MODEL FOR PREDICTING MECHANICAL COUNTER WEIGHING EQUIPMENT REPLACEMENT TIME

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A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN ADVANCED MANUFACTURING SYSTEMS ENGINEERING OF KYAMBOGO UNIVERSITY

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DECLARATION

I, **Raphael Musana**, do hereby declare that this dissertation is my original work, except where other people's works have been cited and acknowledged. The report has never been presented to any institution of higher learning for any degree or other award.

Sign:…………………………………………….. Date:……………..………….

APPROVAL

This dissertation has been developed under the supervision of the undersigned academic supervisors and it is due for approval.

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DEDICATION

This dissertation is dedicated to my parents, Christopher Wabwire (RIP) and Bernadette Wabwire for the care and decision to educate me, it is upon this background that I pursue this masters. To my sisters Claire Nabwire, Bangi Rose, Christine Nabwire, my brother Tom Musana and my daughter Bangi Victoria, I thank you very much for being a strong pillar in my academic journey.

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LIST OF SYMBOLS AND ABBREVIATIONS

GDP	Gross Domestic Product
KACITA	Kampala City Traders Association
KCCA	Kampala Capital City Authority
MTIC	Ministry of Trade Industry and Cooperatives
NIST	National Institute of Standards and Technology
OIML	International Organisation of Legal Metrology
SI	International System of Units
UBOS	Uganda Bureau of Statistics
UMA	Uganda Manufacturers Association
UNBS	Uganda National Bureau of Standards

ABSTRACT

Weighing equipment is so important in business transactions, as it guides the exchange of goods through measurements. However, the equipment is susceptible to many factors that increase their degradation in service, which tend to reduce their service Accurate weighing is essential for fair trade and consumer protection, particularly in markets where mechanical weighing equipment remains prevalent. In Uganda, these devices often degrade over time due to poor handling, environmental exposure, and limited maintenance, leading to measurement inaccuracies and consumer complaints. This study aimed to develop a Weibull-based predictive model to estimate the optimal replacement time for mechanical counter weighing equipment. The specific objectives were; First to assess the failure patterns and causes of mechanical weighing equipment degradation, Secondly, to identify the key factors influencing equipment performance through perception surveys and inspection data, and thirdly, to develop and validate a predictive model using the Weibull distribution. A cross-sectional research design was employed, with data collected from four major trading centers in Kampala. Binary logistic regression was used to analyze factors affecting degradation, while Maximum Likelihood Estimation (MLE) was applied for Weibull parameter fitting. Model validation was conducted using standard Goodness-of-Fit tests. Out of 310 scales inspected, 76% exhibited degradation, largely due to dust exposure, overloading, vibrations, and humidity. The estimated optimal replacement time was 8.4 years. The resulting model offers a data-driven decision-support tool to guide timely replacement, enhance legal metrology enforcement, and protect consumers in trade environments.

Key words: Replacement time, mechanical counter weighing scale, levels of degradation, metrology, and Weibull model.

CHAPTER ONE: INTRODUCTION

1.1 Background to the Study

Globally, business transactions across different platforms are vital for social-economic transformation (Fountain, 2017). According to Karanina et al., (2017), trade between people, firms and countries among others is critical for inter-territorial social and economic stability. This stability is demonstrated through the creation of employment opportunities, penetration of new markets, and innovation of new products and services among others (Lajili et al., 2007). Vera, (2016) stated that measurement is the major driver of most of the business transactions, as it regulates the transfer of goods in commerce to guarantee fair exchange of goods for money. The fact that measurements are involved in most trade transactions, there is an unyielding need to ensure fairness to all parties for increased acceptability, adaptability and consumer protection (Hampaign, 2017).

For Uganda to continue achieving an average economic growth rate of 4.5% per annum, the government through its respective regulatory authorities such as the Uganda National Bureau of Standards (UNBS) must promote fairness and transparency in business activities (Kaziba Mpaata et al., 2017). This fairness could be achieved through effective distribution, accuracy, and precision determination of different weighing equipment across the existing business and trading platforms (UNBS, 2020). UNBS is mandated to ensure that weighing equipment used in business transactions is checked and maintained for accuracy and precision by the use of a series of certified and traceable calibration masses. According to Thiel, (2018), weighing equipment inspection and verification services are delivered through the provision of standards, metrology, and conformity assessment to the general public. Measurements are critical aspects of every business transaction and form a basis for determining the prices of all goods consumed by people (Hampaign, 2017; Yorkin et al., 2013). Moreover, according Zeija, (2018), legal metrology's consumer protection aspects are achieved by verifications that adhere to predetermined standards.

Thus, Accuracy is essential for all weighing equipment, whether digital or analogue (Hampaign, 2017; Yorkin et al., 2013), and its degradation depends on usage, with equipment used for heavy loads typically showing lower accuracy (Nzumile & Nyamweru, 2022b; Yorkin et al., 2013). Over time, factors such as wear and tear, environmental conditions, and electronic faults lead to accuracy loss (Ross & Wing, 2016), necessitating regular calibration. Although calibration in Uganda is typically scheduled annually, many SMEs go much longer without it due to limited awareness and enforcement (UNBS, 2020). This calls for research into failure patterns that affect weighing accuracy, and the effectiveness of current inspection systems, to guide technical and policy improvements. Weibull models are commonly used to analyze and predict failures caused by mechanical wear, fatigue, and stress (Lai et al., 2006), with advanced Weibull model forms such as the four-parameter, exponentiated, and generalized Weibull distributions offering greater flexibility in modeling early life failures, shocks, and aging effects (Murthy et al., 2004). These models enhance reliability assessments and maintenance planning; for example, Murthy et al., {2004) modeled changes in failure rates over time, while Ohta et al., {2002) used Weibull-based control charts to detect shifts in system conditions. This study applies a Weibull model to predict optimal replacement time for weighing equipment based on observed failure patterns.

1.2 Problem Statement

Despite the importance of weighing equipment in ensuring fair trade, a significant number of mechanical and digital weighing scales in Uganda are unfit for use, with nearly 90% failing to meet metrological standards (UNBS, 2020). Frequent breakdowns, tampering, and natural failures especially among weighing equipment used by SMEs have led to widespread consumer exploitation. Moreover, there is a lack of reliable tools to predict when weighing equipment should be withdrawn or replaced. Limited research has been done on the distribution, accuracy, and precision of weighing scales in Uganda, highlighting the need for a predictive model to determine replacement time based on failure patterns and performance characteristics (Luwedde et al., 2022; UNBS, 2018).

1.3 Objectives

1.3.1 Main Objective

To predict the optimal replacement time for weighing equipment using a Weibull model based on observed failure patterns.

1.3.2 Specific Objectives

The specific objectives of the study are:

(i) To determine the parameters influencing the precision and accuracy of weighing equipment used for business transactions in the selected firms.

(ii) To establish the factors influencing weighing equipment degradation in stochastic environments.

(iii) To establish the most optimal time for weighing equipment replacement.

1.4 Research Questions

(i) What are the most critical parameters that influence the performance of weighing equipment in the selected areas?

(ii) What is the relationship between weighing equipment degradation and the level of accuracy?

(iii) What is the most opportune replacement time for weighing equipment?

1.5 Conceptual Framework

The conceptual framework as presented in Figure 1.1 shows the different variables and their close interactions. The independent variables comprise the different weighing equipment inspection and verification processes, failure tendencies and replacement model parameters. On the other hand, the regulatory inspection and verification requirements and customer complaints constitute the dependent variables.

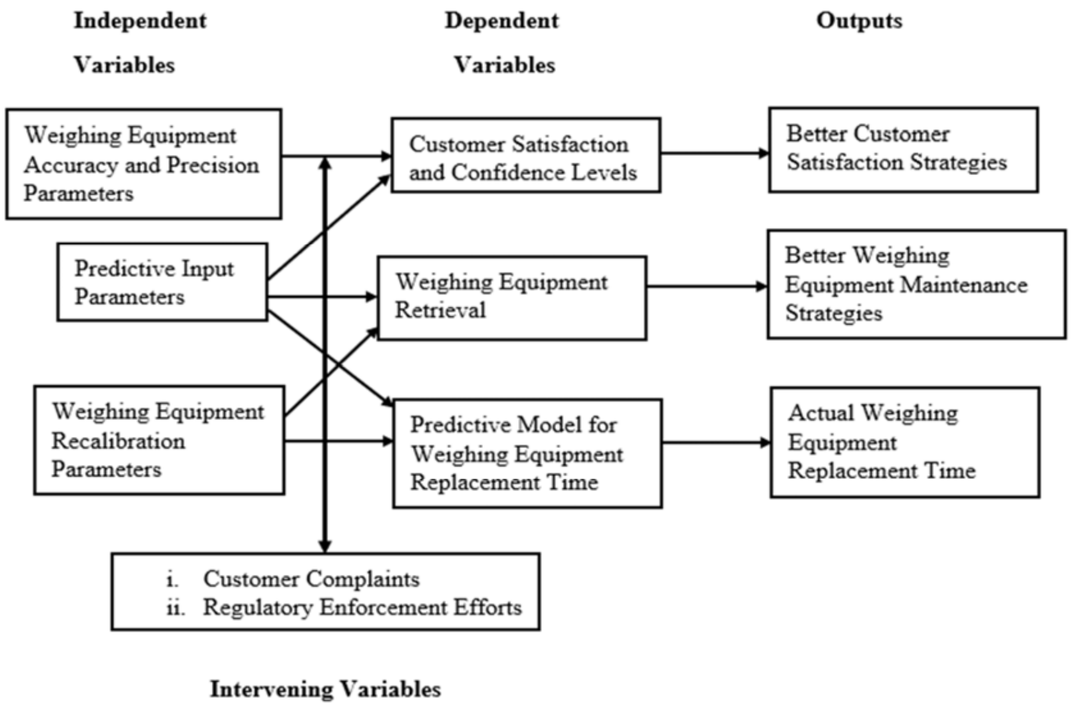

Figure 1.1: Conceptual Framework.

