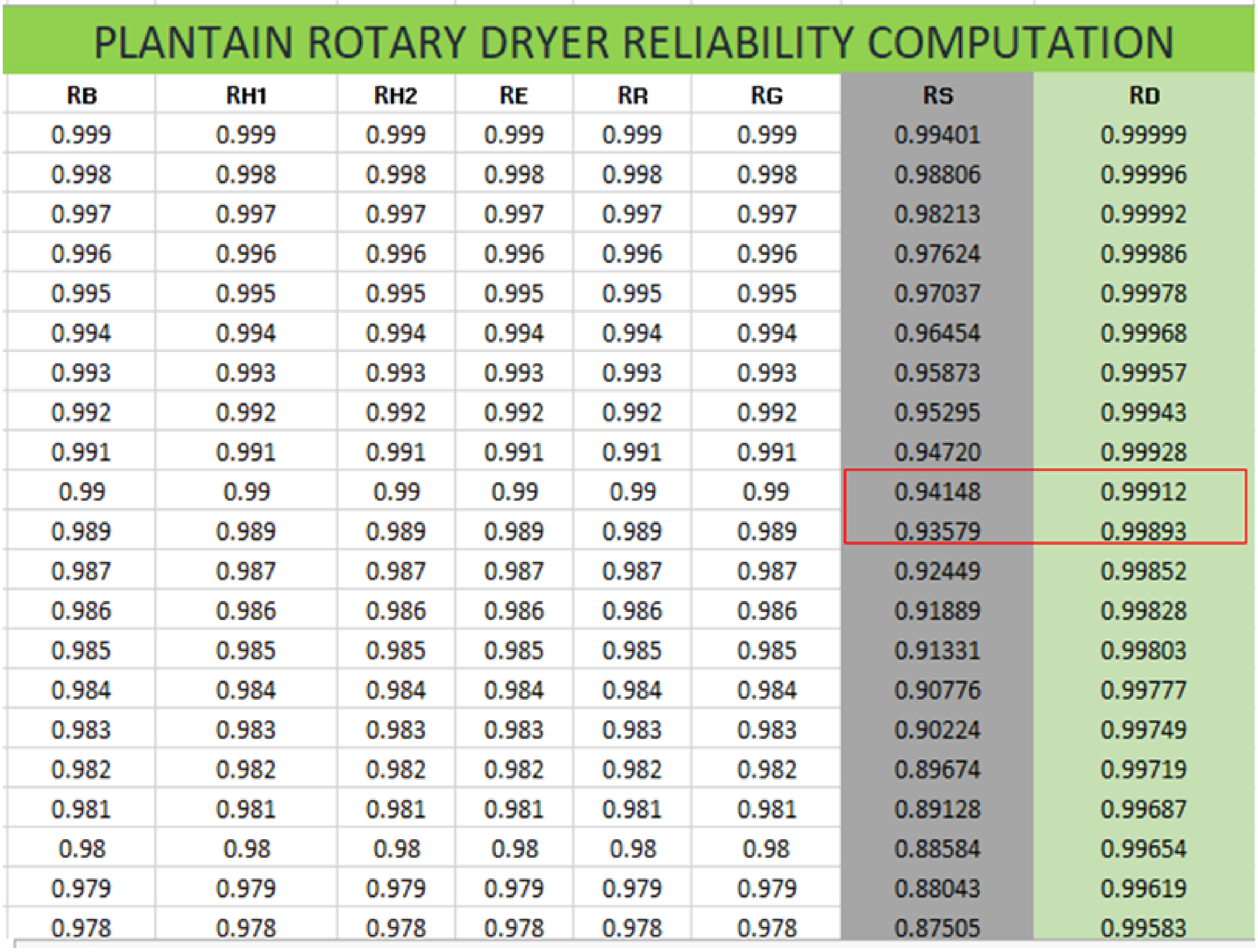
4.1 | System Reliability Modelling Outputs

The MS-Excel program was used to programme equation (1) to (11) of the section 2.2 for ease of simulating the parameters of the plantain rotary dryer. The snapshots presented in Tables 1 and 2 show the outcome of the simulation of blower, heaters, electric motor, roller and gear system under an assumed homogeneous (same) value and varying states, respectively.

