Original Research

A Modified Bayesian Model for Sustainable Production System Effectiveness Measurement under Competitive Environment

Buliaminu Kareem*[1], Jimoh Anakobe Yakubu[2], Basil Olufemi Akinnul[3]

Received: 12 March 2023/ Accepted: 10 April 2025/ Published online: 15 June 2025

***Corresponding Author Email, bkareem@futa.edu.ng.**

1,3 – Department of Industrial and Production Engineering, Federal University of Technology Akure (FUTA), Akure, Nigeria.
2- Department of Mechanical Engineering, Federal University of Technology Akure (FUTA), Akure, Nigeria.

Abstract
The need to determine the sustainability of the established industries demands the development of a model at resolving sustainable productivity challenges. The attributes (internal and external) of industrial failure were identified from the literature and the responses of the interviewed industrial experts. System Effectiveness (PSE) factors (availability, performance and quality) were determined using both traditional and Modified Bayesian (MBA) models in order to arrive at manageable decision-making criteria under certainty and uncertainty conditions. Initial measurements of PSE were based on the identified internal factors (manpower, machine, material, energy, management, information / communication, money and marketing), while sustainability decisions were determined using external factors (sustainability trend, globally acceptable standards, industrial revolution class, and competition level). The model was tested using weighted and normal data from the five selected companies to determine their sustainability performances, while paired t-test statistic was used to test the levels of significant difference between weighted and normal PSE at 5 %. The results indicated varying optimum decisions which were influenced by the nature/types of competition, uncertainty and standards of measurement. Statistical result showed that there was a significant difference between the normal and weighted PSE; p (0.007 < 0.05). However, the differences had little or no effect on sustainable decision making in all companies investigated.

Keywords: Productivity Challenges, System Effectiveness, Sustainable Decision, Competition

INTRODUCTION

Sustainability means meeting the needs without compromising the needs of future generations [1]. Apart from material resources, machinery, manpower, energy, marketing, information technology, and money/funding sustainability are very important. Sustainable productivity performance of industries required optimum harmonization of the stated resources in the delivery of core production process [2]. Efforts and programs targeted at improving productivity in Nigerian industries have not yielded significant results [3]. Energy is an important factor in all the sectors of any country's economy [4]. The *per capita* energy consumption is a measure of the *per capita* income as well as a measure of the prosperity of a nation [5].

The energy improvement challenges have adversely affected the productivity of other resources in the production systems. With increasing globalization, human capital and manpower development, machine revolution, material advancement, modern communication, advanced marketing and energy hybridization, a good sources utilization policy is required and can be accessed through qualitative education and training in sources management [6]. Human capital development is crucial and ultimate in propelling productivity. Equipment and technology are products of human minds and can only be made productive by human beings.

From the past studies [7]-[13], factors that influence sustainable production process were grouped into internal and external factors. Internal factors are manpower development, machine revolution, material choice and selection, management strategy, energy utilization/availability, information acquisition method, money/funding rate, and marketing strategy [3]. The external factors are sustainable trend, sustainable global trend and industrial revolution class [14]-[17].

The persistent failure in production process due to inadequacy of production resources has been affecting the production system productivity performance. The study that identified and integrated both internal and external factors responsible for productivity failure is rare. A model is necessary to holistically consider all factors that affect both productivity performance and sustainable development. Consideration of internal and external factors in such a model is important to realize a sustainable system that allows a best choice of process that gives room to elimination of wastes. Hence, a Modified Bayesian Model (MBA) was developed as alternative to static traditional effectiveness models to enable measures of effectiveness under uncertainty, risk or competitive conditions. This aim was achieved by identifying the factors that influence sustainable productivity in production system; develop a sustainable effectiveness decision making criteria MBA model using the identified factors; and evaluate the performance of the MBA developed. The target is to enhance production system effectiveness through application of MBA as an instrument of wastes (losses) eradication.

LITERATURE REVIEW

The manufacturing industry is a large industry that undertakes series of activities, which include the production of different items, machines, equipment etc. There are a range of sections in the manufacturing industry, starting from the managerial, production, maintenance sections down to inspection departments. Due to competition among corporations, industries, businesses, firms and organizations, there are always the need for innovation to enhance sustainable development [18]-[19]. Sustainable development is a long-term continuous development of society, which aims at satisfying humanity's need at present and in the future via rational usage, replenishment and preservation of resources [20]. Manufacturing (production) industries have been playing a prominent role in resources management towards achieving a sustainable development goal by 2030 [3].

In line with the sustainable development goal, production industries required a good transportation system (by land, water or air) which comprises automobiles, marines and aeronautics. Transportation industries have played a good role in sustainable development in the areas of safe transportation of raw materials and finished goods to/from the production industries [21]. Good transportation system has enabled wastes elimination, and prompt delivery of raw materials and other production resources, and thereby enhancing resources utilization, management and sustainability [22]-[23]. This means a huge investment is necessary on infrastructure for the industries to thrive, reach their sustainable capacities and attain accelerated Gross National Product (GNP). On this basis, strategic planning geared towards promoting adequate investment in the manufacturing industry is necessary [23].

The global demand for effective utilization of resources is increasing due to excessive wastes during manufacturing that have made entrepreneurs find it difficult to breakeven. The development of dynamic error-proof Overall Equipment Effectiveness (OEE) model for optimizing the operations of a complex production system is targeted at minimizing/eradicating wastes/losses [3]. Automation of industrial processes has been done to improve efficiency [24]. Lean tools have been applied to eliminate unproductive activities [25]. Strategies for personnel's heath cost reduction have been devised to improve efficiency, effectiveness and productivity [26]. Standard energy management procedures have been applied to enhance energy conservation and utilization effectiveness [27]. A unified linear programming model and data envelopment analysis method has been applied to assess the efficiency and effectiveness of a process [28]. Fuzzy Failure Mode and Effects Analysis (FMEA) model has been applied to a case of material quality challenge [29].

Performance of an industry has been evaluated using an integrated fuzzy structured methodology [30]. A resilience model that combined competitive risk model and semi-Markov process has been utilized to manage maintenance and reliability challenges [31]. Operational and management practices effectiveness has been assessed [32]. Sustainable industrial development has been determined using promotional and consumption behavior of customers [1]. Sustainable measures have been re-designed to include accountability measurement [33]-[34].

The digital transformation through incorporation of information and communication technologies (ICT) is changing the manufacturing landscape as companies begin to use: the Internet of Things to connect manufacturing assets; big data analytics to monitor plants; and artificial intelligence to support decision-making processes [16], [35]-[39]. Historic product characteristics (origin, quality, lead time, design change, etc.) data can be saved and retrieved when required [40]. Smart supply chain and transportation system is critical to industrial productivity [41] . The integration of simulation/artificial intelligence with physical systems has made virtual models to be sensitively aligned with the current state of physical processes [42]. Awareness on application of innovative energy system has resulted to minimizing losses in production process [43]-[44]. Many strategies, [27] for example, have been developed at reducing energy wastes to enhance sustainable and competitive industrialization.

Many of the stated studies have been developed to eliminate wastes in the production environment in order to attain global desire for sustainable development. Despite these efforts, many nations are still suffering from industry's sustainable challenges due to continuing losses in the process. The strategies of eliminating (reducing) losses have been widely discussed in literature. However, many of these challenging losses are being treated in isolation. There is the need for a new strategy capable of addressing all the sources of losses as a whole. This is one of the gaps to address by this study.

I. Production System Effectiveness (PSE)

The losses encounter in the production process have direct effects on the three critical factors (availability rate, performance efficiency and quality rate) on which production system effectiveness (PSE) measurement depends. PSE increases with increasing any of the three factors. Increase in availability rate means breakdowns is reducing while effective production capacity is increasing. Quality improvement is an indication of less scrap/rework [45]-[46]. PSE is a complete performance measurement indicator, but to make it realistic it requires modification in terms of weights allocation [47], inclusion of production system dynamism, and consideration of production competitiveness. Factors affecting PSE are not equally important in all aspects and hence different weight allocation to elements is necessary. Many strategies of weight sharing have been proposed [48]-[49]. In all cases, the choice of weighting method depends on the nature and objective of the problem.

Kwon [50] proposed how to calculate increasing profits or decreasing costs from an increasing percentage of PSE. Wudhikarn *et. al.* [51] proposed new PSE indicator based on cost losses without considering production competitiveness. Formulation of MBA model that considers integration of dynamism and competitiveness into the convention methods of PSE and weighed PSE measures is expected to produce a more realistic result. Sustainable standards in which production system effectiveness are measured and their sources are enumerated in Table I. In this study, choice of sustainable PSE is made by considering the sustainable standards simultaneously; this type of combination is rare in literature.

TABLE I:
SUSTAINABLE STANDARD OF PRODUCTION SYSTEM EFFECTIVENESS / PRODUCTIVITY

Sustainable Standards/Classes	Effectiveness/Productivity Range	Sustainability Implication
Sustainable Global Standard, P(G)	≥ 0.85	Sustainable
	< 0.85	Not Sustainable [14]-[15]
Sustainable Trend, P(T)	0 – 0.5	Not sustainable
	0.51 – 0.84	Fairly/averagely sustainable
	0.85 – 1.0	Sustainable [52], [3]
Industrial Revolution Class I, P(R)	0 – 0.5	I1.0 (Not Sustainable)
	0.51 – 0.84	I2.0 (Fairly sustainable)
	0.85 – 1.0	I3.0 – I4.0 (Sustainable)

≥ 1.0	I5.0 (Sustainable) [16], [3]

There have been a number of studies that applied Bayesian approach to productivity, efficiency, and/or effectiveness measures of a production process. In those studies possible losses on the three principal effectiveness factors- availability, performance and quality are the main focus of address. Bayesian based models have been applied to production processes for decision making in the areas of: risk/resources management by utilizing best and worst scenario/prediction [53]-[55]; quality control/ tolerance management [56]-[59]; supply chain management [4], [60]-62]; process design choice [48], [63]; energy utilization effectiveness [64]-[65]; surveillance and control [66]; process monitoring [67]; resources allocation/management [68]-[69]; reliability, availability or integrity monitoring [70]-[76]; material removal-rate/management [77]; and system shock and maintenance management based on resilience model using semi-Markov process [31], [78].

It is noticeable from the Bayesian related studies that models are applied to measure efficiency, effectiveness or productivity of a process in terms of availability, performance or quality. The MBA model, apart from taking measurement of the combined factors, a suitable weight sharing Rank-Order Centroid (ROC) strategy is integrated into the model to enable effective sensitivity analysis across process factors. Also process dynamism and competitiveness have been considered in the new model through introduction of seven competitive criteria- minimin, minimax, maximax, maximin, hauwitcz, laplace and minmax-regret, and their associated weights. Sustainability of the outcomes was determined by comparing them with the established standards- sustainable trend, sustainable global trend and industrial revolution class. The stated modifications of Bayesian models have not been holistically considered in the past studies.

In MBA formulation, acceptability of a process was determined on success ‘good’ or failure ‘poor’ basis. The two attributes (prior probabilities) are used to generate three possible binomial process probabilities with expected outcomes sustainable, average or unsustainable process. Process improvement was made in favour of new information that reveals a number of successes in failure and vice versa. On this basis posterior probabilities of the process- sustainable, average, or unsustainable are generated. The steps are applied to predict process sustainability status of individual or combined-factor of effectiveness; availability, performance and quality. Sensitivity and competitive analyses are done by varying weights across the process factors and introducing seven risk/competitive criteria. Performance evaluation of the MBA is carried out by comparing its outcomes with a traditional model and the three sustainable standards. Significant difference statistic between the methods is done using paired t-test.

METHODOLOGY

I. Framework for Model Development

Factors that hinder productivity in terms of availability, performance and quality in selected production systems are identified from previous studies and responses by relevant industrial experts. These productivity challenges are subjected to external (outside production system) and internal (within production system) factor assessments. The identified internal factors (sources of challenges) are manpower, money, machine, energy, management, information/communication, material and marketing while external factors are sustainable development trend, sustainable global standard and industrial revolution class. The block diagram that relates the internal and external factors called challenges is shown in Figure I. The proposed solution strategies to eliminate these (wastes/loses) challenges are as depicted in Figure II. These challenges can either be treated in isolation or simultaneously. Figure III shows modeling characteristic solution proposed to address industrial sustainability challenges.