1.6 Justification

Legal metrology is essential to a country's scientific, technological, and industrial advancement in addition to being a crucial too for consumer protection (Thiel, 2018). Due to the direct linkage between legal metrology to the economy, society, health and the environment, its continuous improvement is crucial to total consumer confidence, satisfaction and accurate measurement. With the significantly huge volumes of customer complaints on the quality and inaccuracy of weighing equipment in the market, a sizable amount of customers' trust has been lost. This has significantly impacted the effectiveness of business trading activities thus hindering economic growth across the country. Failure to conduct this research so as to establish strategies for continuous weighing equipment inspection, verification, withdrawal and replacement keeps the economy in a vicious cycle of customer cheating and dissatisfaction.

1.7 Significance

The study findings if implemented will provide guidelines to UNBS and related stakeholders on how to ensure effective standardization and distribution of weights and measures for better business performance in Uganda. This study will also provide strategies to facilitate fairness between buyers and sellers in the respective markets where goods are sold by weight. Furthermore, the research findings will provide bankable information to key metrology stakeholders on the different weighing equipment failure patterns, inspection, servicing, withdrawal from use, and replacement time for enhanced consumer protection.

1.8 Scope of the Study

The study was conducted in Nakawa business district, Kalerwe market, Nateete business area and Kibuye market. During the study, experimental measurements were conducted for a small observation period of one month. Technically, the researcher concentrated on determining the different parameters influencing mechanical counter weighing equipment performance during business transactions and predict the optimal replacement time for weighing equipment using a Weibull model based on observed failure patterns.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Globally, accurate measurements are an important part of every business transaction because they form the basis upon which the price of commodities used in day-to-day life is derived (Romero et al., 2012). Everything in the value chain is covered by accuracy, from the reliability of end-user measurements to the definition of measuring units that governments throughout the world have agreed upon through standard measurement techniques. Uganda National Bureau of Standards (UNBS) does not distribute weighing scales to traders as they buy their own weighing scales from the open market. UNBS only undertakes to verify the trader's equipment before they are used for conducting business transactions. Under Sec.23 (a) of the Weights & Measures Act, any person involved in the selling of weighing scales that are to be used for trade will ensure that the scale is duly verified and stamped.

2.2 The effectiveness of the weighing equipment verification processes used by UNBS

2.2.1 National Rules and Regulations on Weighing Equipment

Any weighing equipment possessing novel features shall not be deemed fit for business transactions unless it is of a pattern approved by the Minister. Use for trade means application for the transfer or rendering of money or its worth ("Weights & Measures Act Cap 103," 1965). The metric system is lawfully accepted and authorized by statutory order. The lack of a database of weighing scales in Uganda has caused traders to buy non-trade type scales, only for them to be seized during inspection. These incidents leave many traders complaining as to why the national metrology regulator implements inadequate and ineffective strategies for public sensitization. Repairing weighing equipment without a license is prohibited under the repair rules (Wanjiru, 2012). Weighing equipment suitable for trade should have a valid stamp that shows its suitability and accuracy. A study by the International Organization of Legal Metrology (OIML) noted that most of the weighing equipment being used for trade are unfit for transactions due to their consistent failure to meet the stipulated requirements (De,et al., 1992).

2.2.2 General requirements for weighing instruments

Globally, weighing equipment whether digital or analog shall have to possess certain minimum characteristics if they are to be considered suitable for use in business transactions (Hampaign, 2017; Romero et al., 2012). These requirements have been established and recognized by several local, regional and international bodies. However, majority of the requirements cited below are taken from the National Institute of Standards and Technology (NIST) of the United States of America (USA) and harnessed with those developed and recognized by UNBS (NIST, 2015). The following are minimum requirements for a weighing instrument: it must be properly constructed, free of materials, construction methods, and conditions that could render it unfit for use; it must not have unusual or novel features; it must be complete in its own right; it must not bear a manufacturer's mark or any other mark that could be mistaken for a verification stamp; it must not have interchangeable or reversible parts, unless doing so, as the case may be, does not affect its accuracy; it must not have removable parts because removing the parts affects its accuracy.

2.3 Types of Weighing Scales

According to Campus, (2023), weighing scales are actually indispensable tools used across the world in various industries and fields to accurately measure the weights of objects. The weighing scales are designed to suit certain specific needs and applications and therefore come in a variety of types. Therefore, understanding the different weighing scales types available can help users to choose the most suitable option depending on their requirement. According to Ohgushi et al., (2007), mechanical and digital weighing are the two major types of weighing scales used for business transactions;

2.3.1 Digital weighing scales

With technological advancements and developments, digital weighing scales have become popular and are increasingly utilized because of their accuracy, convenience, precision, portability, and ease to use (OIML, 2006b). Despite their increasing popularity, third world countries including Uganda lack the necessary resources for; designing, configuring, manufacturing, installing and maintaining of digital weighing scales. Additionally, digital scales are more expensive than mechanical scales as they require batteries or electrical power to operate (Ivanova & Rudzitis, 2010). This can limit their applicability in some situations. These challenges continue to slow the uptake and acceptability of such weighing scales by several business stakeholders in Uganda. In addition, the increased popularity of these weighing scales varies from region to region due to linkages in technology adoption, access to information, cooperative society performance and government's desire to promote development and adoption of digital technologies within business transactions. Alexander De et al., (2016.) Stated that digital weighing scales utilize electronic components for them to be able to provide fast and reliably accurate weight measurements. Figure 2.1 shows the different types of digital weighing scales used and these are further subdivided into other categories such as electronic kitchen scales, digital bathroom scales, laboratory scales, medical scales, and retail/industrial scales depending on the purpose they serve.

According to Arruda & da Silva, (2023), digital scales utilize electronic components such as strain gauges or load cells to measure weight. The author further states that the digital weighing scales consist of sensors underneath their flat surfaces that can figure out how much of the weights weigh and then an accurate figure is displayed on the screen.

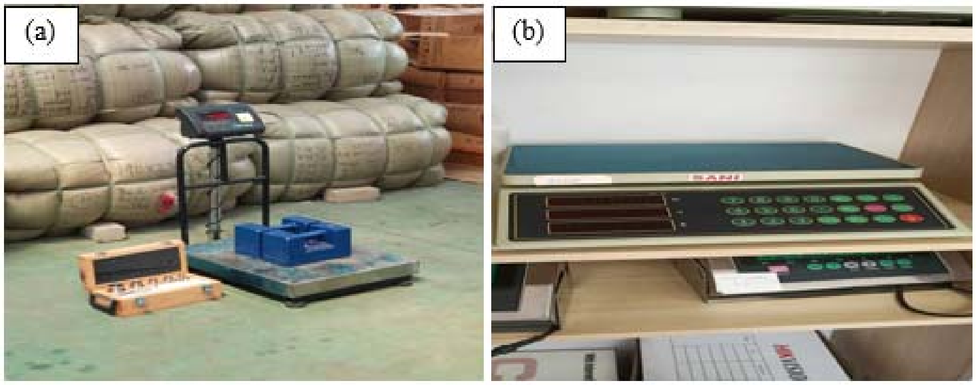

Figure 2.1: (a) the platform, and (b) the table top digital weighing scales

2.3.2 Mechanical weighing scales

Mechanical weighing scales, also known as analog scales have been in use for many years and they are characterized by their simple design (Rahmstorf, 2007). According to Campus, (2023), unlike digital weighing scales, the mechanical weighing scales operate on mechanical principles by making use of springs or balances to give accurate measurements. They work by first measuring a deflection and then convert it into weight.

Mechanical weighing scales can have generously sized platforms and equally suitable for use in homes, hotels and clinics among others. Additionally, the advantage that these scales have over the digital scales is that they are suitable for use in areas without electrical power supplies and or areas requiring intrinsically safe weighing equipment since they do not require any power to operate. This makes them ideal for use in remote and off-grid areas. Furthermore, these scales have a guaranteed long life with minimal maintenance costs, remain sustainably precise, simple and reliable, and are easy to calibrate (Marshall & Murphy, 2003). Figure 2.2 shows the different types of the mechanical weighing scales.