Under the homogeneous state of the system reliability, the overall reliability R_S and R_D for the dryer is lower in series arrangement when compared to the series/parallel arrangement as evident in the 0.99 and 0.989 shown in Table 1. This implies that the series arrangement will be more prone to system failure as the simulated values are not as high as the series-parallel arrangement. Hence, the series /parallel arrangement is confirmed to preferably define the rotary dryer system reliability and its signature.

To validate this finding, varying values were simulated as shown in Table 1. Setting R_{H1} as zero (0), the R_S value gives zero (0), while the R_D value gives 0.98507. Similarly, when degradation sets into the system, setting R_{H2} at 0.85, and R_G at 0.8, the

Table 1 | Reliability modelling computation Table snapshot for the dryer under homogeneous state



PLANTAIN ROTARY DRYER RELIABILITY COMPUTATION

RB	RH1	RH2	RE	RR	RG	RS	RD
0.999	0.999	0.999	0.999	0.999	0.999	0.99401	0.99999
0.998	0.998	0.998	0.998	0.998	0.998	0.98806	0.99996
0.997	0.997	0.997	0.997	0.997	0.997	0.98213	0.99992
0.996	0.996	0.996	0.996	0.996	0.996	0.97624	0.99986
0.995	0.995	0.995	0.995	0.995	0.995	0.97037	0.99978
0.994	0.994	0.994	0.994	0.994	0.994	0.96454	0.99968
0.993	0.993	0.993	0.993	0.993	0.993	0.95873	0.99957
0.992	0.992	0.992	0.992	0.992	0.992	0.95295	0.99943
0.991	0.991	0.991	0.991	0.991	0.991	0.94720	0.99928
0.99	0.99	0.99	0.99	0.99	0.99	0.94148	0.99912
0.989	0.989	0.989	0.989	0.989	0.989	0.93579	0.99893
0.987	0.987	0.987	0.987	0.987	0.987	0.92449	0.99852
0.986	0.986	0.986	0.986	0.986	0.986	0.91889	0.99828
0.985	0.985	0.985	0.985	0.985	0.985	0.91331	0.99803
0.984	0.984	0.984	0.984	0.984	0.984	0.90776	0.99777
0.983	0.983	0.983	0.983	0.983	0.983	0.90224	0.99749
0.982	0.982	0.982	0.982	0.982	0.982	0.89674	0.99719
0.981	0.981	0.981	0.981	0.981	0.981	0.89128	0.99687
0.98	0.98	0.98	0.98	0.98	0.98	0.88584	0.99654
0.979	0.979	0.979	0.979	0.979	0.979	0.88043	0.99619
0.978	0.978	0.978	0.978	0.978	0.978	0.87505	0.99583

resulting R_S gives 0.57869 and R_D yields 0.94304. This thus validate that the system is fully in line with the signature of the series/parallel system. However, going by the definition of what series system is, this finding does not support it as the non-functionality of any of the system does not disturb the overall efficiency.