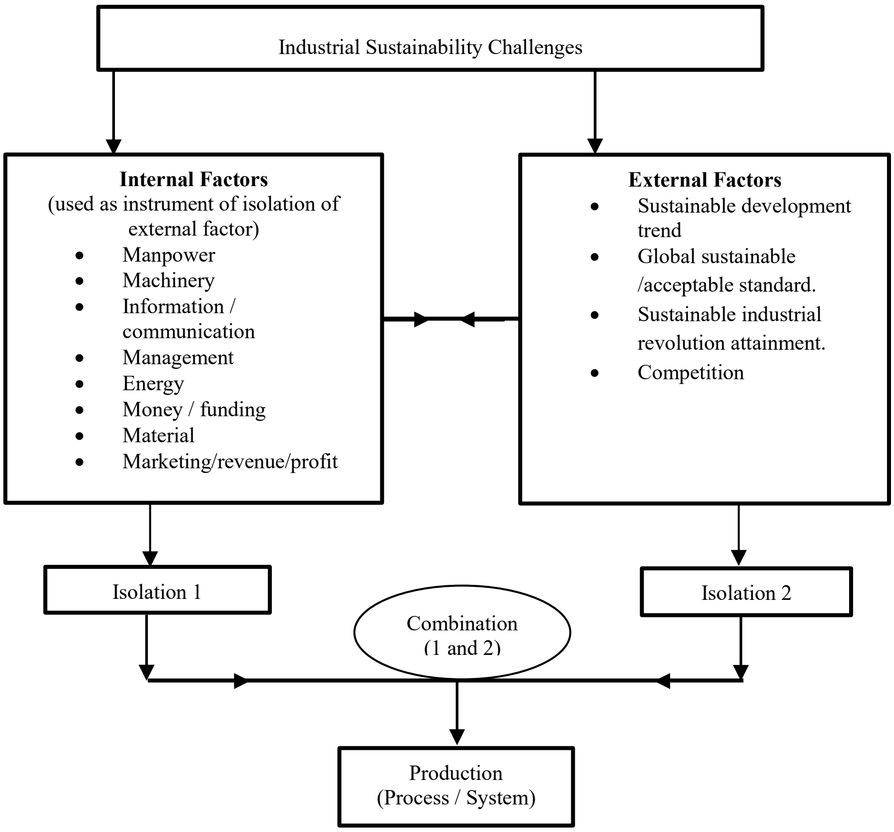

FIGURE I

PRODUCTION PROCESS CHALLENGES RELATIONSHIP

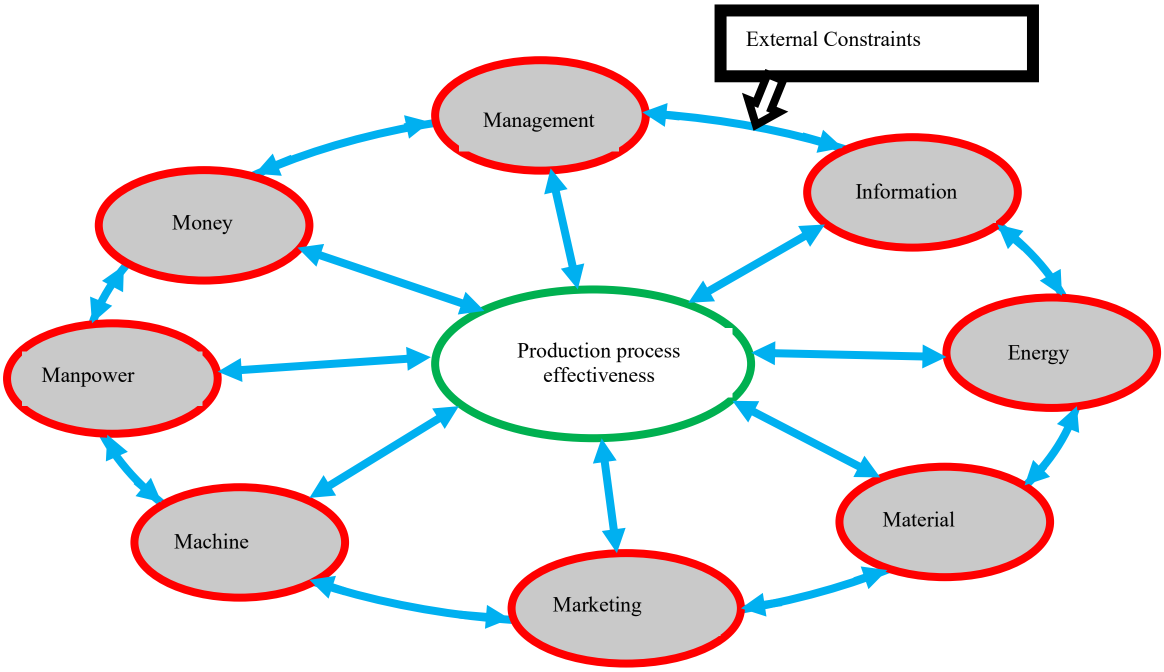

FIGURE II

BLOCK DIAGRAM FOR COMBINED PRODUCTION SYSTEM EFFECTIVENESS CHALLENGES

On the basis of traditional equations (Table II(1)) PSE is modified to form Eqn.1 after considering the challenges (Figure II). The established improvement strategy to attain normal (perfect) condition is illustrated by Figure III.

$$PSE = P(S) = P(I)P(p)P(O) < 1 \quad (1)$$

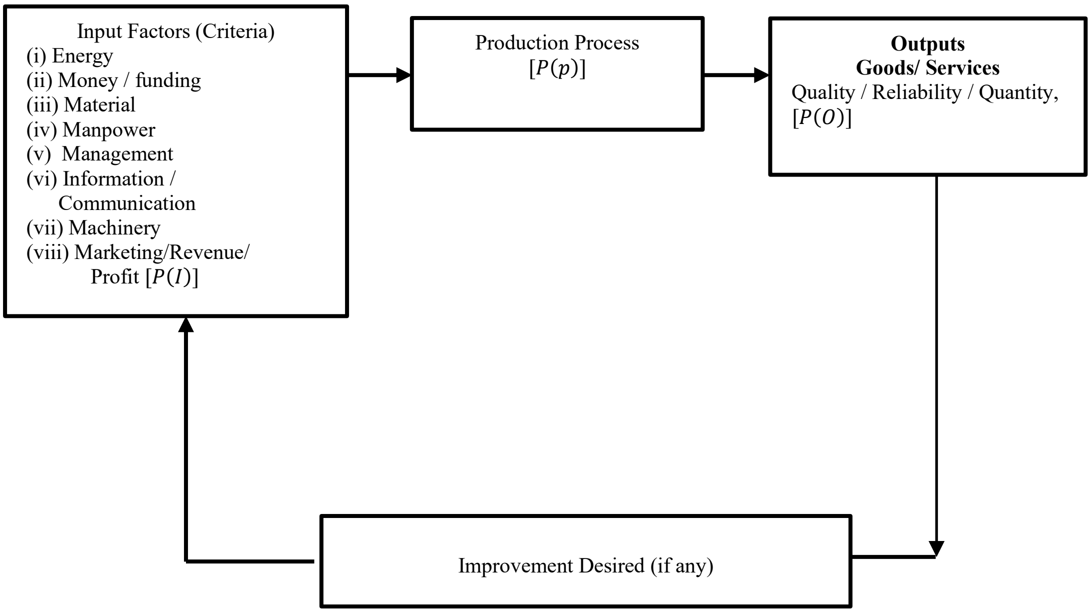

FIGURE III

BLOCK DIAGRAM OF MODELING CHARACTERISTICS

The problem is how to improve productivity P(S) such that external factors (sustainable trends, $P(T)$, sustainable global standard, $P(G)$, and industrial revolution class, $P(R)$) hindrance is satisfied (Table I); as presented in Eqns 2, 3 and 4, respectively.

$$P(S) = P(I)P(p)P(O) \geq P(T) \quad (2)$$

$$P(S) = P(I)P(p)P(O) \geq P(G) \quad (3)$$

$$P(S) = P(I)P(p)P(O) \geq P(R) \quad (4)$$

The main objective of meeting the condition of productivity for perfect system (Eqn. 5) is rear in practice.

$$P(S) = P(I)P(P)P(O) = 1 \quad (5)$$

Eqn. 5 is modified further to allow: weighting of the system effectiveness factors using Rank-Order Centroid (ROC) method [47], [49], because it can be easily fitted into the three effectiveness factors in which ranks 1, 2, and 3 are allocated as highest, average and lowest weights respectively to satisfy the three contending factors; and inclusion of seven risk/uncertainty management criteria that are capable of representing competitive state of production environment. The weighting production system effectiveness (WPSE) was estimated using Eqns. 6, 7, 8, 9 and 10 [47]. Also, Eqn. 6 is for the weighted perfect system, which is very rear in practice.

$$P(S) = WPSE = w_1 I + w_2 P + w_3 O = 1 \quad (6)$$

Based on ROC method (Raouf, 1994):

$$W_i = \left(\frac{1}{K}\right) \sum_{j-i}^{K} \frac{1}{r_k} \quad (7)$$

$$w_1 = \left(1 + \frac{1}{2} + \frac{1}{3} + \cdots \ldots . +1/K\right)/K \quad (8)$$

$$w_2 = \left(0 + \frac{1}{2} + \frac{1}{3} + \cdots \ldots . +1/K\right)/K \quad (9)$$

$$w_3 = (0 + 0 + 0 + \cdots \ldots . +1/K)/K \quad (10)$$

All the stated parameters are as defined before in Table II. It is inferable from the foregoing that if $P(S) = 1$, no challenges in the system (sustainable), (11)

$P(S) = 0,$ System has collapsed, (12)

$P(S) < 1,$ System is gradually collapsing but may be sustainable (13)

These (Eqns 11-13) have led to two major decisions (success or failure), under three conditions: good (sustainable); fair (averagely) sustainable; and poor (unsustainable). These alternatives decision outcomes are shown in Figure IV. The main target is to have an agile production system in which P(S) ≈ 1 by satisfying the predetermined process demands and sustainable standards (Eqns. 2, 3 and 4). See Table II(5) for definition of symbols.

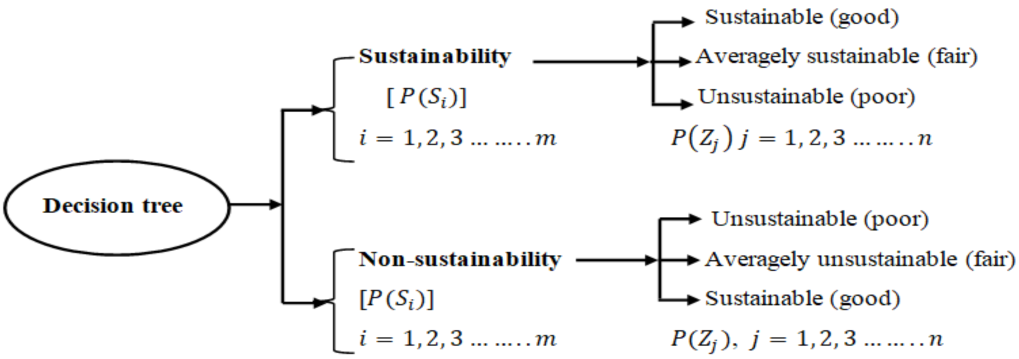

FIGURE IV

DECISION TREE ON SUSTAINABLE PRODUCTION PROCESS

The value of $P(S)$ has been priory estimated from data/information obtained from a production process. This is improved upon to accommodate better information leading to emerging conditions of the process $P(Z_j)$ at a known $P(S_i)$ (Table II(5)) as:

$$P[Z_j] = \sum_{i=1}^{m} P[S_i, Z_j] = \sum_{i=1}^{m} P\left[\frac{Z_j}{S_i}\right] \times P[S_i] \quad (14)$$

On this basis, condition-based probability of the process sustainability $P[Z_j/S_i]$ has been posterior modeled as $P[S_i/Z_i]$.

$$P\left[\frac{S_i}{Z_j}\right] = \frac{P[S_i, Z_j]}{P[Z_j]} = \frac{P\left[\frac{Z_j}{S_i}\right] \times P[S_i]}{\sum_{i=1}^{m} P\left[\frac{Z_j}{S_i}\right] \times P[S_i]} \quad (15)$$

where:

$P[S_i/Z_j]$ is posterior probability

The stated approach is termed Bayes' probabilities for initial production process effectiveness based on salient production factors (manpower, machine, material, energy, management, information / communication, money and marketing) (Table II(6)).

II. PSE Factors Analysis using Modified Static Traditional Model

*Availability P(A)***:** Probability of attaining desired availability output production process (Table II(1)) is modified as Eqn. 16.

$$P(A) = \frac{\frac{\sum_{i=1}^{N} t_i^L}{N} - \frac{\sum_{i=1}^{N} t_i^S}{N}}{\frac{\sum_{i=1}^{N} t_i^L}{N}} \quad (16)$$

$$\sum_{i=1}^{N} t_i^S = summation\ of Processing\ \ loss\ time$$

Other terms are as defined in Table II(1).