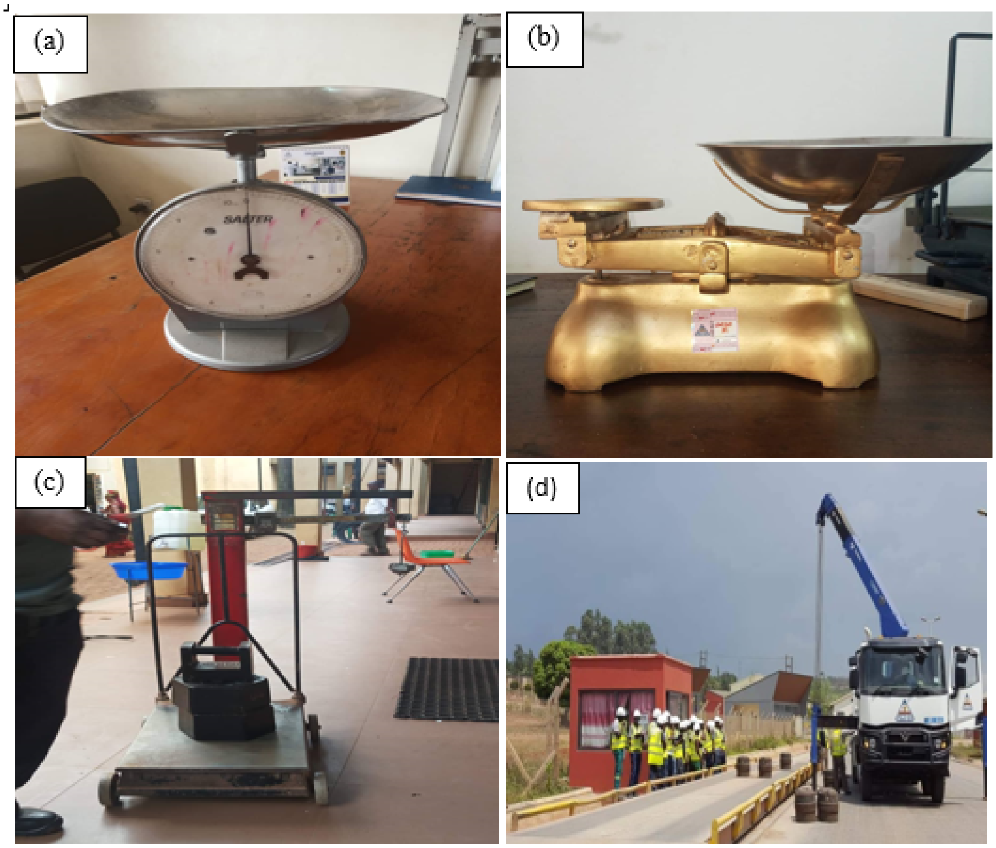

Figure 2. 2: (a) pedestal, (b) counter, (c) platform, and (d) weigh bridge mechanical scales.

2.3.3 Tests performed on weighing equipment during the verification process

The testing process of the weighing equipment over the entire measuring range is a preconditioned process to serve the purpose of correct interpretation of metrological control results, such as calibration, followed by a verification process of the weighing equipment (Vâlcu, 2012). According to Gajdosik et al., (2021), weighing equipment calibration is a set of operations under well-defined conditions used to determine the relationship between the measurement value displayed by a meter and the realised value from the reference standard (OIML, 2006a). Ivanova & Rudzitis, (2010) asserted that the verification process of the weighing equipment is carried out to verify their accuracy.

According to Ohgushi et al., (2007), when carrying out a metrological test on weighing equipment, a correct load is supposed to be applied in accordance with the standardized performance test requirements. Firstly, the repeatability test is the first test subjected to the weighing equipment. This is conducted to assess the equipment's ability to produce identical results when the same load or weight is loaded several times practically in the same manner on the load carrier under sufficient and constant test conditions (Maury-Toledo & García, 2018).

Secondly, the weighing equipment is then subjected to the accuracy test to determine and identify the errors. In this test, the indication errors should be possibly calculated as a difference between the weight indication and the corresponding value of the weight realized by the measuring weighing equipment (Nishino et al., 2010). In metrology, complete metrological tests are conducted or performed and comparisons made to assure metrological confidence (Taccola & Leão, 2016).

2.3.4 Error limits for generalized non-self-indicating weighing machines

According to ReliaSoft, (2015), technical requirements serve the purpose of eliminating from use, weights, measures, weighing, and measuring equipment that give false readings or would facilitate the perpetration of fraud. This implies that apparatus that conforms to the practicable official standards are calibrated with minimal error limits (Vogel & Esbensen, 2021). Thus, a minimum mass value is necessary for a weighing device to be utilized without producing weighing mistakes, i.e., at loads that are low in relation to the device's maximum capacity (OIML, 2006b). As the weighing apparatus's capacity increases, so does the absolute error. A weighing equipment is often used with rather low loads compared to its maximum capacity. According to the OIML recommendation, a class (III) equipment must have a minimum capacity value that is clearly shown on the weighing machine and corresponds to 20 scale intervals (i.e., 100g for an equipment graduated in 5g intervals). As a result, the worst-case relative weighing inaccuracy for operational equipment at this load might be 5%. The different limits of error for standard weighing equipment are illustrated in Table 2.1.

Table 2.1: Limits of error for general trade(OIML, 2006)

Maximum capacity	Limit of error
100g - 500g	+/-0.5g
500g- 1 kg	+/-1g
1kg – 2.5kg	+/-2g
2.5kg – 5kg	+/-5g
5kg – 10kg	+/-10g
10kg -20kg	+/-20g
20kg – 30kg	+/-50g
30kg – 40kg	+/-100g
40kg - 50kg	+/-200g

Accuracy classes in weighing instruments, as recommended by the OIML R 76-1 are shown in Table 2.2.

Table 2.2: Accuracy classes in weighing instruments (Fritsch et al., 2016)

Name	Symbol used on the instrument
Special accuracy	I
High accuracy	II
Medium accuracy	III
Ordinary accuracy	IIII

2.4 Factors Affecting Weighing Equipment Accuracy

For any industry, a credible weight system is vital when measurement of weights is to be used as a benchmark for product sales. Del Castillo et al., (2017) stated that understanding the factors that affect accuracy of any weight system is important if errors in measurements are to be minimized. Yorkin et al., (2013) stated that inaccuracies in weights measurement are often attributed to social desirability and erroneous measurements or recalls. According to Marshall, et al., (2003)**,** the accuracy of weighing equipment is affected by a variety of factors such as quality, handling, environmental factors, wear, and tear among others.

However, Alexander et al., (2016) stated that a combination of three weighing hoppers can reduce the variability in the quantities when the expected coefficient of variation of the final weight is minimal. Additionally, the weight of any product, observed as one of the quality characteristic to be monitored, must be close to any specified target weight as possible if it is to comply with the applicable regulations (Carlos García-Díaz & Pulido-Rojano, 2017).

2.5 Sources of measurement variations

In metrology, calibration and verification of weighing results are essential aspects that are always considered to ensure that the weighing equipment operate within their specified parameters (Eltawil et al., 2024). Variations in measurement results arise from the errors made. According to González & Herrador, (2007), measurement variations in the weighing equipment can arise from influences that bring in both systematic (bias) and random errors. Typical systematic errors are due to buoyancy and deviation of the reading from the standard mass (González et al., 2005). The random contributions arise from the repeatability, linearity, and readability which is the measure of the weighing equipment's ability to give incremental changes in its output value (M.Salahinejad & F.Aflaki, 2007). Factors such as object not being well-centered on the weighing pan, as it produces a torque that creates a counterforce in the system can also contribute to variations in results (Valcu & Baicu, 2012). Therefore, it is relevant to always have the objects well placed at the centre.

Nevertheless, it is important to note that when the weighing equipment are being tested and legally stamped for approval, they are considered to be consisting of mechanical and electronic components, which can all lead to inherent variability in the measurement results (Ross & Wing, 2016). Additionally, other sources of variation are; drift in accuracy with time, environmental variation, moisture and dirt, temperature, humidity, shock loading, and vibrations (Desoky et al., 2024; OIML R76-2, 2007).

2.6 Emerging Challenges in Legal Metrology

Inspectors are not up-to-date with weighing instrument design and development due to rapid technological advancements and inadequate training (Thiel,2014). Poor quality infrastructure such as standards, tools and equipment are a challenge which needs to be addressed so that metrology matches the fast pace of the private sector. Competent and well-trained personnel should be recruited to man the various service points as the country is wide and demanding metrology services. Inadequate knowledge sharing and collaborations with international and regional standards bodies among others negatively affects the ability for a country to compete internationally on matters of standards (City & Nam, 2007). Lack of awareness about the importance of metrology in business, health and safety is still a challenge in Uganda leading to severe losses in business, loss of life and property because of high accident rates. Legal Metrology has an old law that has failed to significantly control the use of unsuitable weighing scales in business transactions in Uganda. Metrology in Uganda lacks a pattern approval law and this leaves the economy open to the importation of many substandard and undesirable designs of weighing scales leading to a vicious cycle of customer complaints.

2.7 Weighing Equipment Failure Patterns

Weighing equipment failures are mainly initiated by the malfunctions in the operating mechanism first and then in the individual components (Akogwu & Kabir, 2024; Bourassa et al., 2016; UNBS, 2020). Aging, wear and corrosion are also reported as the most common causes (accounting for almost 50%) of major weighing equipment failures. In addition to the aforementioned causes, design faults, manufacturing faults, and incorrect maintenance also contribute 15% (Karthik et al., 2022).