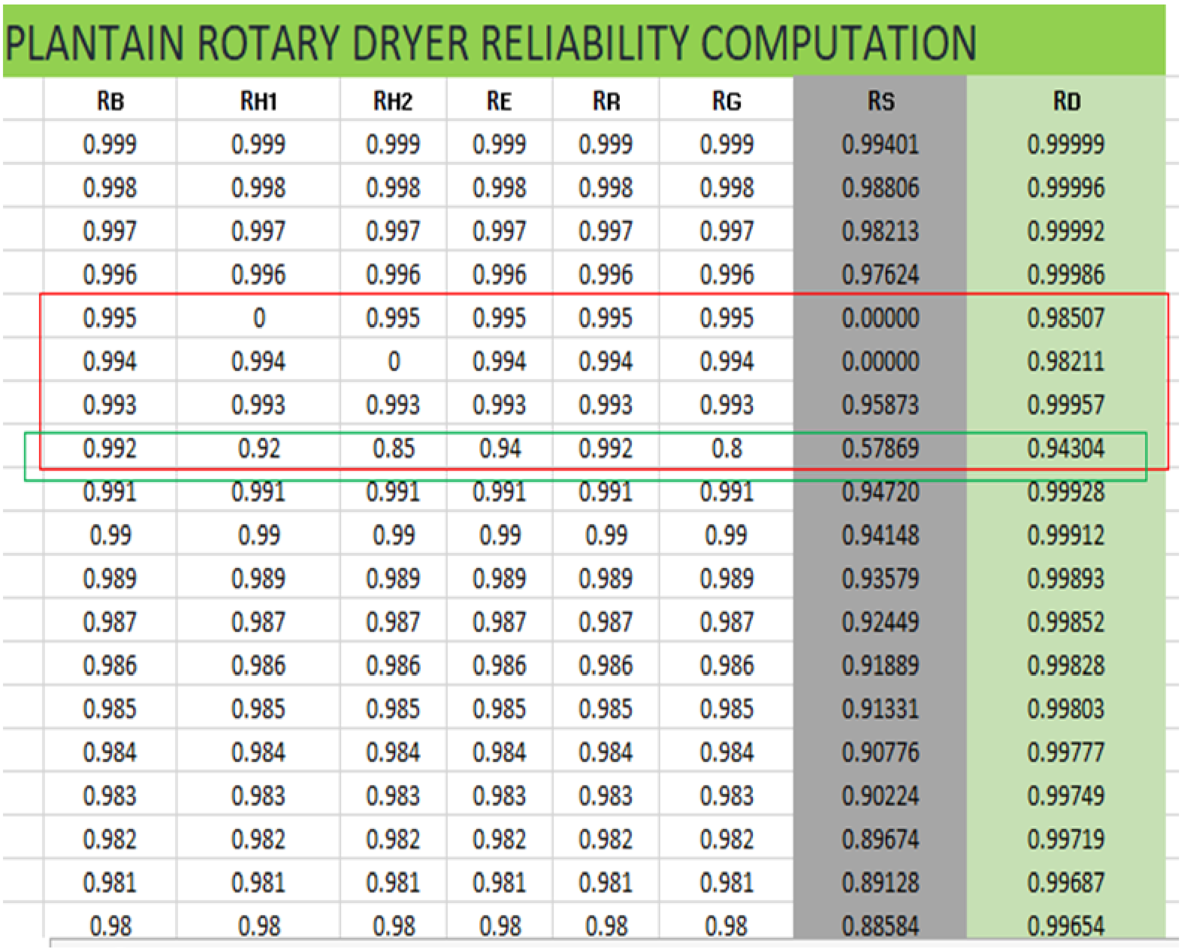
4.2 | Analysis of the Retrieved Plantain Rotary Dryer Data

4.2.1 | Establishment of the dryer signature without degradation at no load and loaded states

Figures 8, 9, 10 and 11 show and describe the one hour machine signature spectral relative to temperature, vibration and sound responses of the dryer's conditions under "no degradation" at no load and loaded states. Figure 8 shows the characteristic of the dryer's response to temperature, vibration and sound, respectively under normal and at no loading state. Considering these four figures, it is observed that as the system is loaded, the signature spectral of the dryer becomes more pronounced than those observed in the no load states. Inference from these shows that the attenuation is a function of the dryer's carrying capacity. The lower the load, the more the attenuation becomes widened. Conversely, the more the load, the more the pitch or sinusoidal spectral becomes deepened.

Similarly, Figures 11, 12 and 13 represent the characteristic of the rotary dryer's response to temperature, vibration and sound at various degraded states and loading conditions. Considering the various loading states as displayed in Figure 11,

Table 2 | Reliability modelling computation Table snapshot for the rotary dryer under varying values



PLANTAIN ROTARY DRYER RELIABILITY COMPUTATION

RB	RH1	RH2	RE	RR	RG	RS	RD
0.999	0.999	0.999	0.999	0.999	0.999	0.99401	0.99999
0.998	0.998	0.998	0.998	0.998	0.998	0.98806	0.99996
0.997	0.997	0.997	0.997	0.997	0.997	0.98213	0.99992
0.996	0.996	0.996	0.996	0.996	0.996	0.97624	0.99986
0.995	0	0.995	0.995	0.995	0.995	0.00000	0.98507
0.994	0.994	0	0.994	0.994	0.994	0.00000	0.98211
0.993	0.993	0.993	0.993	0.993	0.993	0.95873	0.99957
0.992	0.92	0.85	0.94	0.992	0.8	0.57869	0.94304
0.991	0.991	0.991	0.991	0.991	0.991	0.94720	0.99928
0.99	0.99	0.99	0.99	0.99	0.99	0.94148	0.99912
0.989	0.989	0.989	0.989	0.989	0.989	0.93579	0.99893
0.987	0.987	0.987	0.987	0.987	0.987	0.92449	0.99852
0.986	0.986	0.986	0.986	0.986	0.986	0.91889	0.99828
0.985	0.985	0.985	0.985	0.985	0.985	0.91331	0.99803
0.984	0.984	0.984	0.984	0.984	0.984	0.90776	0.99777
0.983	0.983	0.983	0.983	0.983	0.983	0.90224	0.99749
0.982	0.982	0.982	0.982	0.982	0.982	0.89674	0.99719
0.981	0.981	0.981	0.981	0.981	0.981	0.89128	0.99687
0.98	0.98	0.98	0.98	0.98	0.98	0.88584	0.99654