For every industry, it is expected that time loses due to failure/idle time should not exceed the minimum allowable range for availability (Table II(10)). For example, on the basis of industrial revolution class [3], [12], we have the following ranges: 0.1 – 0.50% for Industry 1.0 (poor, unsustainable); 0.51– 0.84% for Industry 2.0 (fair, averagely sustainable); 0.85 – 1.0% for Industry 3.0 to 4.0 (good, sustainable; and 1.0 for Industry 5.0 (excellently sustainable).

The same procedures are applied to evaluate performance and quality effectiveness using their respective equations as stated in Table II(1). The similar models stated in Table II(1) are also applied across the case study companies.

III. Bayesian Model Modifications

The Bayesian model was modified by integrating weighting factors and competitive criteria into it. Decision analysis based on Modified Bayesian Approach (MBA) was utilized to model the stochastic nature of the production system. The modeling outcomes, after integrating weighting factors and risk/competitive criteria into it are given in Table II. First, the initial (availability, A, performance, P, and Quality, Q) productivity measures were modified to reflect real and dynamic probabilistic situation of production system (as probabilities of: input resources availability, $P(I)$; process performance, $P(p)$; and output quality, $P(O)$). Second, the outcomes from first step were partitioned into either success (good), $P(\,)_S^*$, or failure (poor), $P(\,)_f^*$ productivity. Third, binomial probability model was modified and applied to translate the process into three real life productivity scenarios: good or sustainable; fairly or averagely sustainable; and poor or unsustainable. Fourth, prior probabilities of process sustainability were measured based on functionality of available production resources by focusing on radical production machinery. Fifth, process conditional probability was estimated based on success, failure and success/failure sustainability scenarios. Sixth, process sustainability (posterior) probability, $P[S_i/Z_j]$ was established under normal and weighting for availability, performance and quality, $S_i$respectively at a given condition, Z_j good, poor, or both. Next, Production System Effectiveness (PSE), $P(S)$ was determined under normal and weighting conditions. Then, further decision analysis under risk/competition was done using the seven (maximin, minimax, maximax, minimin, laplace, Hurwitz, and minimax regret) criteria [79]. Finally, sustainable decision (sustainable or unsustainable) was made using three sustainable standards: sustainable trends, $P(T)$, global acceptable standard, $P(G)$, and industrial revolution class, $P(R)$. Results were tests using paired t-test statistic to determine whether there are significant difference between the traditional model and MBA's PSE and WPSE outcomes for a company.

TABLE II
SUMMARY OF THE MATHEMATICAL MODELS DEVELOPMENT

S/n	Parameter	Traditional / Convectional (Old Model)	Newly Bayesian-based Modified Model	Definition of symbols
1	Initial condition of production process	$Availability\ (A)$ $A = \frac{Operation\ time}{Loading\ time}$	$P(I)^1 = \frac{\frac{\sum_{i=1}^{N} t_i^L}{N} - \frac{\sum_{i=1}^{N} t_i^S}{N}}{\frac{\sum_{i=1}^{N} t_i^L}{N}}$	i = 1, 2, 3 ……. N is number of input load $\sum_{i=1}^{N} t_i^L$ summation of loading time in hour $\sum_{i=1}^{N} t_i^S$ is summation of processing time
		$Performance\ (P) = \frac{Net\ Processing\ ti}{Operating\ tim}$	$P(p)^1 = \frac{\frac{\sum_{i=1}^{N} t_i^P}{N} - \frac{\sum_{i=1}^{N}\sum_{j=1}^{M} t_{ij}^S}{N\times M}}{\frac{\sum_{i=1}^{N} t_i^P}{N}}$	i = 1, 2, 3 ……. N = number of input load $\sum_{i=1}^{N} t_i^P$ is Processing time in hour $\sum_{i=1}^{N}\sum_{j=1}^{M} t_{ij}^S$ is summation of loses due to start-up, shutdown, changeover etc.

		$Quality\ (Q) = \frac{Processed\ amount - defect\ amount}{Processed\ amount}$	$P(O)^1 = \frac{\frac{\sum_{i=1}^{N} Q_i}{N} - \frac{\sum_{i=1}^{N}\sum_{j=1}^{M} Q_{ij}^S}{N\times M}}{\frac{\sum_{i=1}^{N} Q_i}{N}}$	i = 1, 2, 3 ……. N = number of input load $\sum_{i=1}^{N} Q_i = processed\ amount$ $\sum_{i=1}^{N}\sum_{j=1}^{M} Q_{ij}^S = rework\ or\ defects$
2	Success in failure and failure in success Probability	Availability Effectiveness P(I)*	(i) $P(I)_S^* = \frac{\sum_{j=1}^{N} T_C}{\sum_{j=1}^{N} T_t}$ (ii) $P(I)_f^* = 1 - P(I)_S^*$	$P(I)_S^*$ is Availability Success probability $\sum_{j=1}^{N} T_C$ is summation of corrective Loading time process $\sum_{j=1}^{N} T_t$ is summation of total Loading time process $P(I)_f^*$ is probability of failure in success process
		Performance Effectiveness $P(p)^*$	(i) $P(p)_S^* = \frac{\sum_{j=1}^{M} L_C}{\sum_{j=1}^{N} L_t}$ (ii) $P(p)_f^* = 1 - P(S_{FP})$	$P(p)_S^*$ is performance Success in failure probability $\sum_{j=1}^{N} L_C$ is summation of corrective Loss time process $\sum_{j=1}^{N} L_t$ is summation of total Loss time process $P(p)_f^*$ is probability of failure in success process
		Quality Effectiveness $P(O)^*$	$(i)\ P(O)_S^* = \frac{\sum_{j=1}^{M} P_{CA}}{\sum_{j=1}^{N} L_{TA}}$ (ii) $P((O)_f^* = 1 - P(Q_{FQ})$	$P(O)_S^*$ is Quality success in failure probability $\sum_{j=1}^{N} P_{CA}$ is summation of corrective processed amount $\sum_{j=1}^{N} L_{TA}$ is summation of total Loss amount process $P(f_Q)$ is probability of failure in success process
3	Prior probability of success in failure	(All processes are sustainable, Processes are averagely sustainable and all processes are unsustainable)	$Success, P = \frac{Total\ input\ factor - Machinery\ input\ factor}{Total\ input\ factor}$	Total input factor is 8 Machinery input factor is 1
		Prior Probability failure in Success	$Failure, 1 - P = (1 - probability\ of Success)$	
4	Prior Probability of process events (success, failure, both)	(i) Binomial probability (i) $P(X) = \left[\begin{smallmatrix}N\\X\end{smallmatrix}\right] P^X(1-P)^{N-X}$	$P(Z_j) = C_j^{N-j} P^j(1-P)^{N-j}$ $j = 0,1, \dots N$	X is the number of successes in N binomial trials, P is the probability of success in each trial. q = 1- p Means = Np, standard deviation = $\sqrt{(Npq)}$

5		(ii) Conditional probability	(ii) $P[Z_j] = \sum_{i=1}^{m} P[S_i, Z_j] = \sum_{i=1}^{m} P[Z_j/S_i] \times P[S_i]$	$P[Z_j]$ is prior probability $P[S_i, Z_j]$is posterior probability based on new information (sustainable, averagely sustainable and non-sustainable). $P[Z_j/S_i]$is conditional probability of system sustainability. $P[S_i]$ is probability of system probability j $= 1, 2, 3 \dots \dots . . n$is the j[th] conditional outcomes (fully sustainable, averagely sustainable and non-sustainable) of the production system. $i = 1, 2, 3 \dots \dots . . mis\ the i$[th] sustainability level (sustainable or non-sustainable) associated with production system.
6		(iii) Posterior probability	(iii) $P[S_i/Z_j] = \frac{P[S_i Z_j]}{P[Z_j]} = \frac{P[Z_j/S_i] \times P[S_i]}{\sum_{i=1}^{m} P[Z_j/S_i] \times P[S_i]}$ (Bayes' probabilities)	Same as in 2(ii)
7	Decision Making under Condition of Uncertainty	(i) Maximin criterion max $\theta_j[v(a_i, \theta_j]$ minθ_j $[v(a_i, \theta_j]$ (Pessimistic approach)	max $Z_j[v(a_i, Z_j]$ minZ_j $[v(a_i, Z_j]$	$\theta_j = \ Action\ choosen$ $[v(a_i, \theta_j]$ = Decision outcome
		(ii) Minimax criterion max $Z_j[v(a_i, Z_j]$ minZ_j $[v(a_i, Z_j]$ (Optimistic approach);	max $Z_j[v(a_i, Z_j]$ minZ_j $[v(a_i, Z_j]$	$Z_j = \ Action\ choosen$ $[v(a_i, Z_j]$ = Decision outcome
		(iii) Maximax criterion;	max $\theta_j[v(a_i, Z_j]$	The decision maker becomes completely optimistic and choose a strategy that is expected to give the best of the best payoffs.
		(iii) Minimin criterion	minθ_j $[v(a_i, Z_j]$	The alternative which minimizes the minimum cost is selected. This is termed as minimin criterion
		(iv) Laplace criterion $\theta_1 = max_{n_j}\left[\frac{1}{n}\sum_{j=1}^{n} v(\theta_i,\right.$	$Z_1 = max_{n_j}\left[\frac{1}{n}\sum_{j=1}^{n} v(Z_i, Z_j)\right]$	θ is probability associated with occurrence $\frac{1}{n}$ is the probability that $\theta_j (j = 1, 2, \ . \ . \ ., n)$ occurs

		(vi) Hurwitz criterion $D_i = \alpha M_1 + (1-\alpha)m_2$	$H_i = \alpha M_{S_1} + (1-\alpha)m_{S_2}$	$D_i = H_i$ = hurwicz criterion decision index α = hurwicz decision maker's degree of optimum $M_1 = M_{S_1}$ = maximum payoff from any of the outcomes resulting from the ith strategy. $m_2 = m_{S_2}$ = minimum payoff from any of the outcomes resulting from the ith strategy.
		(vii) Minimax Regret Criterion (Savage Criterion)	(i) ith regret = max payoff $-ith$ payoff for jth event (ii) ith regret = ith payoff $-$ maximum payoff. Choose the minimum of the maximum regret.	-
8	Production System Effectiveness (PSE)	$P(S) = APQ$	$P(S) = P(I)P(p)P(O)$	$P(S)$is production process A is Availability P is Performance Q is Quality $P(I)$ is probability of Input Availability $P(p)$ is is probability of process performance $P(p)$ is is probability of output quality.
9	hted Production m Effectiveness ;E)	$W_i = \left(\frac{1}{K}\right)\sum_{j-i}^{K}\frac{1}{r_k}$	$WPSE =$ $w_1P(A) + w_2P(p) + w_3P(O)$ $w_1 = \left(1 + \frac{1}{2} + \frac{1}{3} + \cdots \dots + 1/K\right)/K$ $w_2 = \left(0 + \frac{1}{2} + \frac{1}{3} + .. + 1/K\right)/K$ $w_3 = (0 + 0 + 0 \pm - + 1/K)/K$	$WPSE$ is weighted production process effectiveness r_k $is\ rank\ of\ the\ kth\ objecti$ $K\ istotal\ number\ of\ objecti$ $w_i$is the weight optimizing objectives $w_1$is weight of availability p(I) w_2 is weight of performance P(p) w_3 $is\ weight\ of\ quality\ P(O$ attribute
10	Sustainability evaluation		$P(S) = P(I)P(p)P(O \geq P(T)$ $P(S) = P(I)P(p)P(O) \geq P(G)$ $P(S) = P(I)P(p)P(O) \geq P(R)$	$P(T), Sustainable\ trend \geq 0.85, 1.0$ $P(G), Global\ standard \geq 0.85$ $P(R), Industrial\ Revolution \geq 0.85, 1.0$

IV. *Model Performance Analysis*

In order to analyze the efficacy of the model, relevant data were collected using questionnaire and oral interview from the five (5) selected companies namely: plastic industry- Company A; steel industry-Company B; food processing industry-Company C; beverage industry-Company D; and fabrication industry-Company E. The data were collected on production process, working hours, downtime, product rejection etc; these data were used for estimating relevant parameters (Sections 3.1 – 3.3, Table II). Estimated parameters include: Availability Rate, Production Process Performance, Quality rate, Production System Effectiveness (PSE), and decisions on sustainable production process are made based on established standards (Tables I and II). The summaries and nature of the data collected from Company-A, B, C, D, and E are given in Tables III, IV, V, VI and VII, respectively. The data obtained include: production data (plant time, set-up time, loading time and off-loading time), downtime data (idling losses, minor stoppage and reduced speed), and product reject data (rework losses, defect losses, start-up losses and scrap losses. In addition, data were collection on weights ranking of Production System Effectiveness factors as given in Table VIII.