2.8 Licensing and training of fabricators

UNBS has the mandate to license and revoke weighing equipment local manufacturers and repairers. This is done to ensure that the weighing scales produced and repaired are durable and possess all the desired metrological features in their design (Statutory Instrument, 2007). Additionally, weighing scale fabricators often get training and skilling from UNBS and other relevant stakeholders so as to contribute to Uganda's economy (Matiso, 2017). Manufacturers of weighing scales are required to be licensed and supervised by UNBS to ensure conformance with the regulatory requirement. To achieve this all-weighing scale fabricators are identified through a survey and their premises are inspected annually. The trainings are always organized and facilitated by UNBS to sensitize and educate potential and existing fabricators about the regulatory and technical requirements of a suitable weighing scale. However, in house trainings are conducted to examine the trainees prior to being issued licenses.

2.9 Imported and assembled weighing scales

UNBS always conducts pattern approval to prevent unsuitable weighing scales from entering Uganda (De et al.,1992). Majority of weighing digital and heavy duty weighing scales used in Uganda are imported because manufacturers have not yet ventured into their production. Currently, the mechanical counter scale is the only weighing scale being locally manufactured by our artisans on a rather small scale and the quality is inferior compared to those produced by foreign markets. Most weighing scales used in Uganda are imported from countries such as China, India, South Korea, Japan and Kenya among others.

2.9.1 Weighing equipment inspection challenges

Inspection and seizure of weighing equipment is provided for under the law so as to protect the public from being cheated (Statutory Instrument, 2007). UNBS metrology officers inspect trader's weighing equipment to ensure that their weighing equipment comply with the existing law. The common challenges faced during weighing equipment inspection and retrieval in Uganda include but not limited to; obstruction, impersonation by people who are not UNBS officers, falsified weighing scales, use of unsuitable weighing equipment, assaulting UNBS officers by traders, and use of unverified weighing equipment (Seiler, 2017).

2.9.2 Impact of faulty weighing equipment

A Faulty weighing equipment has a negative impact on business transactions, affecting both buyers and sellers through wrong declaration of quantities during custody transfers such as in production processes (ACCSQ, 2016; Desoky et al., 2024; Nzumile & Nyamweru, 2022a). Use of faulty weighing equipment has significant impacts that results into wrong computation of revenue to the government thus leading to loss of revenue, loss of capital to business owners, and loss of stock and produce to farmers and traders.

2.10 Trends in legal metrology

Legal metrology, as the regulatory branch of metrology ensures measurement accuracy and directly affects transparency in economic activities, public health, safety, and law enforcement (ACCSQ, 2016; OIML, 2006a; OIML R76-2, 2007). The International Organization of Legal Metrology (OIML) was founded to foster global harmonization in legal metrology practices (Nzumile & Nyamweru, 2022b). As technological advancements reshape business operations and societal needs, metrology systems must evolve to remain relevant and effective. Innovations offer new opportunities for improving the efficiency and accuracy of these systems (OIML D1, 2020). Consequently, there is a growing global emphasis on type evaluation, approval, and verification of measuring instruments, as well as on quantity and labeling standards for packaged products (Charles, 2020).

This evolution necessitates formal international and regional agreements for mutual recognition of calibration, testing, and certification capabilities. The adoption of international documents as standards for legal metrology is also becoming widespread. Another significant trend is the push for localized, single-instance type evaluation testing for weighing equipment to streamline compliance (Charles, 2020). Enforcement remains a vital component, with a strong emphasis on ensuring compliance with legal metrology regulations across diverse types of weighing instruments (Chourasia et al., 2023). Asset management standards, such as ISO 55000 and PAS 55-1:2008, support this compliance framework by introducing structured approaches to managing equipment lifecycle and failures, ultimately enhancing consumer protection (Blackmore & Leeprechanon, 2016; Germán Moreno, Molina, 2014).

2.11 Parameters influencing the performance of weighing equipment

2.11.1 Maximum Likelihood Estimation and Weibull Parametrization

The Weibull distribution is widely used in reliability engineering for modeling failure times due to its flexibility in representing various life behaviors. It is defined by three key parameters: the location parameter (α), the shape parameter (β), and the scale parameter (η) (Harper et al., 2011; Montoya et al., 2019; Örkcü et al., 2016). These parameters allow the distribution to accommodate different failure rate patterns over time. The Weibull model is particularly useful for estimating the life expectancy of assets, such as weighing equipment, in asset management systems.

Ren et al., (2019) stated that the Maximum Likelihood Estimation (MLE) method is an effective and widely used technique for estimating these parameters. The method involves maximizing the likelihood function to obtain estimates for the three unknown parameters of the Weibull distribution (Ren et al., 2019). The Cumulative Distribution Function (CDF) and Probability Density Function (PDF) for the three-parameter Weibull distribution are expressed as follows:

$$F(t, \propto, \beta, \eta) = \begin{cases} 1 - e^{-\left(\frac{(t_i - \alpha)}{\eta}\right)^{\beta}}, & t > \propto \\ 0, & t \leq \propto \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}1)$$

$$F(t, \propto, \beta, \eta) = \begin{cases} \frac{\beta}{\eta}\left(\frac{t - \propto}{\eta}\right)^{\beta - 1} e^{-\left(\frac{(t_i - \alpha)}{\eta}\right)^{\beta}} & t > \propto \\ 0, & t \leq \propto \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}2)$$

Here, α, β, and η are location, shape, and scale parameters, respectively. Figure 2.3 illustrates PDF shapes for different parameters. In addition, the figure shows the flexibility in shape of the Weibull PDF is very flexible for fitting into a wide range of experimental data (Montoya et al., 2019).

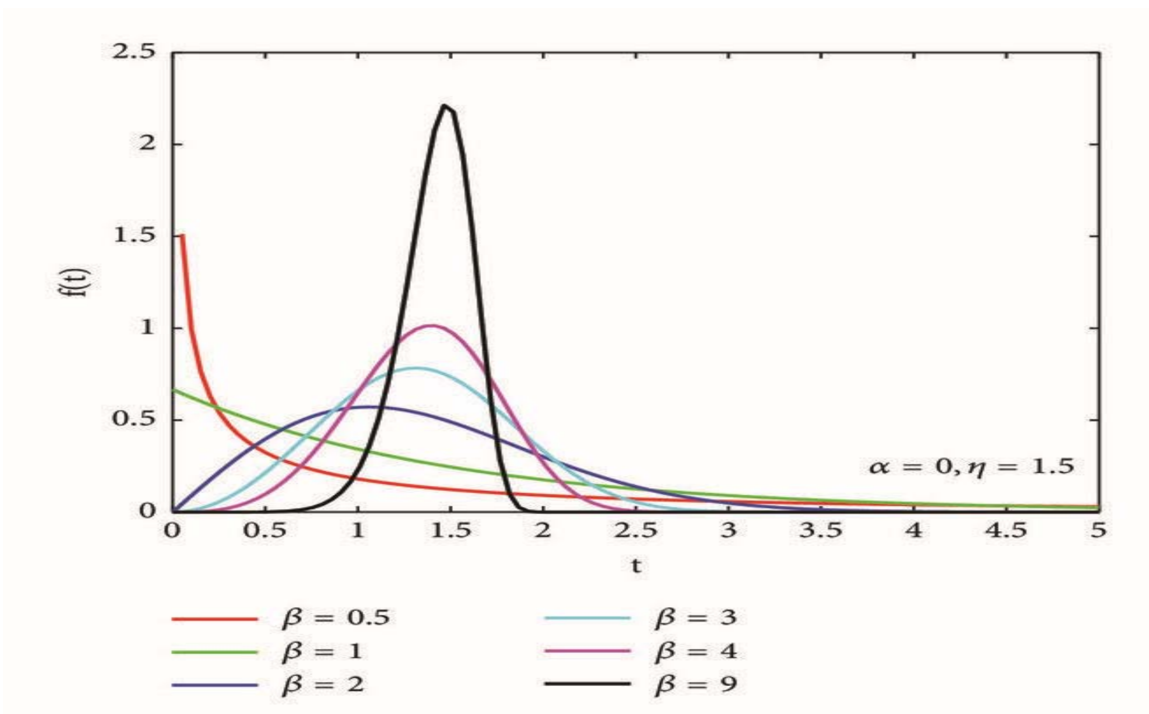

Figure 2.3: Weibull Probability Density Function (PDF) with various values of β when assuming α =0 and η = 1.5 (Ren et al., 2019).