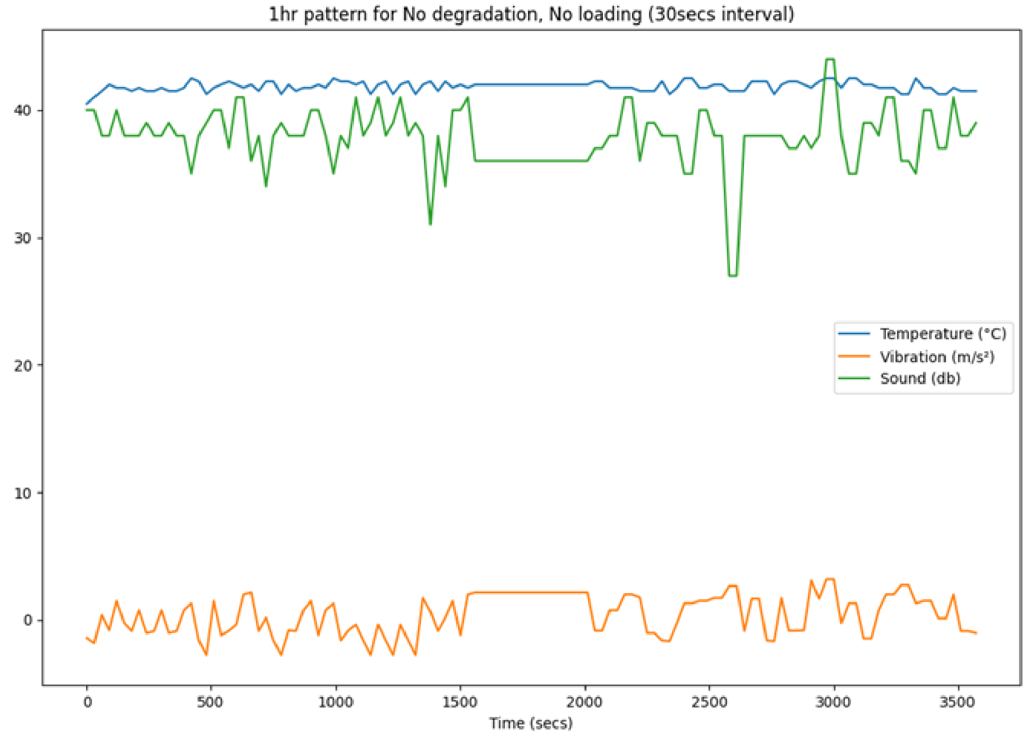


Figure 8 | Monitoring spectral for the rotary dryer under normal at no loading state