Data was processed using the established parameters for PSE measurement for the companies in steps: computation of PSE losses; computation of Availability value; computation of Production Process Performance value; computation of process Quality value; and the final, computation of overall PSE value. The PSE results obtained were compared at traditional, Bayesian and modified Bayesian (normal and weighted) levels to determine the performance of the MBA model.

TABLE III
TRADITIONAL APPROACH APQ RESULTS OF COMPANY A

Company A											
Process line Product: Cement processing line/Eight (8) hours shift											
Input Factor	Availability P(I) /hour = A		Performance P(p) /hour = P				Quality P(O)/quantities (kg) = Q				
	Plants Time/(Set-up /h	Loading Time = (Process + loading + off-loading) time /h	Process Time /h	Operating time (Cycle time)/h: Idling losses/h	minor stoppage /h	Reduced speed /h	Processed Input Quantity kg	Defect loses amount/kg: Rework losses	Defect losses	Start-up loses	Scrapped loses
Manpower	8	8	8	1	2	0.5	1,200	25	10	5	2
Machinery	6	8	7	1	2	1	1,000	50	22	12	3
Info./comm	8	8	8	0.5	1	1	950	15	5	5	1
Management	6	8	7	0.5	0	1	700	20	14	5	2
Energy	7	8	6	0.5	0	3	1500	22	12	5	4
Money/fund	8	8	7	0.5	0	1	2000	50	15	7	5
Material	8	8	7	1	0.5	0.5	1150	12	20	20	7
Marketing	8	8	8	0.5	1	0.5	1100	11	20	18	2
$\boldsymbol{PSE = APQ}$	0.9210		0.8806				0.9890				
	$(0.9210 \times 0.8806 \times 0.9890) = 0.8021$										

TABLE IV

TRADITIONAL APPROACH APQ RESULTS OF COMPANY B

Company B											
Process line Product: Cocoa bean processing line/Eight (8) hours shift											
Input Factor	Availability P(I) /hour = A		Performance P(p) /hour = P				Quality P(O)/quantities (kg) = Q				
	Plants Time/(Set-up /h	Loading Time = (Process + loading + off-loading) time /h	Process Time /h	Operating time (Cycle time)/h: Idling losses/h	minor stoppage /h	Reduced speed /h	Processed Input Quantity kg	Defect loses amount/kg: Rework losses	Defect losses	Start-up loses	Scrapped loses
Manpower	4	6	8	1	2	1	2,500	24	11	4	2
Machinery	6	8	7	1	2	1	1,700	45	22	3	1
Info./comm	4	7	6	1	1	1	1,200	0	6	7	3

Management	4	8	6	1	2	1	900	20	12	4	3
Energy	6	6	7	1	2	2	1400	22	14	4	2
Money/fund	8	8	6	1	2	2	1920	0	12	7	1
Material	2	8	6	2	1	0.5	2150	10	12	5	1
Marketing	1	5	6	1	2	0.5	1800	22	12	6	1.5
$\boldsymbol{PSE = APQ}$	0.62			0.79				0.99			
	$(0.62 \times 0.79 \times 0.99) = 0.4849$										

TABLE V

TRADITIONAL APPROACH APQ RESULTS OF COMPANY C

Company C											
Process line Product: Cement processing line/Eight (8) hours shift											
Input Factor	Availability P(I) /hour = A		Performance P(p) /hour = P				Quality P(O)/quantities (kg) = Q				
	Plants Time/(Set-up /h	Loading Time = (Process + loading + off-loading) time /h	Process Time /h	Operating time (Cycle time)/h			Processed Input Quantity kg	Defect loses amount/kg			
				Idling losses/h	minor stoppage /h	Reduced speed /h		Rework losses	Defect losses	Start-up loses	Scrapped loses
Manpower	4	7	8	2	1	0.5	5,500	5	9	3	3
Machinery	4	8	7	1	2	1	2,300	5	11	3	2
Info./comm	4	8	8	0.5	1	1	2,050	7	22	0	4
Management	4	8	8	0.5	0	1	1,700	0	11	2	5
Energy	4	6	8	1	1	3	1800	22	13	6	5
Money/fund	3	8	7	0.5	1	1	2,550	14	10	0	5
Material	1	8	6	2	1	0.5	7,000	11	10	2	1
Marketing	1	6	8	1	0.5	0.5	2,100	15	5	5	2
$\boldsymbol{PSE}$	0.4			0.86				0.997			
$\boldsymbol{= APQ}$	$(0.4 \times 0.86 \times 0.997) = 0.3430$										

TABLE VI

TRADITIONAL APPROACH APQ RESULTS OF COMPANY D

Company D											
Process line Product: Beverage processing/Eight (8) hours shift											
Input Factor	Availability P(I) /hour = A		Performance P(p) /hour = P				Quality P(O)/quantities (kg) = Q				
	Plants Time/(Set-up /h	Loading Time = (Process + loading + off-loading) time /h	Process Time /h	Operating time (Cycle time)/h			Processed Input Quantity kg	Defect loses amount/kg			
				Idling losses/h	minor stoppage /h	Reduced speed /h		Rework losses	Defect losses	Start-up loses	Scrapped loses
Manpower	5	8	8	1	2	1	3,200	15	14	2	1
Machinery	8	8	8	2	1	1	6,500	13	13	2	2
Info./comm	6	8	8	0.5	1	1	1,700	8	20	2	1
Management	6	6	8	0.5	0	1	2,200	11	0	2	1
Energy	5	8	6	0.5	0	3	3,000	21	22	3	3
Money/fund	8	8	8	0.5	0	1	3,000	12	11	2	4
Material	5	8	8	0.5	0.5	1	6,500	13	0	3	2
Marketing	5	5	8	0.5	1	0.5	3,200	10	15	3	1
$\boldsymbol{PSE}$	0.8			0.88				0.99			
$\boldsymbol{= APQ}$	0.6970										

TABLE VII
TRADITIONAL APPROACH APQ RESULTS OF COMPANY E

Company E											
Process line Product: Production processing line/Eight (8) hours shift											
Input Factor	Availability P(I) /hour = A		Performance P(p) /hour = P				Quality P(O)/quantities (kg) = Q				
	Plants Time/(Set-up / h	Loading Time = (Process + loading + off-loading) time /h	Process Time /h	Operating time (Cycle time)/h			Processed Input Quantity kg	Defect loses amount/kg			
				Idling losses/h	minor stoppage /h	Reduced speed /h		Rework losses	Defect losses	Start-up loses	Scrapped loses
Manpower	8	8	8	1	2	1	15,000	20	11	7	2
Machinery	8	8	6	0.5	4	0.5	11,000	22	4	7	3
Info./comm	8	8	8	1	2	0.5	12,500	18	11	7	3
Management	7	8	7	0.5	3	1	7,300	5	5	7	3
Energy	6	7	7	1	4	1	8,000	10	30	15	5
Money/fund	7	7	8	1	1	1	15,000	11	10	5	3
Material	6	8	6	0.5	2	1	4,500	17	12	7	1
Marketing	7	7	6	0.5	2	1	14,200	11	12	4	5
$\boldsymbol{PSE = APQ}$		0.9			0.8				0.99		
	$(0.9 \times 0.8 \times 0.99) = 0.7128$										

TABLE VIII
WEIGHTS RANKING ANALYSIS ON PRODUCTION EFFECTIVENESS FACTORS

Attributes PSE	Ranking $(\boldsymbol{r_k})$	Numerical calculation	Weight
		Company A	
P(I)	1	$W_1 = (1 + 1/2 + 1/3)/3$	0.61
P(p)	3	$W_2 = (1/3)/3$	0.11
P(O)	2	$W_3 = (1/2 + 1/3)/3$	0.28
		Company B	
P(I)	3	$W_2 = (1/3)/3$	0.11
P(p)	1	$W_2 = (1 + 1/2 + 1/3)/3$	0.61
P(O)	2	$W_3 = (1/2 + 1/3)/3$	0.28
		Company C	
P(I)	2	$W_1 = (1/2 + 1/3)/3$	0.28
P(p)	3	$W_2 = (1/3)/3$	0.11
P(O)	1	$W_3 = (1 + 1/2 + 1/3)/3$	0.61
		Company D	
P(I)	1	$W_1 = (1 + 1/2 + 1/3)/3$	0.61
P(p)	3	$W_2 = (1/3)/3$	0.11
P(O)	2	$W_3 = (1/2 + 1/3)/3$	0.28
		Company E	
P(I)	2	$W_1 = (1/2 + 1/3)/3$	0.28
P(p)	1	$W_2 = (1 + 1/2 + 1/3)/3$	0.61
P(O)	3	$W_3 = (1/3)/3$	0.11

V. *Methods of Model-based Data Analysis*

An experimentation of prior probability from the success in failure and failure in success of PSE factors (availability, performance and quality) in production process was performed on the data collected from the selected industries (Tables III-VII). The failures were recorded from occasional malfunctions in the production process (bad lots) which resulted to defects and other losses. Company's past experience (as evidenced from the data analysis) indicated that the probability of producing bad lots (losses) due to failure is 0.125, in which case the probability of production success (good lots) is 0.875. Let $S = S_1 (= S_2)$ indicates that the lot is good (bad), then $P(S = S_1) = 0.875$ *and* $P(S = S_1) = 0.125$ (Section 3.6).

The production company realized that by producing out a bad lot, many productions effectiveness were adversely affected. Due to small failures realized in the stated prior probability, it is saved for among the companies to implement randomly their production methods. However, further decision can be made after testing a method from the available choices; the additional information could definitely affect the final decision (failure/success). To fit the situation, a test of sample of two (2) processing methods was assumed from which three (3) outcomes were expected. The outcomes of the test were assumed to be: all processes are sustainable; processes are averagely sustainable (one sustainable, other unsustainable); and all processes are unsustainable.

Let $Z_1,\ Z_2, and\ Z_3$ represent these three outcomes, respectively.

The conditional probabilities $P[Z_j/S_i]$ are assumed to be available due to the fact that the method utilized is liable to failure (success). The ultimate objective is to use these conditional probabilities of the process together with the prior probabilities to compute the required posterior probabilities which are defined by $P[S_i/Z_j]$, that is, the probability of selecting either (good) or (bad lot)($S = S_1, or\ S_2$) given the outcome Z_j of the experiment. These probabilities formed the basis of making a decision (sustainable or unsustainable) depending on the outcome of the conditional probability test. The posterior probabilities $P[S_i/Z_j]$ were computed from the prior $P[S_i]$ and the conditional probabilities $P[Z_j/S_i]$, using Eqns. 14 and 15.

VI. Success and Failure Probability Analysis of the Companies

It was assumed that prior probabilities of success in failures are the same for all the five companies under investigation since eight (8) input factors (Manpower, Machinery, Information /Communication, Management, Energy, Money/fund, Material and Marketing) were considered (Tables 3-7) for all of them. It was believed that out of the input factors only 'machinery' cannot be instantaneously corrective during the process running.
Therefore,

$$P(Success) = \frac{Total\ input\ factor - Machinery\ factor}{Total\ input\ factor} \quad (17)$$

For a total input factor of 8 less the machinery factor (Tables 3-7), then

$$P(Success) = \frac{8-1}{8} = \frac{7}{8} = 0.875$$

Prior probability of success = 0.875
The corresponding prior probability of failure is obtained by subtracting success probability from unity.

Thus:

$$P(Failure) = (1 - probability\ of Success) \quad (18)$$

$$Failure = (1 - 0.88) = 0.125$$

Prior probability of failure =0.125
The outcome is similar for all the companies since all is operating on equal number of factor.

VII. Effectiveness Measures Based on New Information

From Table III, it shows that among the input factor identified machinery cannot be corrective during process running, the success in failure and failure in success probability of Company A of Availability [P(A)] effectiveness is calculated as follows. The success in failure of the production process of company A was modeled by the Eqn. 19 as stated (Table II(2)):

$$P(S_{FA}) = \frac{\sum_{j=1}^{N} T_C}{\sum_{j=1}^{N} T_t} \quad (19)$$

And

$$P(f_A) = 1 - \frac{\sum_{j=1}^{N} T_C}{\sum_{j=1}^{N} T_t} \quad (20)$$

$P(f_A)$ is probability of failure in success process. Other parameters are as defined in Table II (2).