In general, there are several methods that can be used to estimate the parameters of a distribution. These methods include but not limited to; probability weighted moment, Maximum Likelihood (ML) method and least square method. Amongst these methods, the Maximum Likelihood (ML) estimators are asymptotically unbiased with the minimum variance under regularity conditions (Wascom & Xiang, 2021). Then the Maximum Likelihood Estimation for three-parameter Weibull distribution is described briefly. Let $t1$, $t2$, $\cdots$, tn be a random sample of size n; $\vec{\boldsymbol{\theta}} = (\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\eta})$is noted as the Weibull model parameters which are to be estimated; namely, $\vec{\boldsymbol{\theta}} = (\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\eta})$, then the likelihood function is written as;

$$\boldsymbol{L} = \prod_{i=1}^{n} \boldsymbol{f}_{i}(\boldsymbol{t}_i; \overrightarrow{\boldsymbol{\theta}}) = \prod_{i=1}^{n} \frac{\boldsymbol{\beta}}{\eta}\left(\frac{\boldsymbol{t}_i - \propto}{\eta}\right)^{\boldsymbol{\beta}-\mathbf{1}} \boldsymbol{e}^{-\left(\frac{(\boldsymbol{t}_i-\boldsymbol{\alpha})}{\eta}\right)^{\boldsymbol{\beta}}} \text{.....................................(2-3)}$$

The aim of estimation is to determine the unknown vector $\vec{\boldsymbol{\theta}}$ and the three unknown parameters α, β, and η by maximizing the likelihood function. Since it contains the exponential term, it is easier to obtain the maximum by its logarithm leading to reduced complexity during calculations. The logarithm of the likelihood function is shown as;

$$\boldsymbol{In}\left[\boldsymbol{L}\left(\boldsymbol{t}_i; \vec{\boldsymbol{\theta}}\right)\right] = \sum_{i=1}^{n}[\boldsymbol{In}(\boldsymbol{\beta}) + (\boldsymbol{\beta} - \mathbf{1})\boldsymbol{In}(\boldsymbol{t}_i - \boldsymbol{\alpha}) - \boldsymbol{\beta}\boldsymbol{In}(\boldsymbol{\eta}) - (\frac{(\boldsymbol{t}_i-\boldsymbol{\alpha})}{\boldsymbol{\eta}})^{\boldsymbol{\beta}}] \text{ ..... (2-4)}$$

Then, the vector $\vec{\boldsymbol{\theta}}$ can be obtained by maximizing of the likelihood function. To achieve this, the conventional approach is to take the partial derivation of the likelihood function in terms of vector

$\overrightarrow{\boldsymbol{\theta}}$ and set the partial equations to zero, as

$$\frac{\partial \boldsymbol{In}[\boldsymbol{L}(\boldsymbol{t}_i;\vec{\boldsymbol{\theta}})]}{\partial \boldsymbol{\alpha}} = 0 \text{ .... (2-5)}$$

$$\frac{\partial \boldsymbol{In}[\boldsymbol{L}(\boldsymbol{t}_i;\vec{\boldsymbol{\theta}})]}{\partial \boldsymbol{\beta}} = 0 \text{ .... (2-6)}$$

$$\frac{\partial \boldsymbol{In}[\boldsymbol{L}(\boldsymbol{t}_i;\vec{\boldsymbol{\theta}})]}{\partial \eta} = 0 \text{ .... (2-7)}$$

We substitute the log-likelihood function into the above equations. The following equations are obtained:

$$\boldsymbol{L_1} = \sum_{i=1}^{n}\left[\frac{1}{\beta} + \boldsymbol{In}(t_i - \alpha) - \boldsymbol{In}(\eta) - \left(\frac{(t_i - \propto)}{\eta}\right)^{\beta} \boldsymbol{In}\left(\frac{(t_i-\alpha)}{\eta}\right)\right] = \mathbf{0} \text{.............(2-8)}$$

$$\boldsymbol{L_2} = \sum_{i=1}^{n}\left[-\frac{\beta}{\eta} + \left(\frac{\beta}{\eta}\right)\left(\frac{(t_i-\alpha)}{\eta}\right)^{\beta}\right] = \mathbf{0} \text{ .... (2-9)}$$

$$\boldsymbol{L_3} = \sum_{i=1}^{n}[-\frac{(\beta-1)}{(t_i-\alpha)} + \left(\frac{\beta}{\eta}\right)\left(\frac{(t_i-\alpha)}{\eta}\right)^{\beta-1}] = \mathbf{0} \text{.................................... (2-10)}$$

The values of $\boldsymbol{\beta}$ and η in Maximum likelihood estimation are determined by a relationship such that:

$$\frac{1}{\beta} + \frac{1}{\eta}\sum_{i=0}^{n} x_i + \frac{\sum_{i=1}^{n} x_i^{\beta} In x_t + \sum_{j=n+1}^{N} y_j^{\beta} In y_j}{\sum_{i=1}^{n} x_i^{\beta} + \sum_{j=n+1}^{N} y_j^{\beta}} = \mathbf{0} \text{ .... (2-11)}$$

$$\eta = \left[\frac{1}{n}\left(\sum_{i=1}^{n} x_i^{\beta} + \sum_{j=n+1}^{N} y_j^{\beta}\right)\right]^{\frac{1}{\beta}} \text{..(2-12)}$$

2.11.2 Goodness-Of-Fit-Tests

The Goodness-of-Fit (GOF) test is a useful statistical tool used to assess the suitability of a selected probability distribution such as the Weibull model for a given dataset. In reliability analysis, where the Weibull distribution is frequently applied, GOF tests help determine how well the Weibull model represents the observed failure data. Common GOF methods include the Kolmogorov-Smirnov (K-S) test, the Cramér–von Mises (CM) test, and the Anderson-Darling (AD) test (Harper et al., 2011). These tests evaluate the discrepancy between the empirical Cumulative Distribution Function (CDF) derived from observed failure times and the theoretical CDF of the Weibull distribution. As explained by Bothma, Allison, and Visagie (2022), a specific hypothesized distribution, such as the Weibull, is accepted only if the maximum deviation between the empirical and fitted CDFs across "n" failure points falls within an acceptable threshold. If the deviation exceeds this threshold, the Weibull model is rejected as a poor fit (Bothma et al., 2022).

2.11.3 Median Rank Determination

The process of determining the median rank takes the CDF of the distribution and attempts to linearize it (Nassar, Gunnarsson & Hegab, 2005). The procedure followed is; ranking the data – adjust the item "times to failure" in ascending order for all cases i.e., failed and censored. If all data were complete, then the order forms the rank positions for the times. In cases where item data contains both complete and censored data then rank positions for the failed items need to be adjusted to appreciate the potential influence of censored items. The rank adjustment order numbers are achieved using the equation below:

$$\textbf{Rank Increment} = \frac{(\mathbf{N+1}) - (\textbf{previous adjusted rank})}{\mathbf{1} + (\textbf{Number of items beyond present censored item})} \ldots\ldots\ldots\ldots \text{(2-13)}$$

Where N is the total number of items under consideration regardless of whether failed or censored.

Estimate the CDF or the Median Rank F' (t) using either (N<50) or using Bernard's Median Rank Estimator (BMRE) as in equation (2-14) by applying the adjusted rank order numbers (for N<100)

$$\boldsymbol{P_i} = \frac{\boldsymbol{i-0.3}}{\boldsymbol{N+0.4}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-14)}$$

Where i is the i^{th} adjusted rank order value and N as defined before. The P_i gives the median rank F_i' (t) which is the observed CDF while the fitted CDF is the calculated F_i' (t) according to the presumed distribution using the obtained parameters.

2.11.4 Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov (K-S) test was adopted among others for this study. (Shaik & Reddy, 2018) defines the K-S test as non-parametric and has an advantage of not being distribution-specific, does not require large sample size, easy to implement and can reject any inadequately hypothesized distributions. The K-S measures the greatest discrepancy between observed and hypothesized distributions. This random variable discrepancy which is denoted as $\boldsymbol{D_n(r)}$ and measures how good the fit (distribution) is while the K-S critical values are denoted by $\boldsymbol{D^{/\alpha}{}_n(r)}$ can be found in probability tables at different levels of significance ($\boldsymbol{\alpha}$) for various values of n.The hypothesized distribution is accepted at a selected significance level if$\boldsymbol{D_n(r) < D^{\alpha}{}_n(r)}$. The K-S criterion, the critical value and $\boldsymbol{D_n(r)}$ are denoted as follows:

KS Criterion: $\boldsymbol{P(D_n(r) < D^{\gamma}{}_n(r) = 1 - \gamma}$………………………………... (2-15)

$\boldsymbol{D_n(r)}$: $\boldsymbol{D_n(r) = \max |F_i(t) - F'_i(t)|}$∀ i = 1, 2, 3, …. n failures……….. (2-16)

Critical value $\boldsymbol{D^{\gamma}{}_n(r) = \frac{\gamma_{1-\gamma}}{\sqrt{n}}}$ …………………………………………….(2-17)

Where;

$\boldsymbol{\gamma}$ is the significant level and in engineering practice set to 0.05

$\boldsymbol{\gamma_{1-\gamma}}$ is the critical value and *n* being the number of failures. "R" is the portion of failures out of the total number of products N defined as: $\boldsymbol{R = \frac{n}{N}}$……………..(2-18)

2.12 Predictive Modeling of Weighing Equipment Degradation in Stochastic Environments

2.12.1 Predictive modeling using life assessment

Life data analysis involves estimating the lifespan of products by fitting statistical distributions to life data collected from a representative sample of units. This method allows for the prediction of key reliability metrics, such as mean life, failure rate, and the probability of failure at specific time intervals. As outlined by Yang et al. (2018), the process includes several key steps: collecting life data for the product, selecting an appropriate lifetime distribution to model the product's behavior, estimating the parameters that best fit the chosen distribution, and generating analytical plots and results. These outputs help assess important life characteristics, enabling predictive modeling of equipment degradation in stochastic environments.