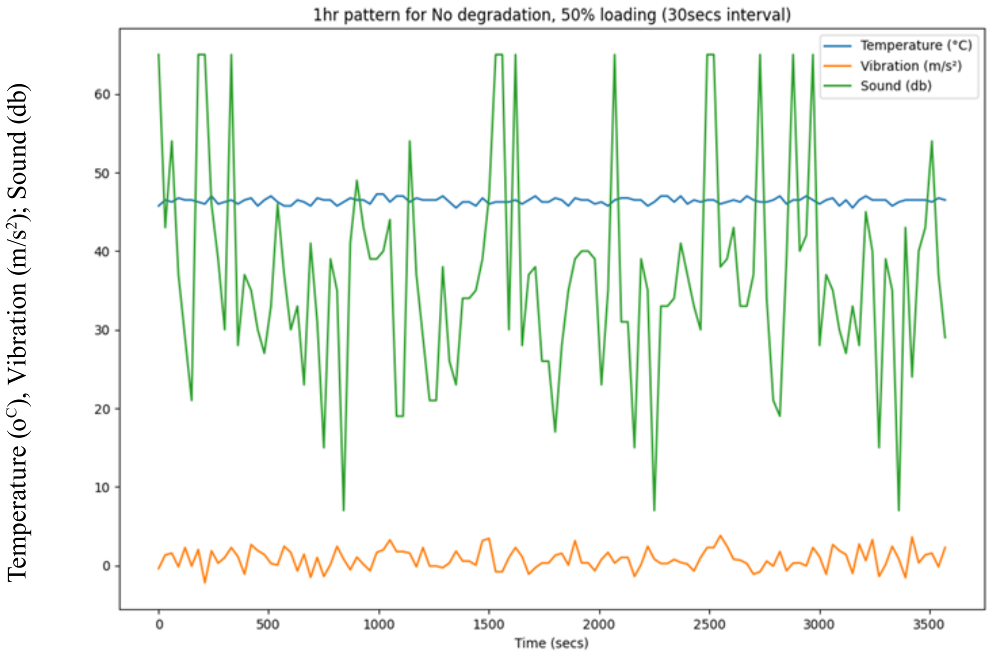


Figure 9 | Monitoring spectral for the rotary dryer under no degradation at 50% loading state

Figure 10 | Monitoring spectral for the rotary dryer under no degradation at 75% loading state

the 100% loading has pronounced amplitude of 2.45 m/s2 which is more and higher when compared with other loading states under the same degraded condition. Also, in Figure 12, when the blower is degraded, the pitch of sound increases to 63 db with the loading capacity as found at the instance of the 20th second of operation when compared with other loading capacities which are at 40 - 44 db. The same trend of behavior is observed for the degraded bearing as found in Figures 12, 13 and 14.

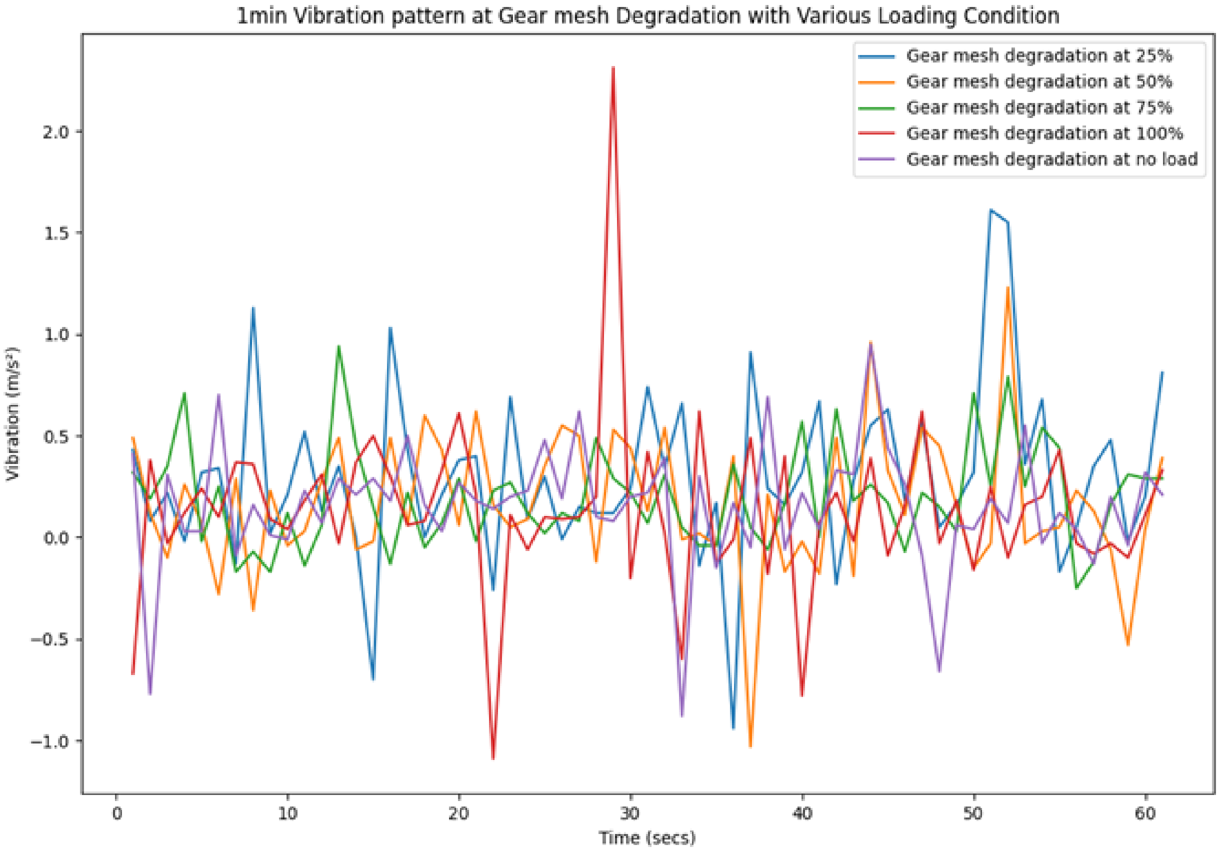


Figure 11 | One minute vibration spectral for gear mesh degradation with various loading condition