Success in failure probability: From the data collected and values obtained in Table 3 of Company A, the process effectiveness of Availability can be calculated by dividing the difference of Plant time and Loading time of the input factors (manpower, machinery, info/comm., management, energy, money/fund, material and marketing). The calculation for the individual input factor for Availability (A):

(i) Manpower: $Loading\ time - Plant\ time = 8 - 8 = 0$

(ii) Machinery: $Loading\ time - Plant\ time = 8 - 6 = 2$

(iii) Info./Comm: $Loading\ time - Plant\ time = 8 - 8 = 0$
(iv) Management: $Loading\ time - Plant\ time = 8 - 6 = 2$
(v) Energy: $Loading\ time - Plant\ time = 8 - 7 = 1$
(vi) Money/fund: $Loading\ time - Plant\ time = 8 - 8 = 0$
(vii) Material: $Loading\ time - Plant\ time = 8 - 8 = 0$
(viii) Marketing: $Loading\ time - Plant\ time = 8 - 8 = 0$

The input factor which cannot be simultaneously corrective (Machinery) during process running is represented by (0). Therefore, the combined success in failure probability is calculated thus:

$$P(S_{FA}) = \frac{\sum_{j=1}^{M} L_j^C}{\sum_{j=1}^{M} L_j^{LT}} = \frac{0 + 0 + 0 + 2 + 1 + 0 + 0 + 0}{0 + 2 + 0 + 2 + 1 + 0 + 0 + 0} = \frac{3}{5} = 0.6$$

$P(S_{FA}) = 0.6$

Failure in success probability: Failure in success probability is obtained by subtracting the value of success in failure probability from unity and is calculated as follows (Table II(2)):

$P(f_A) = 1 - P(S_F) = 1 - 0.6 = 0.4$

$P(f_A) = 0.4$

Similar procedures are applied for analyzing performance and quality factors (Table 2) in other companies. Table IX shows the summary of Production System Effectiveness (PSE) on success in failure and failure in success probability for Availability P(A), Performance efficiency P(P) and Quality products P(O) across the companies.

TABLE IX
PSE SUCCESS IN FAILURE AND FAILURE IN SUCCESS PROBABILITIES

Industry type	Overall Production Effectiveness	Success in Failure	Failure in Success
Company A	Availability P(A)	0.6000	0.40
	Performance Efficiency P(P)	0.9189	0.08
	Quality product P(O)	0.9007	0.10
Company B	Availability P(A)	0.9048	0.09
	Performance Efficiency P(P)	0.8500	0.15
	Quality product P(O)	0.8773	0.12
Company C	Availability P(A)	0.8800	0.12
	Performance Efficiency P(P)	0.9150	0.08
	Quality product P(O)	0.9071	0.09
Company D	Availability P(A)	1.0000	0.00
	Performance Efficiency P(P)	0.9020	0.09
	Quality product P(O)	0.7770	0.22
Company E	Availability P(A)	1.0000	0.00
	Performance Efficiency P(P)	0.9565	0.04
	Quality product P(O)	0.8698	0.13

VIII. Conditional Probabilities of Company A

Availability (0.60 / 0.40) for good/bad in good lot of Company A

Since the percentage of defective in a good lot is 40%, while a bad lot has 60% defective items (Table 9). Then based on a binomial distribution and a sample of size 2, the conditional probabilities of an outcome Z_j given a lot is good or bad are as follows:

(i) $P[Z_1/S_1] = C_2^2(0.60)^2(0.40)^0 = 0.3600$
(ii) $P[Z_2/S_1] = C_1^2(0.60)^1(0.40)^1 = 0.4800$
(iii) $P[Z_3/S_1] = C_0^2(0.60)^0(0.40)^2 = 0.1600$

Availability (0.40 / 0.60) for good/bad in bad lot of Company A

The percentage of defective in a good lot is 60%, while a bad lot has 40% defective items, then based on a binomial distribution and a sample of size 2, the conditional probabilities of an outcome Z_j given a lot is good or bad are as follows:

(i) $P[Z_1/S_1] = C_2^2(0.40)^2(0.60)^0 = 0.1600$
(ii) $P[Z_2/S_1] = C_1^2(0.40)^1(0.60)^1 = 0.4800$
(iii) $P[Z_3/S_1] = C_0^2(0.40)^0(0.60)^2 = 0.3600$

These probabilities can be summarized conveniently as shown in the Table X.

TABLE X
AVAILABILITY PROBABILITY OF GOOD/BAD OF THE PROCESS OF COMPANY A

$P(Z_j/S_i) =$

	Z_1	Z_2	Z_3
S_1	0.3600	0.4800	0.1600
S_2	0.1600	0.4800	0.3600

Given $P(S = S_1) = 0.875$ *and* $P(S = S_1) = 0.125,$ the joint probabilities $P(S_{i,}Z_j) = P(Z_j/S_i/\ P/S_i)$ can be determined from the foregoing Table 10 by multiplying its row by 0.875 and its second row by 0.125. Thus, we obtain Table XI:

TABLE XI
AVAILABILITY JOINT PROBABILITY OF GOOD/BAD OF THE PROCESS OF COMPANY A

$P(S_i/Z_j) =$

	Z_1	Z_2	Z_3
S_1	0.3150	0.4200	0.1400
S_2	0.0200	0.0600	0.0450

Next, we determine $P(Z_j)$ by using the formula from Eqn. (14):

$$P(Z_j) = \sum_{i=1}^{2} P(S_I, Z_j)$$

This is equivalent to summing the columns of the Table X. Thus, we obtain:
$P(Z_1) = 0.3350 \quad P(Z_2) = 0.4800, P(Z_3) = 0.1850$
Finally, we obtain the posterior probabilities by using the formula from Eqn.15:

$$P\left(\frac{S_i}{Z_j}\right) = \frac{P(S_i, Z_j)}{P(Z_j)}$$

Therefore, probabilities are by dividing the columns of the last Table 11 by the associated $P(Z_j)$. Thus, we obtain the following Table XII;

TABLE XII
AVAILABILITY POSTERIOR PROBABILITY OF GOOD/BAD PROCESS OF COMPANY A

$P(S_i/Z_j) =$

	Z_1	Z_2	Z_3
S_1	0.9403	0.8750	0.7568
S_2	0.0417	0.1250	0.2432

These posterior probabilities have effects on the final decision based on the outcomes Z_j of the test. If both items tested are good $(Z = Z_j)$, the probability the lot is good is Z_1S_1= 0.9403**.** If both are bad $(S = S_i)$ is almost equally likely that the lot is good or bad.
Similar procedures are used to evaluate probabilities for performance and quality and across the companies as well. Table XIII shows the summary of the outcomes of the posterior probabilities for Production System Effectiveness PSE.

Production System Effectiveness (PSE) of Company A

$Production\ System\ Effectiveness\ (PSE) = \ Avaliability\ (I) \times Performance\ (P) \times Quality\ (O) \qquad PSE = P(I)\ X\ P(P)\ X\ P(O)$

$PSE = 0.9403\ X\ 0.9989\ X\ 0.9927$

$PSE = 0.9324$

This procedure was applied to other companies in similar way to obtain their respective PSE (Table XIII).

IX. Weighted Production System Effectiveness (WPSE) Computation

First, PSE elements A, P, Q were computed using traditional applications (Table II (1)). After that a weight was attached on each element using ROC method [47]. Then, Weighted Production System Effectiveness (WPSE) was calculated using Eqn. (6) (Table II(9)), that is;

$$WPSE = w_1I + w_2P + w_3O$$

Where all symbols are as defined before (Table II(9):

WPSE of Company A:

From Eqn. (6) and Table VIII and XI;

$$WPSE = w_1 I + w_2 P + w_3 O$$

Then,

$WPSE = (0.61 \times 0.9403) + (0.11 \times 0.9989) + (0.28 \times 0.9827)$

$WPSE = 0.5736 + 0.1099 + 0.2752$

$$WPSE = 0.9587$$

Computations were done for other companies using the same method. Summary of the PSE and WPSE results across the companies are given in Table XV.

X. Effectiveness Choice under Competitive Condition

Decision choice was made under the following seven types of competitive criteria (Table II (7)). Company A for example on availability factor (Table XII):

Maximin Criterion (Availability Company A): It is clear that from table that maximum of minimum (maximin) effectiveness based on posterior probability is 0.7568.

Minimax Criterion (Availability Company A): The minimum of maximum effectiveness (minimax) is Z_3/S_2 of 0.2432 as revealed in the table.

Maximax Criterion (Availability Company A): In this computation, effectiveness was chosen based on posterior probability of 0.9403 (Z_2/S_1) with assumption of no competition.

Minimin Criterion (Availability Company A): Effectiveness posterior probability of Z_3/S_2 of 0.0417 was selected to take care of worse and highest-levels of competition that pressurized to exist in the production environment.

Laplace Criterion (Availability Company A): In this criterion, a balanced ½ (0.5) probability was to arrive at the best effectiveness as follows: posterior probability using the Laplace criterion, expected values is worked out as:

$$S_1 = \frac{1}{3} \times 0.9403 + \frac{1}{3} \times 0.8750 + \frac{1}{3} \times 0.7568 = \frac{2.5721}{3} = 0.8574$$

$$S_1 = \frac{1}{3} \times 0.0417 + \frac{1}{3} \times 0.1250 + \frac{1}{3} \times 0.2432 = \frac{0.4099}{3} = 0.1366$$

From this, the best effectiveness posterior probability, $S_1$was selected having maximum expected value of 0.8574.

Hurwicz Criterion (Availability Company A): For each strategy, the value of the decision index was computed with the highest $D_i$chosen usingα = 0.5 from Table II (7):

$$D_i = \alpha M_1 + (1 - \alpha) m$$

$D_1 = 0.5 \times 0.9403 + (1 - 0.5) \times 0.7568 = 0.8486$

$D_2 = 0.5 \times 0.2432 + (1 - 0.5) \times 0.0417 = 0.1425$

The best effectiveness strategy is D_1, 0.8486 is selected for this criterion.

Minimax Regret Criterion (Availability Company A): The minimum of the maximum regret is chosen by computing the ith regret using equation in (Table II (7)) as follows:

Condition	**Alternatives**			**Maximum**
	Z_1	Z_2	Z_3	**Regret**
S_1	$0.9403 - 0.9404$ 0	$0.9403 - 0.8750$ 0.0658	$0.9403 - 0.7568$ 0.1835	0.1835
S_2	$0.2432 - 0.0417$ 0.2015	$0.2432 - 0.1250$ 0.2307	$0.2432 - 0.2432$ 0	0.2307

Since maximum Regret value obtained for condition S_2/S_2 is 0.1897 and 0.2307 then, the minimum of the maximum possible regrets is chosen as the best effectiveness posterior probability, 0.1835.

Performance and quality estimation are obtained in the same manner for the company. The outcomes for all the companies are presented in Table XVII. A sample paired t-test statistic comparing scenarios is shown in Table XVI.

RESULTS AND DISCUSSION

I. Production System Effectiveness (PSE) Influential Factor

Eight internal factors (manpower, machine, material, energy, management, information/communication, money and marketing) and four external factors (sustainability trend, globally acceptable and industrial revolution standards) were established as PSE influential factors of the primary (industrial based) and secondary (past studies) data obtained. These formed the basis of achieving availability, performance and quality measurement outcomes in the selected industry. Traditional Approach APQ results obtained on Availability, Performance, and Quality are presented in Tables III-VII. It was revealed that under traditional approach all companies under investigation were not sustainable: APQ values for the companies are 0.8021, 0.4849, 0.3430, 0.6970 and 0.7128 respectively against minimum sustainable level, 0.85. In addition, the calculation of weights assigned to PSE factors (Availability, Performance and Quality) where centroid rankings (1, 2, 3) are been assigned to those factors are weighted results of 0.61, 0.28 and 0.11 respectively as stated in Table VIII. From these tables it is evident that availability was the highest followed by performance while quality has least weight. This shows that the companies should concentrate more on performance and quality productivity than availability.

The summary of conditional probabilities for PSE (Table XIII) indicated that Prior probability (good/bad) lots of 0.875/0.125 respectively give corresponding values of posterior probability and shows that all the companies were sustainable from company A, B, C, D and E with PSE values of 0.9324, 0.9761, 0.9949, 0.9716 and 0.9963 respectively. The companies would consolidate on their sustainability if they pay more attention to performance and quality improvement.