2.12.2 Probability Density Functions

With the help of modern computing devices, statistical approaches have become more sophisticated and readier to use in many cases. Failure data in general such as time-to-failure can be evaluated statistically using parametric or non-parametric methods. Parametric methods make assumptions about the underlying population from which the data are obtained while non-parametric methods do not assume any particular family for data distribution (ReliaSoft, 2015). In both methods, the failure processes are described and considered as random variables. For this study, only continuous variables were considered. The Cumulative Distribution Function (CDF) and Probability Density Function (PDF) are the key statistical functions from which other functions of interest such as reliability, hazard, mean time and median life functions among others can be obtained. The PDF fully describes a statistical distribution and indicates the relative probability of failure at different times (Nemati, 2016). If T is a non-negative continuous random variable representing a lifetime of equipment, then the probability that any randomly chosen item fails during the time $\boldsymbol{t}$ to $\boldsymbol{t} + \Delta\boldsymbol{t}$ is its PDF and represented by the function f (t):

$$\boldsymbol{f(t)} = \mathbf{lim}\, \Delta\rightarrow \boldsymbol{t} \frac{\boldsymbol{Pr}(\boldsymbol{t} < T < t+\Delta t)}{\Delta \boldsymbol{t}} \boldsymbol{for\ small}\ \Delta\boldsymbol{t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-19)}$$

For the whole area under the density function:

$$\int_{\mathbf{0}}^{\infty} \boldsymbol{f(t)dt} = \mathbf{1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-20)}$$

Further any values of $\boldsymbol{t_1\ and\ t_2}$ where $\boldsymbol{t_1} \leq \boldsymbol{t_2}$ then the probability is the area under the density function from $\boldsymbol{t_1\ and\ t_2}$ expressed as:

$$P(t_1 < t < t_2) = \int_{t_1}^{t_2} f(t)dt \; where \; f(t) \geq 0 \text{ ....(2-21)}$$

2.12.3 The Cumulative Distribution Function F (t)

Nemati, (2016) defines the CDF f (t) of a random variable T as the probability that an item under consideration will fail before time t within the interval (0, t) which is the integral of the f (t) from 0 to t and can be expressed mathematically as:

$$F(t) = \Pr(T \leq t) = \int_0^t f(x)dx \; for \; t > 0 \text{ .... (2-22)}$$

Further, the F (t) in terms of a population is the proportion of units in the population that will fail before time "t" (Botev *et al*, 2016). The term F (t) has some two useful interpretations that is;

(i) Within the product population, any product has the probability of F(t) to fail prior to time "t"

(ii) For a group of products that have failed, F(t) is the portion of products that fails by the time "t"

Conversely:

$$f(t) = \frac{d(F(t))}{dt} = -\frac{dR(t)}{dt} \text{ ....(2-23)}$$

***B(x)* Lives**

B(x) lives are often used to indicate certain levels of reliability based on the age of a component. The B(x) lifetime can be defined as the estimated time when the probability of failure will reach a specified point (X %). The B(x) lives are another way to represent the CDF where the "x" is the CDF in % (Zhang et al., 2017). In most engineering applications, the B(x) usually starts around B (10) suggesting that 10% of the population will fail at a certain age and that 90% will survive. For example, if 10% of the products are expected to fail within 4 years of operation, then B (10) lifetime is 4 years.

2.12.4 Reliability Function R (t)

The reliability function R (t) also known as survival function, is the probability that the equipment will operate properly for a specified period under the design operating conditions without failure i.e., failures occur after time "t" This is expressed as:

$$\boldsymbol{R(t) = \mathrm{Pr}(T \leq t)} \qquad \text{(2-24)}$$

The reliability function may also be defined as the probability that the equipment will not live up to time "t" which in general is the integral of function f (t) from t to infinity and is given by:

$$\boldsymbol{R(t) = \int_t^\infty f(t)dt} \qquad \text{(2-25)}$$

R(t) has two common interpretations according to (Han & Ding, 2017).

(i) Within the product population, R (t) is the probability of having a randomly drawn unit at time "t" that is alive (i.e. has not failed).

(ii) R (t) within the product population, is the portion of products that will survive for at least time "t".

In practice, as a complementary function of F (t), R (t) is often expressed as:

$$\boldsymbol{R(t) = 1 - F(t) = 1 - \int_t^\infty f(x)dx \ for \ t} > 0 \qquad \text{(2-26)}$$

2.12.5 The Hazard Function h (t)

The condition probability of failure in the time interval from t to (t+$\Delta \boldsymbol{t}$) given that the system has survived to time t is given by (ReliaSoft, 2015). In addition, Rinne, (2014) noted that the hazard function describes the *'intensity of death'* at the time *t* given that the equipment has already survived past the time t. Like the reliability, PDFs, CDFs the hazard rate function assumes a bathtub pattern emphasized on three stages of the asset's lifespan including; the infant mortality, constant failure and the deterioration stages. Hazard rate analysis is carried out basing on the stages of random and wear-out failures. This is because failures indicate asset's propensity to death as shown in figure 2.4.

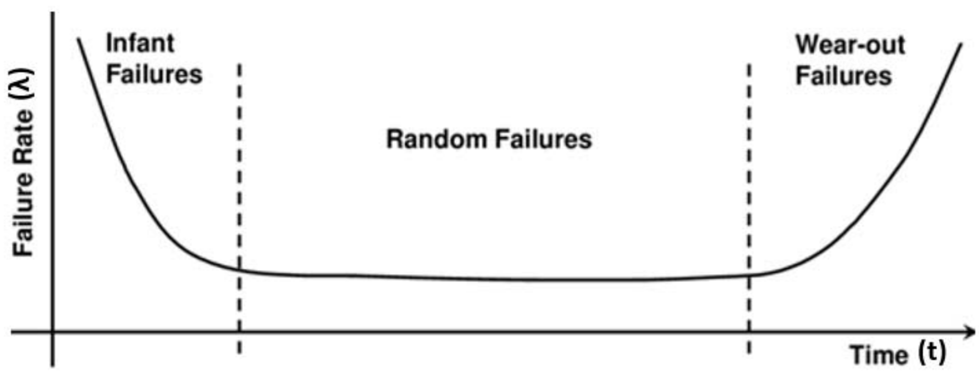

Figure 2.4: Stages of asset aging from commissioning to death (Kayenga et al., 2023).

2.12.6 The Methodology of Condition Based Risk Management

Condition Based Risk Management (CBRM) is a technique of asset management which is a key application for management of engineering assets. The purpose of CBRM is to identify the optimal time for asset renewal. According to (Blackmore & Leeprechanon, 2016), the methodology behind CBRM can be broken down into 8 key steps which are; define the condition of the asset, link the current condition to performance, estimate future condition and performance, evaluate potential interventions in terms of Probability of Failure (POF) and failure rates, define and weigh the Consequences of Failure (COF), and build a risk model.

Table 2.3 shows the process of establishing a relationship between current state of an engineering asset and relative probability of failure. Calibration is thus achieved by adjusting the scaling of the calibration curve such that the overall number of asset failures matches with the expected number of failures for the asset population. The relationship is set so that assets exhibit a long period of constant but low failure rate during the normal operating life, having a rapid escalation in POF with increasing deterioration.

Table 2.3: Relationship between health index and probability of failure

Health Index (%)	Probability of failure (%)	Condition
85 -100	1.27 – 1.59	Very Good
70 - 84	1.60 – 1.99	Good
50 - 69	2.00 – 2.69	Fair
30 - 49	2.70 – 3.59	Poor
0 - 29	3.60 – 5.60	Very Poor

(Kayenga et al., 2023)

2.13 The essence of condition-based maintenance as opposed to time-based maintenance

Application of the Condition-Based Maintenance (CBM) assessment strategy will enhance accuracy of replacement schedules in a manner that minimizes the future cost and impact on system reliability (Stevanovic, 2020). Several researchers have applied time based maintenance reliability assessment such as Fault Tree Analysis, Fault Mode and Effect Analysis in Engineering applications (Sun *et al*, 2015).

2.14 Determination of the appropriate time of weighing scale replacement

Optimal replacement time is the time of transition that would have a possibility of affecting the highest failure rate. “At each time step, asset managers are confronted with a maintenance decision. Making the best decision requires consideration of both the immediate effects and also long-term impacts that are difficult to know in advance. Sometimes action with poor immediate impacts can have better long-term ramifications.” Time is then viewed as an inequality constraint such that maintenance should be done before the exact time when the maximum failure rate is close to being attained. The most likely probability when the weighing equipment will exist in a given transitional state. This will be the maximum failure rate.