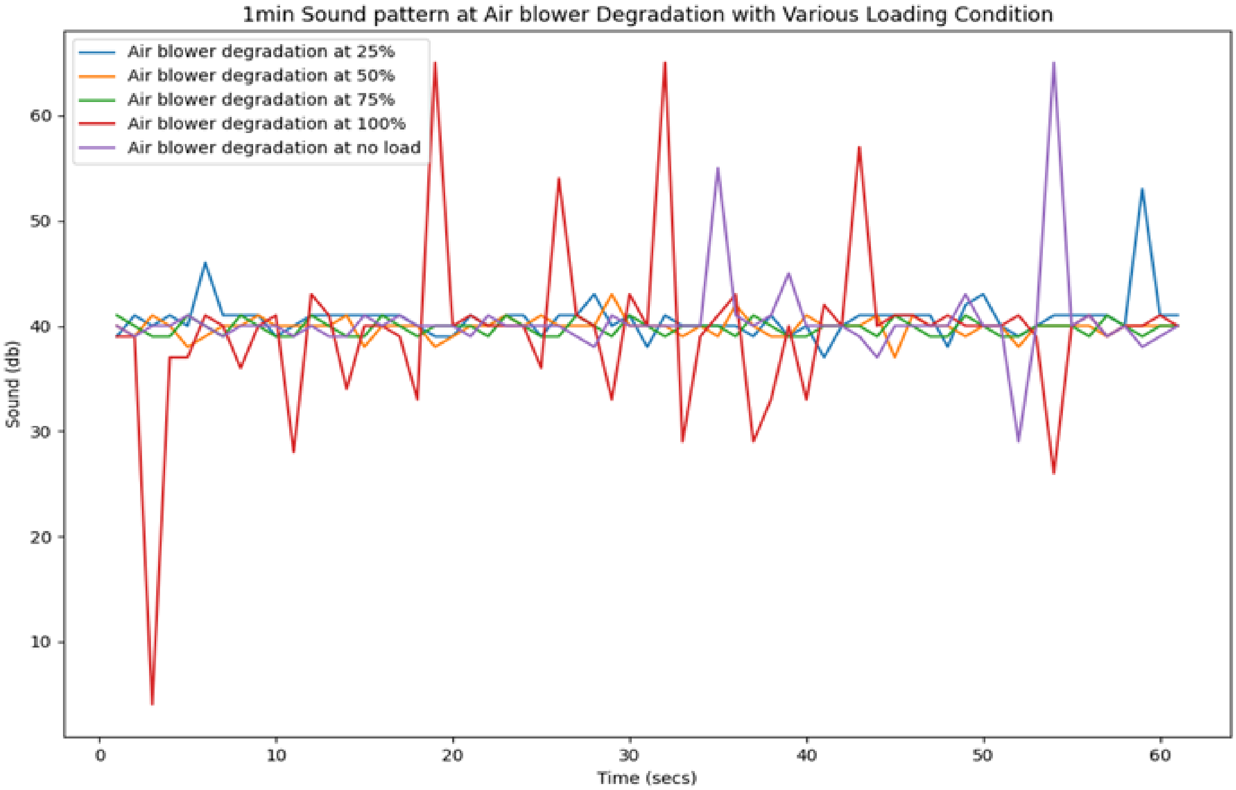


Figure 12 | One minute sound spectral for air blower degradation with various loading condition