TABLE XIII
CONDITIONAL PROBABILITIES FOR PRODUCTION SYSTEM EFFECTIVENESS

Company Type	Production System Effectiveness	Prior probabilities	Posterior probabilities	$PSE = P(A)\ X\ P(P)\ X\ P(Q)$ For each Company
A	Availability P(A)	0.875 / 0.125	Z_1S_1 0.9403	0.9324
	Performance Efficiency P(P)	0.875 / 0.125	Z_1S_1 0.9989	
	Quality product P(Q)	0.875 / 0.125	Z_1S_1 0.9827	
B	Availability P(A)	0.875 / 0.125	Z_1S_1 0.9827	0.9761
	Performance Efficiency P(P)	0.875 / 0.125	Z_1S_1 0.9955	
	Quality product P(Q)	0.875 / 0.125	Z_1S_1 0.9978	
C	Availability P(A)	0.875 / 0.125	Z_1S_1 0.9974	0.9949
	Performance Efficiency P(P)	0.875 / 0.125	Z_1S_1 0.9989	
	Quality product P(Q)	0.875 / 0.125	Z_1S_1 0.9986	
D	Availability P(A)	0.875 / 0.125	Z_1S_1 1.0000	0.9716
	Performance Efficiency P(P)	0.875 / 0.125	Z_1S_1 0.9827	
	Quality product P(Q)	0.875 / 0.125	Z_1S_1 0.9887	
E	Availability P(A)	0.875 / 0.125	Z_1S_1 1.0000	0.9963
	Performance Efficiency P(P)	0.875 / 0.125	Z_1S_1 0.9995	
	Quality product P(Q)	0.875 / 0.125	Z_1S_1 0.9968	

Also, the summary of posterior probabilities for success/failure (Tables XIII) results indicates that the Model PSE in isolation results compare to Model PSE in combination results are similar which shows an agreement across the five companies (Table XIV). Furthermore, the summary results of Normal PSE Decision Making under Conditions of Uncertainty/Competition for Company A – E is presented in Table XVII. Risk tolerance evaluation of selected companies in the presence of competition revealed that all companies can only survive (sustainable) under normal non-competitive Maximax condition while minimum criterion condition cannot survive (Table XVII).

II. Model PSE and Company PSE Evaluation

The compared results of the Company PSE with the Model PSE using traditional APQ approach was in Table XIV from which it is clearly shown that the model adequately represented the companies' performance and that there are improvement in the system (PSE) over the old method of measurement (0.8021 against 0.5940). However, the outcomes show some similarities in other companies (Table XIV). This indicates that traditional approach of PSE measurement in the companies was deficient due to less consideration of process variability in their measured parameters. Consideration of this variability in the new approach has enhanced the productivity of the proactive company.

TABLE XIV.
COMPARISONS OF COMPANY'S TRADITIONAL APPROACH PSE AND MODEL PSE

Company	PSE Factors	Results

	Availability (A)	Performance (P)	Quality (Q)	Company PSE	Model PSE	Decision
A	0.7500	0.8095	0.9783	0.5940	0.8021	Improved
B	0.7500	0.8095	0.9896	0.6008	0.4849	Similar
C	0.5000	0.8095	0.9977	0.4038	0.3430	Similar
D	1.0000	0.8333	0.9988	0.8323	0.6970	Similar
E	1.0000	0.7222	0.9992	0.7216	0.7128	Similar

III. Normal and Weighted PSE under Competition Evaluation

WPSE) results under traditional (APQ) and modified approach (MBA) are presented in Table XV. It can be revealed that traditional approach under equal weights has not produced sustainable outcomes in all companies investigated, while companies A, D and E had sustainable performance under weighted arrangement. The application of the modified Bayesian approach indicated a tremendous improvement due to integration of new production process information. In this case, production system effectiveness was sustainable in all companies in both normal and weighted scenarios. Results of the Normal PSE under Conditions of seven (7) uncertainty criteria to check the level of competition in the industries are presented in (Table XVII). It can be generally revealed from the results that the application of the modified Bayesian approach indicated a tremendous improvement from 0.8021 to 0.9324 due to integration of wastes/loses elimination strategy into the process.

From Table XVII (Figures V-VI), under competitive arrangement, it can be shown that only Maximax criterion seems sustainable (D_S) on Production System Effectiveness (PSE) and Weighted Production System Effectiveness (WPSE) which indicates no presence of competition. Laplace and Hurwitz criteria seem fairly sustainable (D_F) on WPSE only with the presence of fair competition. Maximin, Minimax, Minimin and Minimax Regret criteria can be considered unsustainable (D_U) on PSE and WPSE with assumption that full competition is in place. Therefore, the company A can only survive under Maximax criterion that is without competition. Hypothesis test (paired T-test) results p_{cal} = 0.007, p-value 0.05 (p_{cal}<p_{-value}) between PSE and WPSE indicated that there was significant difference between the normal Production System Effectiveness (PSE) and weighted Production Effectiveness (WPSE) at 5% level of significance (Table XVI). Similar decision outcomes were obtained for company B with little improvement as shown in Figure VII, respectively. There were better decision outcomes in term of sustainable productivity in company C (Figure VIII) as majority of the good decisions fell under either fairly sustainable or sustainable process. However, PSE and WPSE results were significantly different at 5% level. Decision results from company D (Figure IX) indicated that the company cannot sustain productivity under keen competition. The decision results from company E (Figure X) were very close to that of company D, with similar significant difference characteristic between PSE and WPSE. In all cases, however, there were no wide gap in overall decision making related to the PSE and WPSE outcomes.

TABLE XV.
NORMAL AND WEIGHTED PRODUCTION SYSTEM EFFECTIVENESS (PSE AND WPSE)

Company	Conventional/ Traditional Approach (APQ) (normal PSE, and weighed WPSE		Modified Bayesian Approach (MBA) (normal PSE, and weighed WPSE		Minimum acceptable trend, Global acceptable and industrial revolution standards	Sustainability measure based on global acceptable sustainability factor
	$PSE = APQ$	$WPSE = wA + wP + wQ$	$PSE = P(I)P(p)P(O)$	$WPSE = w_1I + w_2P + w_3O$	≥0.85, 1.0	MBA sustainable in all companies under PSE and WPSE. In APQ, PSE not sustainable in all companies while WPSE sustainable in companies A, D and E.
A	0.8016	0.9356	0.9324	0.9587	≥0.85, 1.0	
B	0.4849	0.8273	0.9761	0.9948	≥0.85, 1.0	
C	0.3430	0.8148	0.9947	0.9984	≥0.85, 1.0	
D	0.6970	0.8620	0.9716	0.9947	≥0.85, 1.0	
E	0.7128	0.8489	0.9963	0.9985	≥0.85, 1.0	

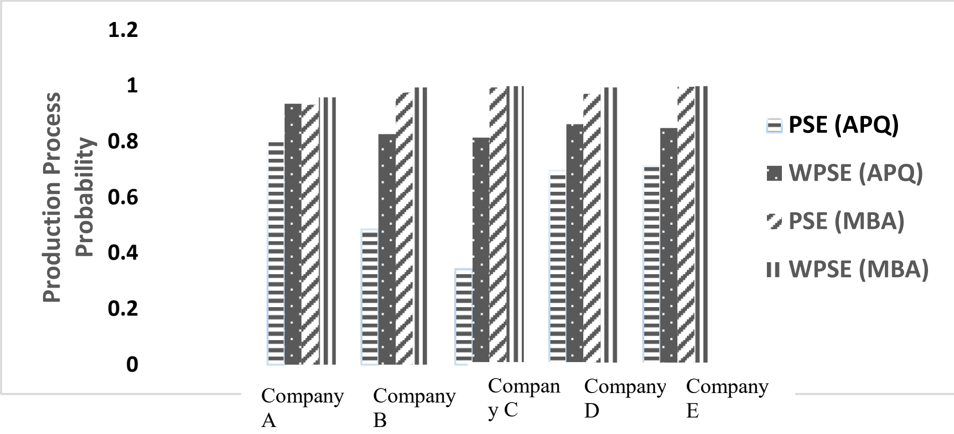

FIGURE V
PSE AND WPSE COMPARISON UNDER CONVENTIONAL AND NEW APPROACH

TABLE XVI

PAIR SAMPLE T-TEST ON PSE VALUES AND WPSE VALUES

		Paired Samples Test				
		Paired Differences		t	df	Sig. (2-tailed)
		95% Confidence Interval of the Difference				
		Lower	Upper			
Pair 1	Production System Effectiveness (PSE) - Weighted Production System Effectiveness (WPSE)	-.4406272	-.1056585	-3.991	6	.007