According to Jardine et al., (2006), there are two major models that can be used to estimate the weighing scale replacement time, and these are; Proportional Hazards Model (PHM) and Hidden Markov Model (HMM).A time-dependent Proportional Hazards Model (PHM), which is a popular model in survival analysis, is suitable for analyzing both event and condition monitoring data together. The merit of a time-dependent PHM is its ability to relate the failure probability to both age and condition variables, so that one can assess the failure probability with given machine condition at any specified age. The model is;

$$\mathbf{h(t) = h_0(t) \exp(\gamma_1 x_1(t) + \ldots\ldots + \gamma_p x_p(t))} \quad \ldots\ldots\ldots\ldots \textbf{(2-27)}$$

$\mathbf{h_0(t)}$ is a baseline hazard function, $\mathbf{x_1(t) \ldots\ldots x_p(t)}$ are covariates which are functions of time and $\boldsymbol{\gamma_1 \ldots\ldots \gamma_p}$ are coefficients. The baseline hazard function can be in non-parametric or parametric form. A commonly used parametric baseline hazard function is the Weibull hazard function, which is the hazard function of the Weibull distribution.

Hidden Markov Model (HMM) is another appropriate model, and it consists of two stochastic processes: a Markov chain with finite number of states describing an underlying mechanism and an observation process depending on the hidden state. A discrete-time HMM is defined by

$$\mathbf{X_{k+1} = AX_k + V_{k+1}} \ldots\ldots\ldots\ldots \textbf{(2-28)}$$

$$\mathbf{Y_k = CX_k + W_k} \ldots\ldots\ldots\ldots \textbf{(2-29)}$$

Where $\mathbf{X_k}$ and $\mathbf{Y_k}$ denote the hidden process and the observation process, respectively, $\mathbf{V_k}$ and $\mathbf{W_k}$ are noise terms with martingale increments, and A and C are parameters. Event data and condition monitoring data are used to train the HMM, i.e., to estimate model parameters.

Since full likelihood function is not available for an HMM, a statistical approach known as EM algorithm is usually used for parameter estimation (Jardine et al., 2006).

2.15 Gaps Detected in Literature

Existing literature reveals a critical gap in the predictive management of weighing equipment specifically, the lack of tools to determine optimal replacement time. Most efforts in legal metrology focus on calibration and verification, without addressing when equipment should be withdrawn from service due to degradation (UNBS, 2020; Luwedde et al., 2022). This gap is particularly significant for mechanical counter scales, which are still widely used in Uganda but experience gradual wear that often goes unnoticed until failure occurs (Ross & Wing, 2016; Marshall & Murphy, 2003). Additionally, much of the research prioritizes digital weighing systems, leaving mechanical devices underexplored despite their accessibility, simplicity, and continued relevance in local trade (Yorkin et al., 2013; Campus, 2023).

This study addresses the gap by using the Weibull statistical model to predict the optimal replacement time for weighing equipment based on observed failure data. The Weibull model is well-suited for modeling equipment life due to its ability to represent various failure behaviors, including early-life, random, and wear-out failures (Murthy et al., 2004; Montoya et al., 2019). Unlike traditional calibration schedules, this approach enables proactive lifecycle management, ensuring equipment is replaced before failure compromises trade fairness or consumer protection. By focusing on replacement timing rather than reactive maintenance, the study provides a data-driven solution for improving metrology enforcement and asset reliability (Kayenga et al., 2023; Thiel, 2018).

CHAPTER THREE: METHODOLOGY

3.0 Introduction

This chapter outlines the systematic approach that was taken to gather and analyze data and draw meaningful conclusions. This chapter presents the systematic methodology adopted to collect, analyze, and interpret data in order to address the research objectives. It details the research design, data collection techniques, analytical tools, and modeling procedures used to predict the optimal replacement time for mechanical weighing equipment. The approach ensures that the findings are both reliable and applicable to real-world conditions, supporting informed decision-making and practical improvements in legal metrology practices.

3.1 Research Approach

This study adopted a systematic approach to develop a Weibull-based predictive model for determining the optimal replacement time of mechanical weighing equipment. It started with field data collection on time-to-failure and usage conditions of mechanical counter scales in selected trading areas. Using Maximum Likelihood Estimation (MLE), the study estimated the Weibull distribution parameters shape (β), scale (η), and location (α) to model failure behavior. The model's accuracy was validated through Goodness-of-Fit tests such as the Kolmogorov-Smirnov (K-S) test. After validation, the model was used to compute reliability metrics like the hazard rate and B(x) life to identify the point at which failure risk justified replacement. This approach enables data-driven decision-making, replacing arbitrary maintenance schedules with predictive strategies, thereby enhancing consumer protection and trade fairness.

3.2 Questionnaire Design for the Perception Survey

A structured perception survey questionnaire was developed using carefully selected closed-ended questions, informed by the need for consistency, clarity, and ease of analysis. Closed-ended questions were chosen to ensure that responses could be easily quantified and compared across a broad respondent base, reducing ambiguity and enhancing the reliability of the data. The questionnaire was designed around key performance indicators related to the inspection and verification of mechanical weighing equipment, and included items on equipment types, failure causes, and factors affecting precision and accuracy. It aimed to capture respondents' perceptions and attitudes toward current inspection practices, equipment performance, and failure trends to support evidence-based process improvements.

3.3 Study Population

The study population comprised of weighing equipment owners, users, traders, manufacturers, and repairers that use mechanical counter weighing equipment within the selected markets of Kalerwe, Kibuye, Nateete and Nakawa.

3.4 Determination of Sample Size

3.4.1 Sampling Techniques and Procedures

Purposive sampling was used, where only mechanical weighing scale users, repairers and inspectors were interviewed. Simple random sampling was then used to choose the number of individuals to be included in the sample from the users, repairers and inspectors. The representative sample of the different categories of weighing scale owners, inspectors, and users was computed using the formula (Israel, 1992).

$$\textbf{Sample size (n)} = \left[\frac{Z^2 X P(1-P)}{e^2}\right] / \left[1 + \frac{Z^2 x p(1-p)}{e^2 N}\right] \quad \text{.............................} \quad (3\text{-}1)$$

Where N= Population size, Z= Z-Score, e = Margin of error, and p = Standard Deviation at a confidence level of 95% and a confidence interval of 5%. The sample size used was 310 respondents as shown by Table 3.1.

Table 3. 1: Sample Size for the study

Market	Number of Equipment Inspected
Nakawa	110
Kalerwe	70
Nateete	60
Kibuye	70
Total	310

3.5 Data Collection

Since both quantitative and qualitative data were collected, cross-cutting data collection methods and instruments were adopted as asserted by Mort (2013).

3.5.1 Quantitative Data

For quantitative data collection, a perception survey questionnaire with carefully selected closed-ended questions was used. The self-administered questionnaire based on a three-point Likert scale including Yes, No and Not Sure. The researcher coded the questionnaire into an online form that was filled out by the respondents through their respective smartphone devices for ease of accessibility and timeliness of data collection activities. The researcher also conducted face-to-face interviews with selected respondents.

Additionally, quantitative data like degree of accuracy was obtained by measuring standard weights (2kg,1kg,0.5kg,0.25kg) against the weights of scales from different traders in the scope markets (Nakawa, Nateete, Kalerwe and Kibuye) as shown by Figure 3.1 and Appendix 4.

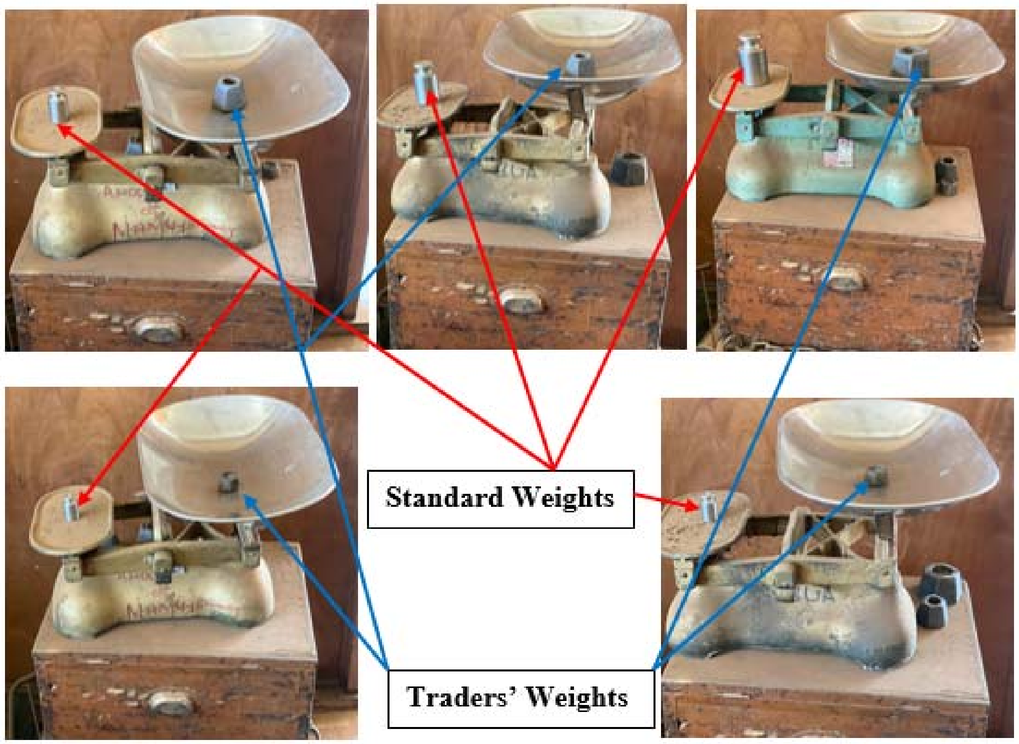

Figure 3. 1: Measurement of traders' weights against standard weights.