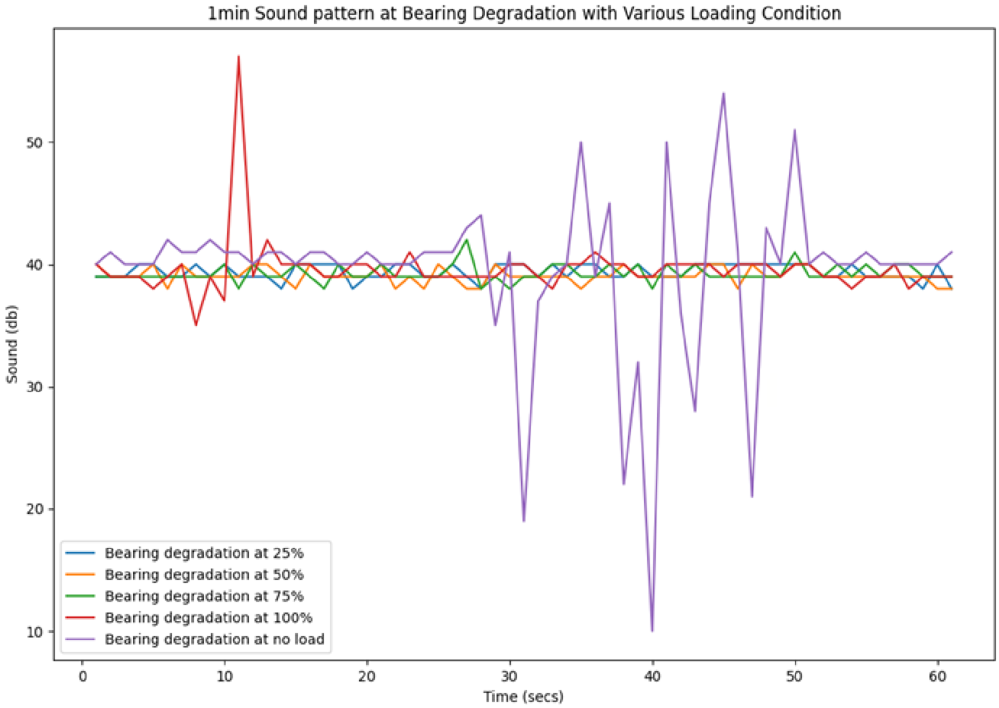


Figure 13. One minute sound spectral for bearing degradation with various loading conditions

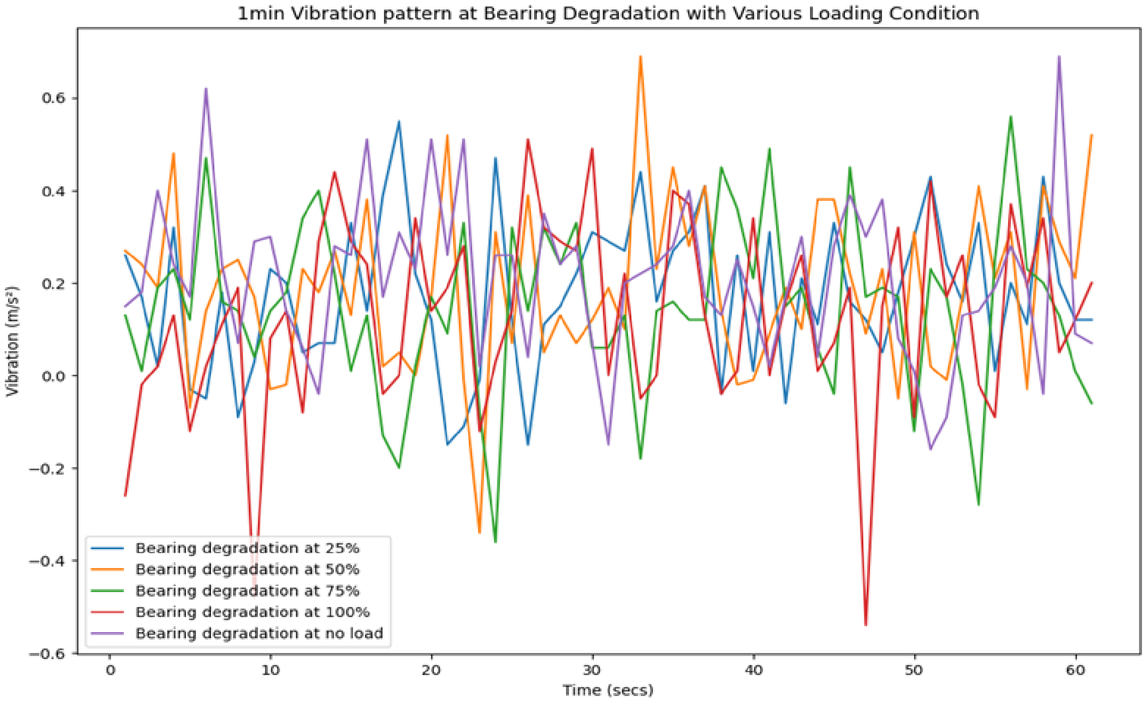


Figure 14 | One minute vibration spectral for bearing degradation with various loading conditions

4.2.2 | Regression model of the rotary drying machine

The resulting model from the lines fitting on the vibration and temperature data through trending approach on the spectral retrieved depicted by the rotary dryer are presented in Tables 3 and 4.