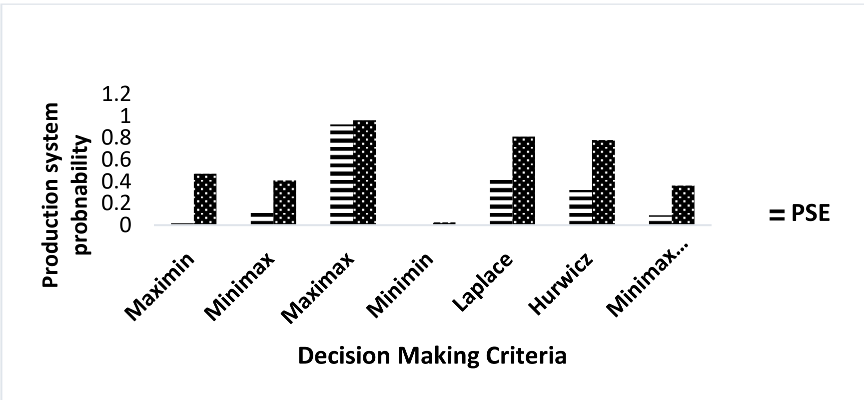

FIGURE VI
PSE AND WPSE COMPARISON FOR COMPANY A UNDER COMPETITION

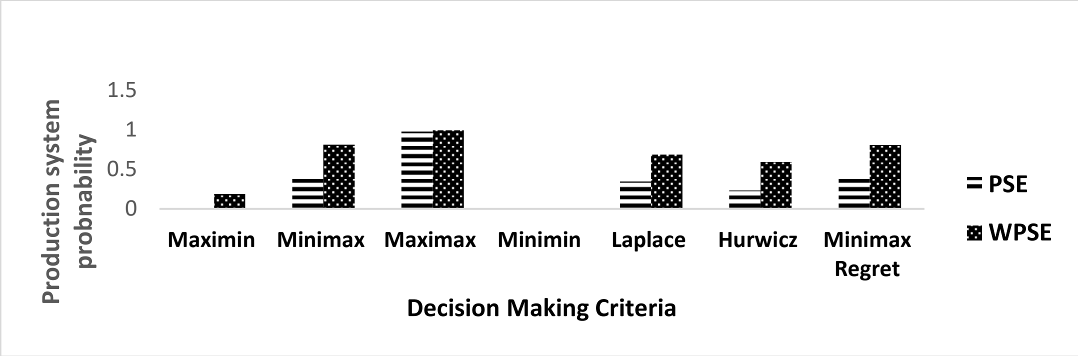

FIGURE VII

PSE AND WPSE COMPARISON FOR COMPANY B UNDER COMPETITION

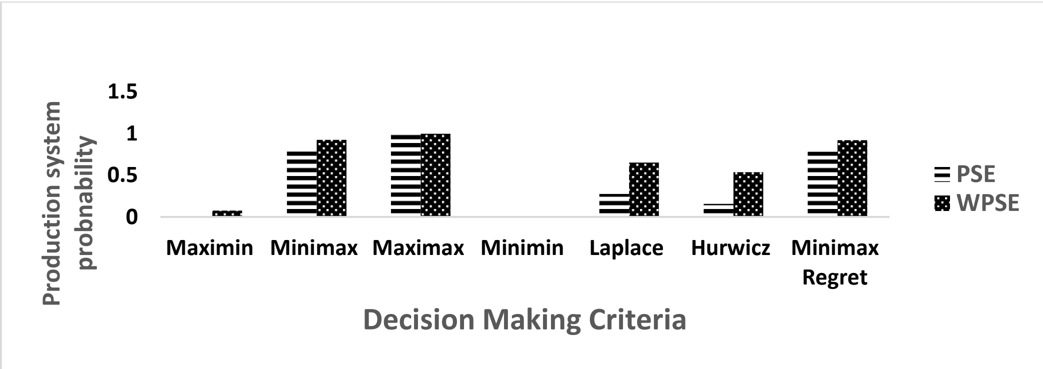

FIGURE VIII

PSE AND WPSE COMPARISON OF COMPANY C UNDER COMPETITION

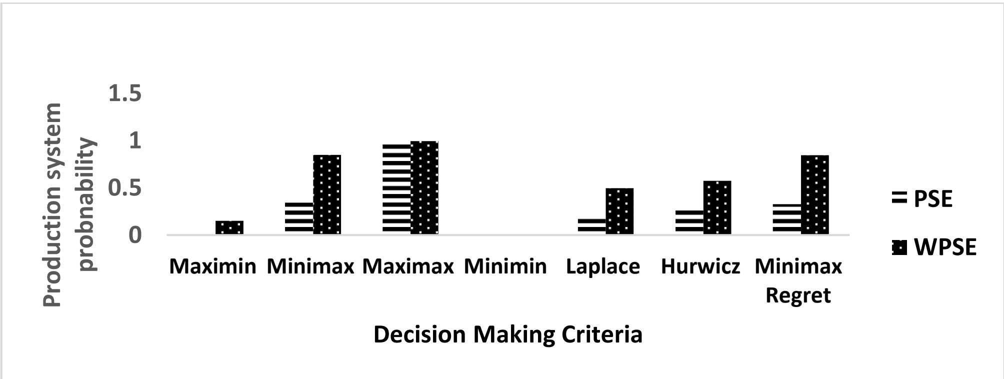

FIGURE IX
PSE AND WPSE COMPARISON OF COMPANY D UNDER COMPETITION

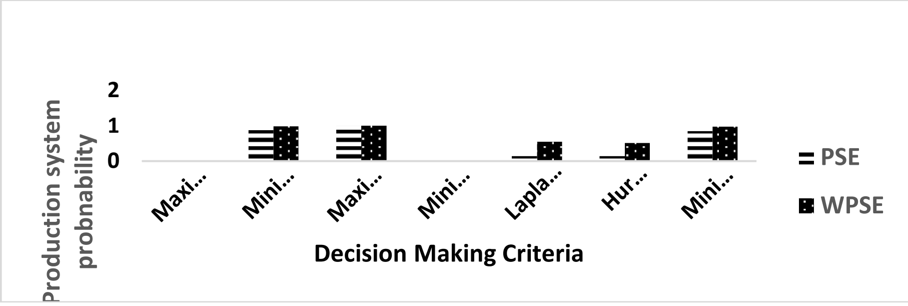

FIGURE X
PSE AND WPSE COMPARISON OF COMPANY E UNDER COMPETITION

TABLE XVII.
PSE AND WPSE SUSTAINABLE DECISION ANALYSIS UNDER COMPETITION

Company Type	Decision Making Criteria													
	Maximin		Minimax		Maximax		Minimin		Laplace		Hurwicz		Minimax Regret	
	PSE	$WPSE$	PSE	$WPSE$	PSE	$WPSE$	PSE	$WPSE$	PSE	$WPSE$	PSE	$WPSE$	PSE	$WPSE$
CompanyA	0.0176	0.4721	0.1240	0.4088	0.9230	0.9583	0.0001	0.0256	0.4255	0.8102	0.3219	0.7778	0.0904	0.3617
Company B	0.0008	0.1873	0.3978	0.8127	0.9761	0.9947	0.0000	0.0034	0.3470	0.6857	0.2324	0.5910	0.3820	0.8074
CompanyC	0.0004	0.0768	0.7863	0.9230	0.9949	0.9983	0.0000	0.0017	0.2744	0.6501	0.1551	0.5376	0.7820	0.9213
CompanyD	0.0000	0.1512	0.3445	0.8488	0.9716	0.9949	0.0000	0.0033	0.1910	0.4958	0.2726	0.5731	0.3276	0.8438
Company E	0.0000	0.0222	0.8758	0.9778	0.9963	0.9995	0.0000	0.0007	0.1402	0.5505	0.1431	0.5108	0.8507	0.9771
Decision:														
$P(T), \geq 0.85$	D_U	D_U	D_S (E)	D_S (C,D,E)	D_S	D_S	D_U	D_U	D_U	D_U	D_U	D_U	D_S (E)	D_S (C,D)
$P(G) \geq 0.85$	D_U	D_U	D_S (E)	D_S (C,D,E)	D_S	D_S	D_U	D_U	D_U	D_U	D_U	D_U	D_S (E)	D_S (C,D)
$P(R) = 0.1 - 0.5$, (I1.0 – I2.0)	D_U	D_F(A, B,D)	D_F(A, B,D)	D_S (A)	D_S	D_S	D_U	D_U	D_F	D_F (D)	D_S	D_S	D_F (B, C)	D_F(A)
$P(R) = 0.51 - 0.84$, (I2.0 – I3.0)	D_U	D_U	D_S (C)	D_S (B)	D_S	D_S	D_U	D_U	D_U	D_F(A, B,C,E)	D_U	D_S	D_F(C)	D_S (B, D)
$P(R) = 0.85 - 1.0$, (I4.0 – I5.0)	D_U	D_U	D_S (E)	D_S (C,D,E)	D_S	D_S	D_U	D_U	D_U	D_U	D_U	D_U	D_S (E)	D_S (C, E)

Decision: D_S is (Sustainable), D_F is (Fairly sustainable), D_U is (unsustainable), $P(T)$ *is sustinable trend*, $P(G)$ *is global acceptable standard*, $P(R)$ *is industrial revolution*, and I *is industrial revolution*

CONCLUSION

The persistence failure in production process due to inadequacy of production resources (internal factor) has been affecting the productivity performance. This study was able to identify the factors (manpower, machine, material, energy, management, information/communication, money and marketing) and external factors (sustainability trend, globally acceptable and industrial revolution standards) responsible for the productivity failure. Thereafter, productivity measurement with reference to external factors: sustainable trend, sustainable global trend, and industrial revolution standards were considered at enhancing industrial sustainable development of the selected companies which was achieved through effective wastes elimination in production process. Generally, the following conclusions can be drawn from this study:

(i) Eight (8) internal factors (manpower, machine, material, energy, management, information/communication, money and marketing) and four (4) external factors (Sustainable development trend, Global sustainable/acceptable standard, Sustainable industrial revolution attainment and Competition were established to have influence on production system effectiveness measures.
(ii) A weighted and modified Bayesian model outcomes were adequate in resolving sustainable productivity challenges of the production industries.

(iii) It was revealed that Production System Effectiveness (PSE) factors (Availability, Performance and Quality) outcomes from the conventional/traditional approach were seemed not normally sustainable for the five companies but. under weighted (preference) approach, seemed sustainable in majority of the companies.
(iv) Under Modified Bayesian Approach (MBA) in which decision was taken based on probability of success or failure of the process, it was revealed that all the companies investigated were sustainable because of inbuilt capability of MBA to eliminate wastes.
(v) Risk tolerance evaluation of selected companies in the presence of competition revealed that all companies can only survive (sustainable) under normal non- corruptive Maximax condition.
(vi) Varying optimum decisions were realized which were influenced by the nature/types of competition, uncertainty and standards of measurement.
(vii) Statistically significant difference between the normal and weighted PSE was realized but the difference had little or no effect on sustainable decision making in all companies investigated. Sensitivity analysis by weight sharing adjustment may lead to change in sustainable decision. This is left for future study.
(viii) Traditional APQ approach seems deficient in realizing sustainable PSE in all companies while weighted version of APQ revealed improve performance in few companies.
(xi) Companies without competitors are normally sustainable based on their normal and weighted Production System Effectiveness (PSE) condition, but fairly sustainable under fewer competitors, and become unsustainable under huge competitors. This means that the companies should strive to improve their productivity to survive ever increasing competitive production environment.
(x) The difference that exists between the normal Production System Effectiveness (PSE) and weighted Production Effectiveness (WPSE) partially indicates dissimilarity between the two approaches. These dissimilarity outcomes had little or no effect on the company's overall decision making under traditional APQ model but wide enough to change decision narratives under the new model (MBA) because of its ability to detect losses in the system and eradicate them.
(xi) Integration of intelligent based online production process monitoring into the model is a good research area in future. This will enable real time monitoring and control of productivity and effectiveness of the production system.

References

[1] Majer, J. M., Henscher H. A., Fischer-Kreer D., and Fischer D. (2022). The Effects of Visual Sustainability Labels on Consumer Perception and Behavior: A systematic review of the empirical literature. *Journal of Cleaner Production*, 33, 1-14, https://doi.org/10.1016/j.spc.2022.06.012.

[2] Wudhikarn, R and Manopiniwes W. (2010). Autonomous maintenance using total productive maintenance approach: A case study of synthetic wood plank factory, Technology Innovation & Industrial Management Conference, TIIM2010, Pattaya, Thailand, in press.

[3] Kareem, B., Alabi A. S., Ogedengbe T. I., Akinnuli B. O., Aderoba O. A. and Idris M. O.(2020). Development of OEE Error-Proof (OEE-EP) Model for Production Process Improvement. The Journal of Engineering Research (TJER), 17(2)59-74.

[4] Dejan, M.,Bahman R., Svetlana N. and Marinko M. (2021). Forecasting hierarchical time series in supply chains: an empirical investigation. Inter. Journal of Production Research, https://doi.org/10.1080/00207543.2021.1896817.

[5] Adenikinju, A. F. (2005). African Imperatives in the New World Order: Country Case Study of the Manufacturing Sector in Nigeria, in O.E. Ogunkola A. and Bankole (eds.), Nigeria'sImperatives in the New World Trade Order. Nairobi. African Economic Research Consortium and Ibadan: Trade Policy Research and Training Programme.

[6] World Bank (2006). Investment Climate Survey Data. Washington, DC: World Bank.

[7] NPC (2009). Nigeria Vision 20:2020: Economic Transformation Blueprint. National Planning Commission, Abuja.

[8] International Institute for Sustainable Development [IISD] (1992). Business Strategy for Sustainable Development: Leadership and Accountability for the 90s, in conjunction with Deloitte &Touche and the World Business Council for Sustainable Development.

[9] Jianjun H., Yao Y., Hameed J. Kamran H. W. Nawaz M. A., Aqdas R., and Patwary A. K. (2021). The Role of Artificial and Non-artificial Intelligence in the New Product Success with Moderating Role of New Product Innovation: A Case of Manufacturing Companies in China. Complexity, 2021(8891298) 1-14. https://doiorg/10.1155/2021/8891298.

[10] World Bank (2012). World Development Indicators. Washington, DC: World Bank.

[11] Akinnuli, B. O. Yakubu A. J. and Adeyemi A. A. (2015). Computer Aided System for Uni-functional Job Shop Machine Selection Based on Production Cost and Technology Advancement. Advances in Research 5(3) 1-12, https://doi.org/10.9734/air/2015/15691.

[12] Mohammed, S.A. (2002). Nigerian Steel Industry-historical Development. African Iron and Steel Development Association, Abuja, Nigeria.

[13] Yakubu, A. J., Kareem B. and Akinnuli B. O. (2018). Computer Aided System for Crankshafts Failure Rate of Automobile Based on Distance Travel and Age, Open Access Library Journal, 5, 1-14.

[14] Almeanazel, O.T. R. (2010). Total Productive Maintenance Review and Overall Equipment Effectiveness Measurement, Jordan Journal of Mechanical and Industrial Engineering (JJMIE), 4(4) 517 – 522. www.jjmie.hu.edu.jo.

[15] Aminuddin, N. A. B., Garza-Reyes I. A., Kumar V. (2015). An analysis of managerial factors affecting the implementation and use of overall equipment effectiveness, International Journal of Production Research, doi:10.1080/00207543.2015.1055849

[16] Felsberger, A., Qaiser F., Choudhary A., and Reiner, G. (2020). The impact of Industry 4.0 on the reconciliation of dynamic capabilities: Evidence from the European manufacturing industries, Production. Planning. & Control: The management Operations 33 (2-3), 277-300

[17] Fayomi, O. S., Akande I. G., Processo R. T., and Ongbali S. O. (2019). Sustainable need in Manufacturing Industry in Nigeria toward Quality, Policy and Planning. Cite as: AIP Conference Proceedings 2123, 020072 (2019); https://doi.org/10.1063/1.5116999.

[18] Dal, B., Tugwell P., and Greatbanks R. (2000): Overall equipment effectiveness as a measure of operational improvement, International Journal of Operations &Production Management, 20(12) 1488–1520.

[19] Vinceta, S. (2014). An Impact and Challenges of Sustainable Development in Global Era. Journal of Economics and Development Studies, 2(2) 327-337.

[20] Kareem, B. and Yakubu A. J. (2017). Modelling Failure Rate of Automobile Crankshafts based on Distance Travelled and Age. International Journal of Advance Industrial Engineering, 5(4) 210-217, http://inpressco.com/category/ijaie/

[21] Shahbazi, S., Salloum M, Kurdve M, and Wiktorsson M. (2017). Material Efficiency Measurement: Empirical Investigation of Manufacturing Industry. Procedia Manufacturing, 8, 112–120.

[22] Virbahu, N. J. and Devesh M. (2018). Blockchain for Supply Chain and Manufacturing Industries and Future It Holds, Int. J. Eng. Res., 7(9), 32-39, doi:10.17577/ijertv7is090020

[23] Micic, V. and Jankovic N. (2017). Investment in the manufacturing industry of Serbia, Bankarstvo, 46(4) 52–73.

[24] Singh, B. N, (2018). Role of Automation in Steel Industry, no. May.

[25] Landry, J. and Ahmed S. A, (2016). Adoption of Leanness in the Manufacturing Industry," Int. J. Eng. Res. V7, Univers. J. Manag., 4(1) 1–4.

[26] Fallah, J. M. (2020). Efficiency, effectiveness and productivity of personnel's health in petrochemical companies, Journal of Research in Industrial Engineering, 7 (3), 280–286.

[27] Saputra, Y., Putra F. E. and Hidayat T. (2022). Energy Effectiveness and Conservation of Pipeline Construction Industry Using Iso 50001 Energy Management System, Journal of Applied Research on Industrial Engineering, 9 (1), 108-114.

[28] Lotfi, F. H. and Jahanbakhsh M. (2015): Assess the efficiency and effectiveness simultaneously in a three-stage process, by using a unified model, Internal journal of Research in Industrial Engineering, 4 (1-4), 15-23.

[29] Jatwa, M. and Sukhwani V. K. (2022). Fuzzy FMEA model: a case study to identify rejection and losses in fibre industry, Journal of Fuzzy Extension and Applications, 3 (1), 19-30.

[30] Li, P., Edalatpanah S. A., Sorourkhah A., Yaman S. and Kausar N. (2023). An Integrated Fuzzy Structured Methodology for Performance Evaluation of High Schools in a Group Decision-Making Problem, Systems: Special Issue on Preference and Consensus Modeling in Group Decision Making under Complex Contexts , 11(3), 159.

[31] Dui, H., Lu Y., and Wu S. (2024). Competing risks-based resilience approach for multi-state systems under multiple shocks, Reliability Engineering & System Safety, 242, 109773.

[32] Zu, X., and Cong Y. (2022). Sustainable Production and Consumption, an Empirical Examination of the Effectiveness and Sustainability of Operational-level Environmental Management Practices in U.S. industry. Journal Science. 33(11-12), 1-14.

[33] Atkins J., Doni F., Gasperini A., Artuso S., La-Torre I., and Sorrentino L. (2022): Exploring the Effectiveness of Sustainability Measurement: Which ESG Metrics Will Survive COVID-19? Journal of Business Ethics, 1-18, https://doi.org/10.1007/s10551-022-05183-1

[34] Baumer-Cardoso, M. I., Ashton W. S., and Campos L. M. S. (2023). Measuring the Adoption of Circular Economy in Manufacturing Companies: The Proposal of the Overall Circularity Effectiveness (OCE) Index. Circular Economy and Sustainability 3(1), 511-534, https://doi.org/10.1007/s43615-022-00188-4

[35] Hannola, L.; Richter A.; Richter S., and Stocker A (2018). Empowering production workers with digitally facilitated knowledge processes—A conceptual framework. Inter Journal. Production Research, 56, 4729–4743.

[36] Ichter, A., Heinrich P., Stocker A, and Schwabe G. (2018). Digital work Design. Business. Information System. Engineering. 60, 259–264.

[37] European Commission Horizon [ECH] (2020). Work Programme 2018–2020. Available online: https://ec.europa.eu/commission/presscorner/detail/en/MEMO_17_4123 (accessed on 12 August 2020).

[38] Culot, G., Nassimbeni G., Orzes G. and Sartor M. (2020). The future of manufacturing: A Delphi-based scenario analysis on Industry, Technological Forecast and Social Change. 157, 120092. https://doi.org/10.1016/j.techfore.2020.120092

[39] Garrido-Hidalgo, C., Hortelano, D., Roda-Sanchez, L., Olivares, T., Ruiz, M. C., and Lopez, V. (2018). IoT Heterogeneous Mesh Network Deployment for Human-in-the-Loop challenges towards a social and sustainable Industry. IEEE Access, 6, 28417–28437.

[40] Pournader, M., Shi Y., Seuring S., and Koh, S.L. (2020). Block-chain Applications in Supply Chains, Transport and logistics: A Systematic review of the literature. International Journal Production Research. 58, 2063–2081.

[41] Zheng. F., Wang Z., Zhang E. and Liu M. (2022). K-adaptability in robust container vessel sequencing problem with week. International Journal of Production Research, 60(9), 2787-2801, https://doi.org/10.1080/00207543.2021.1902014.

[42] Carlos, H. S., Jose A. M., Jose A. Q., Rafael C. M. and Fabiano L. (2021). Decision support in productive processes through DES and ABS in the Digital Twin era: a systematic literature review. International Journal of Production Research. 60(8) 2662-2681

[43] Bevan, D., Collier P., and Gunning J. W. (1999). The Political Economy of Poverty, Equity, and Growth: Nigeria and Indonesia. Oxford: Oxford University Press and World Bank.

[44] McKone, K. E., Schroeder R. G and Cua K. O. (2001). The impact of Total Productive Maintenance Practices on Manufacturing Performance. Journal of Operations Management, 19(1), 39–58.

[45] Lesshammar, M. (1999). Evaluation and Improvement of Manufacturing Performance Measurement Systems. The role of OEE, International Journal of Operations and Production Management, 19(1) 55-78.

[46] Frendall, L. D. J, Patterson J. W and Kneedy W. J. (1997). Maintenance modeling its strategic impact, Journal of Managerial Issues, 9(4) 440-448.

[47] Raouf, A. (1994). Improving Capital Productivity through Maintenance, International Journal of Operations and Production Management, 14(7), 44–52.

[48] Dohale, V., Gunasekaran A., Akarte M., and Verma P. (2021). An integrated Delphi-MCDM-Bayesian Network framework for production system selection, International Journal of Production Economics, 242, 108296.

[49] Barron, F. H. and Barrett B. E (1996): Decision Quality using Ranked Attribute Weights. Management Science, 42(11)1515-1522.

[50] Kwon, O and Lee H. (2004). Calculation Methodology for Contributive Managerial Effect by OEE as a Result of TPMActivities.Journal of Quality in Maintenance Engineering, vol. 10, no. 4, pp.263-272, 2004.

[51] Wudhikarn, R., Smithikul C., and Manopiniwes W. (2009). Developing Overall Equipment Cost Loss Indicator, in Proc.6th Conf. of Digital Enterprise Technology, DET2009, Hong Kong, Hong Kong, pp. 557-567.

[52] Ljungberg, O. (1998). Measurement of overall equipment effectiveness as a basis for TPM activities, International Journal of Operations & Production Management, 18(5) 495-507.

[53] Gupta, H., Kharub M., Shreshth K., Kumar A., Huisingh D., and Kumar A. (2023). Evaluation of strategies to manage risks in smart, sustainable agri-logistics sector: A Bayesian-based group decision-making approach, Business Strategy and the Environment, 32 (7), 4335- 4359.

[54] Debnath, B., Shakur M. S., Bari A.B.M., and Karmaker C. L. (2023). A Bayesian Best–Worst approach for assessing the critical success factors in sustainable lean manufacturing, Decision Analytics Journal, 6, 100157.

[55] Xiang, F., Zhang Y., Zhang S., Wang Z., Qiu L.,and Choi J-H. (2024). Bayesian gated-transformer model for risk-aware prediction of aero-engine remaining useful life, Expert Systems with Applications, 238, Part B, 121859.

[56] Tasias, K. A. (2022). Integrated Quality, Maintenance and Production model for multivariate processes: A Bayesian Approach, Journal of Manufacturing Systems, 63, 35-51.

[57] Chien, C. F., Nguyen T. H. V., Li Y. C., and Chen Y. J. (2023). Bayesian decision analysis for optimizing in-line metrology and defect inspection strategy for sustainable semiconductor manufacturing and an empirical study, Computers & Industrial Engineering, 182, 109421. Doi: 10.1016/j.cie.2023.109421

[58] Khan, I., Khan D. M., Noor-ul-Amin M., Khalil U., Alshanbari H. M., and Ahmad Z. (2023). Hybrid EWMA Control Chart under Bayesian Approach Using Ranked Set Sampling Schemes with Applications to Hard-Bake Process, Applied Science, 13(5), 2837.

[59] Ma, Y., Wang J., and Tu Y. (2024). Concurrent optimization of parameter and tolerance design based on the two-stage Bayesian sampling method, Quality Technology and Quantitative Management, 21 (1) 88-110.

[60] Punyamurthula, S., and Badurdeen F. (2018). Assessing Production Line Risk using Bayesian Belief Networks and System Dynamics, Procedia Manufacturing, 26, 76-86.

[61] Mim, T. I., Fowzia Tasnim F., Shamrat B. A. R., and Xames M. D. (2022). Performance Prediction of Green Supply Chain Using Bayesian Belief Network: Case Study of a Textile Industry, International Journal of Research in Industrial Engineering, 11 (4), 327-348.

[62] Uflaz, E., Sezer S. I., Tunçel A. L., Aydin M., Akyuz E., and Arslan O. (2024). Quantifying potential cyber-attack risks in maritime transportation under Dempster–Shafer theory FMECA and rule-based Bayesian network modelling, Reliability Engineering & System Safety, 243, 109825.

[63] Zhu, Q., Dhavale D. G., Sarkis, J., Wang, X. (2023). Formalizing organizational product deletion through strategic cross-functional evaluation: A Bayesian Analysis Approach, International Journal of Production Economics, 262, 108894.

[64] Dongfeng, C., Yan W. (2018). Bayesian Evaluation Method for Energy Efficiency of Manufacturing System Based on Combined Weights, Journal of System Simulation, 30(11) 4313-4322.

[65] Alruqi, M., and Sharma P. (2023). Biomethane Production from the Mixture of Sugarcane Vinasse, Solid Waste and Spent Tea Waste: A Bayesian Approach for Hyperparameter Optimization for Gaussian Process Regression, *Fermentation*: Special Issue Progress in Microbial Treatment of Wastewater, Solid Wastes and Waste Gases, *9* (2) 120. https://doi.org/10.3390/fermentation9020120

[66] Barnes, B., Parsa M., Giannini F., and Ramsey D. (2023). Analytical Bayesian approach for the design of surveillance and control programs to assess pest-eradication success, Theoretical Population Biology, 149, 1-11.

[67] Puli, V. K., and Huang B. (2023). Variational Bayesian Approach to Nonstationary and Oscillatory Slow Feature Analysis With Applications in Soft Sensing and Process Monitoring, IEEE Transactions on Control Systems Technology, 31 (4), 1708 – 1719.

[68] Chen, W., Gao S., Chen, W, and Du J. (2022). Optimizing resource allocation in service systems via simulation: A Bayesian formulation, https://doi.org/10.1111/poms.13825

[69] Bader, J., Lehmann F., Thamsen L, Leser U., and Kao O. (2024). Lotaru: Locally predicting workflow task runtimes for resource management on heterogeneous infrastructures, Future Generation Computer Systems, 150, 171-185.

[70] Hu, Z., Dang C., Wang L., and Beer M. (2024). Parallel Bayesian probabilistic integration for structural reliability analysis with small failure probabilities, Structural Safety, 106, 102409.

[71] Tohidi, H., Jabbari, M.M., (2012). “Measuring organizational learning capability”. Procedia-social and behavioral sciences, 31, 428-432. https://doi.org/10.1016/j.sbspro.2011.12.079

[72] Tohidi, H., Jabbari, M.M., (2012). “Important factors in determination of innovation type”. Procedia Technology, 1, 570-573. https:// doi: 10.1016/j.protcy.2012.02.124

[73] Jabbari, M.M., Tohidi, H., (2012). “Providing a Framework for Measuring Innovation withinCompanies”. Procedia Technology, 1, 583-585. https:// doi: 10.1016/j.protcy.2012.02.127

[74] Dardeno, T.A., Worden K., Dervilis N., Mills R.S., Bull L.A. (2024). On the hierarchical Bayesian modelling of frequency response functions, Mechanical Systems and Signal Processing, 208, 111072.

[75] Hamdan, B., and Wang P. (2024). Multi-fidelity Bayesian learning for offshore production well reliability analysis, Applied Mathematical Modeling, 125, Part A, 555-570.

[76] Song, J, Cui Y., Wei P., Valdebenito M. A., Zhang W. (2024). Constrained Bayesian optimization algorithms for estimating design points in structural reliability analysis, Reliability Engineering & System Safety, 241, 109613.

[77] Wang, R., Cheung, C., Zang, Y., Wang, C., and Liu, C. (2024). Material Removal Rate Optimization with Bayesian Optimized Differential Evolution Based on Deep Learning in Robotic Polishing, https://ssrn.com/abstract=4690513.

[78] Tong, Q., and Gernay T. (2023). Resilience assessment of process industry facilities using dynamic Bayesian networks, Process Safety and Environmental Protection, 169, 547-563.

[79] Verma, A. P. (2013). Operations Research, 6th Edition, S.K. Kataria & Sons, New Delhi, 1183p.