Table 3 | The rotary dryer regression model on vibration data

Selected Rotary Dryer Operation Status/ Conditions	**Regression Model**	**R^2**	**Remark**
@ no degradation no loading	$y_v = -(6 \times 10^{-5} x_v) + 37.868$	0.0006	A linear signature is prominent
	$y_v = -0.033 \ln(x_v) + 37.984$	0.0001	
@ no degradation and loaded state	$y_v = 6 \times 10^{-8} {x_v}^2 - (7 \times 10^{-5} x_v) + 37.856$	0.0002	Either linear or polynomial is established
	$y_v = 0.0002 x_v + 37.711$	0.0002	
@ degradation under loaded state	$y_v = -(7 \times 10^{-5} x_v) + 39.39$	0.0038	A polynomial signature relationship is formed
	$y_v = 4 \times 10^{-8} {x_v}^2 - (0.0002 x_v) + 39.48$	0.005	
	$y_v = -0.01 \ln(x_v) + 39.338$	8×10^{-5}	

Table 4 | The rotary dryer regression model on temperature data

Selected Rotary Dryer Operation Status/ Conditions	**Regression Model**	**R^2**	**Remark**
@ no degradation no loading	$y_T = -(1 \times 10^{-5} x_T) + 44.032$	0.0021	A logarithmic signature is prominent
	$y_T = 1 \times 10^{-8} {x_T}^2 - (6 \times 10^{-5} x_T) + 44.065$	0.0052	
	$y_T = -0.033 \ln(x_T) + 44.248$	0.0147	
@ no degradation and loaded state	$y_T = (0.0002 x_T) + 39.203$	0.0845	Polynomial signature is established
	$y_T = 5 \times 10^{-8} {x_T}^2 - (4 \times 10^{-5} x_T) + 39.332$	0.0932	
	$y_T = 0.1216 \ln(x_T) + 38.63$	0.0388	
@ degradation under loaded state	$y_T = -(0.0008 x_T) + 33.544$	0.0196	A linear signature relationship is formed
	$y_T = 7 \times 10^{-7} {x_T}^2 - (0.002 x_T) + 35.322$	0.0373	
	$y_T = 0.564 \ln(x_T) + 30.897$	0.0088	

From Table 3, the vibration characteristic of the dryer implies that 0.06% and 0.02% of the variation behavioral mode of the rotary dryer is accounted for under no degradation at no load and loaded states, respectively. While at degraded and loaded states, a polynomial signature relationship is established. In the same vein, from Table 4, considering the temperature signature of the dryer, it shows that 1.4%, and 9.3% of the variation behavioral mode of the rotary dryer under no degradation is accounted for at no load and loaded states, respectively. While at degraded and loaded states, a linear relationship with R^2 value of 0.0196 is established.

5 | Conclusion and Recommendations

The system of the plantain rotary drying machine has been established to be a series/parallel combination reliability network. The retrieved data was analyzed and the data modelling of the rotary drying machine output shows that 0.06%, 0.04% and 0.05% of the variation in behavioral signature at: no degradation no loading; no degradation and loaded state; and degradation under loaded state operation conditions are accounted for by a linear, and polynomial relationship, respectively. This is an indication that the signature of the rotary dryer changes between linear when being normal and polynomial when the components are failing.

Based on the study findings, the following recommendations will be helpful for researchers and engineers (mostly machine developers) within the shores of the country and West Africa countries, whose goal is to meet up with United Nations Sustainable development goal 9, which is basically on technology innovation.

i. i. For better implementation of machine development, critical components or the so called bought out components must be genuinely sought for in order to ensure better reliability of the machine developed. In order words, scraps or already discarded components should not be used on newly fabricated machines.

ii. ii. Installation of machines must be done in accordance with recommended standards.

iii. iii. Performance or functional evaluation should not only be based on throughput assessment, but should start with the components arrangement optimization at cell levels and subsystem levels.

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