3.5.2 Qualitative Data

Qualitative data was collected through the use of observation, inspection of weighing equipment. These in combination were used to categorize the level of degradation of different mechanical weighing equipment from different traders, basing on the physical appearance of the mechanical parts of the equipment.

3.6 Data Collection Tools

The cross-sectional study sought to collect data at a single point in time. In addition, the researcher combined different data collection tools such as the perception survey questionnaire, face-to-face interviews, and observation. The respondents were randomly but carefully selected from a known population including; weighing equipment inspection officers, business owners, weighing equipment manufacturers and repairers. Emphasis was directed towards determining the different parameters that affect weighing equipment accuracy and precision characteristics and the respondent's attitudes toward the same process. In addition, data was collected about the different weighing equipment degradation causes that impact their respective performance during business transactions within the selected markets included in the study. The data collection tools that were used to capture both primary and secondary data include;

3.6.1 Perception Survey Questionnaire

To partially achieve objectives (i) and (ii), a structured, self-administered perception survey questionnaire (Appendix 2) was used to collect quantitative data from 310 respondents, including traders, repairers, and inspectors across selected markets. The questionnaire featured closed-ended questions on a three-point Likert scale (Yes, No, Not Sure) to assess respondents' views on equipment accuracy, degradation causes, and maintenance practices. Responses were collected both electronically and in paper form, then organized using Excel and SPSS for analysis. Data was cleaned, coded, and sorted by respondent category to identify trends and correlations aligned with research objectives.

3.6.2 Face-to-face Interviews

To complement and validate the survey data, various formal and informal face-to-face interviews were conducted with purposively selected stakeholders including traders, weighing scale repairers, and UNBS inspectors using a semi-structured interview guide (Appendix 1). These interviews allowed for deeper exploration of themes such as equipment failure trends, handling practices, and maintenance decisions. Interview responses were transcribed and thematically categorized (e.g., failure causes, user habits) to support qualitative insights that aligned with survey findings. Additionally, consultations with key institutions such as UNBS, the Uganda Manufacturers Association, and the Kampala City Traders Association were carried out using open-ended questionnaires to gather expert input on best practices and generate informed recommendations for process improvement (Hollweck, 2019).

3.6.3 Observation

Objectives (i) and (ii) were mainly achieved by observation of weighing equipment users during the measurement of goods in order to capture; the presence of non-compliance, falsification, and related vices. Since the researcher inspected the weighing equipment for compliance without bias.

3.7 Data Analysis

The parameters influencing the precision, accuracy and level of degradation of mechanical counter weighing equipment. A binary logistic regression model was used to estimate the maximum likelihood of different parameters in affecting the level of precision and accuracy of weighing equipment. The model used was (Peng et al., 2002);

$$\boldsymbol{In}\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots \beta_K X_K \quad \ldots\ldots (3\text{-}2)$$

$$\text{Where P (Y= y)} = \begin{pmatrix} 1 & \mathit{If\ High\ precison\ and\ accurcy} \\ 0 & \mathit{Otherwise} \end{pmatrix}$$

Where X_1, X_2, X_K are independent variables (parameters), β_1, β_2, and β_K are slopes, and β_0 is an intercept. Y represents the level of precision and accuracy.

The level of degradation was categorized into: No indication of degradation, some indication of degradation and critically degraded. Critically degraded weighing equipment were those with severely deformed components, broken parts and no proper movement of the components thereby not able to weigh accurately. Weighing scales with some indication of degradation were those with defects such as cracked components, scratches and visible depreciation but still able to weigh accurately. No indication of degradation referred to weighing scales that were in very sound physical and mechanical condition with no visible defects and able to weigh accurately. A graph was used to summarize the precautionary measures taken by traders to avoid the effect of different parameters that reduce weighing equipment accuracy and precision.

3.8 The most opportune time for weighing equipment replacement.

To determine the most appropriate time for replacing mechanical counter weighing equipment, a Weibull predictive model was developed and applied. This model was built using historical failure data, maintenance logs, recalibration intervals, and usage patterns collected from 310 weighing scales across Kalerwe, Nakawa, Nateete, and Kibuye markets. Key data inputs included the times when scales failed or malfunctioned, frequency and timing of maintenance or recalibration events, and duration of active use per scale. These data points were sourced through structured surveys, interviews, and field inspections, and were cleaned and organized to ensure statistical reliability.

The three-parameter Weibull distribution comprising shape (β), scale (η), and location (α) parameters was fitted to the dataset using the Maximum Likelihood Estimation (MLE) method. This enabled accurate estimation of the failure behavior of the equipment under varying conditions. The reliability function $R(t)$ and the hazard function $h(t)$ were computed to evaluate the probability of survival and the risk of failure over time, respectively. The $B(x)$ life metric was also used to identify the age at which a specific percentage (e.g., 90%) of equipment would be expected to survive.

To enhance statistical significance, the dataset covered multiple scale users**,** representing a diverse cross-section of traders with varying usage intensity, handling practices, and environmental exposure. This diversity helped ensure that the model accurately reflected real-world conditions. The model results were validated using the Kolmogorov-Smirnov

Goodness-of-Fit test, confirming that the Weibull function adequately captured the failure trends in the observed population.

The outcome of this analysis indicated an optimum replacement time of 8.4 years for mechanical counter scales. At this point, the risk of failure increases significantly, as revealed by the sharp rise in the hazard function. By integrating failure records, recalibration logs, and maintenance intervals, the Weibull-based approach provided a data-driven and statistically robust framework for informing equipment replacement policies, helping improve metrology compliance and protect consumers from trade imbalances caused by degraded weighing equipment.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents and discusses the results from the predictive model developed to estimate the optimal replacement time for mechanical counter weighing equipment. Technical data was collected from a representative random sample of users, repairers, and inspectors, and categorized into three degradation levels namely; no degradation, moderate, and critical based on physical inspection of mechanical components. A binary logistic regression was applied to identify significant factors influencing equipment precision and degradation. Subsequently, a Weibull predictive model was implemented in MATLAB 2023 to estimate failure behavior and determine the most opportune replacement time.

4.2 Accuracy of the Weighing Equipment

4.2.1 Measurement of standard weights against traders' weights

The results in Table 4.1 indicate that the performance of traders' weighing scales declined significantly with increasing standard weight. Only 22.26% of the scales were accurate when tested with a 2 kg standard weight, highlighting a high level of inaccuracy for heavier loads, particularly in Nakawa, Kalerwe, Nateete, and Kibuye. For both the 1 kg and 0.5 kg standard weights, accuracy improved to 48.39%, suggesting moderate reliability at mid-range loads, although more than half of the scales still failed to meet the permissible 15g variation threshold. In contrast, the 0.25 kg test recorded the highest accuracy at 96.45%, indicating that most of the scales are still reliable when weighing lighter items. These results suggest that weighing scales in the observed markets are more likely to degrade in precision as the load increases, reinforcing the importance of establishing a predictive model to guide timely withdrawal and replacement of scales based on weight-specific performance trends.

Table 4.1: Performance when standard weights were measured against traders' scale weights

Standard weight used (kg)	Inaccurate Scales				Total Inaccurate scales Out of 310	Accurate scales (≤0.015 kg)	percentage accuracy
	Nakawa (110)	Kalerwe (70)	Nateete (60)	Kibuye (70)			
2	92	53	43	53	241	69	22.26
1	11	53	43	53	160	150	48.39
0.5	11	53	43	53	160	150	48.39
0.25	11	0	0	0	11	299	96.45

4.2.2 Factors influencing the accuracy of weighing equipment

In this study, four critical factors namely; dirt and dust, poor handling, operational errors, and vibrations were analyzed to assess their impact on the accuracy of mechanical counter weighing equipment, as shown by Table 4.2. Data was collected through perception survey questionnaires, field observations, and interviews with traders, repairers, and inspectors. Each weighing scale was assessed and classified based on its degradation level and associated environmental or operational conditions. This data set was then subjected to binary logistic regression analysis, where equipment accuracy was treated as a binary outcome variable and the four factors as predictors.

The regression analysis revealed that dirt and dust ($p = 0.000$) and poor handling ($p = 0.048$) were statistically significant, confirming their strong negative impact on weighing equipment accuracy. Specifically, the presence of dirt and dust reduced the odds of maintaining accurate equipment by 2%, while poor handling practices reduced it by 46.7%. These findings align with earlier studies by Marshall et al. (2003), Chyzhykov et al. (2023), Fritsch et al. (2016), and Robens et al. (2014), all of which reported that environmental exposure and improper handling compromise equipment performance and calibration. Conversely, vibrations ($p = 0.858$) and operational errors showed no significant effect, indicating a lesser influence under the observed market conditions.

Table 4.2: Factors influencing the accuracy of weighing equipment

Explanatory Variable	β	S.E.	df	Sig.	Exp(β)
Dirt and dust	-3.849*	0.506	1	0.000	0.021
Poor handling	-0.762*	0.386	1	0.048	0.467
Operational errors	-0.893	0.476	1	0.061	0.409
Vibrations	-0.067	0.375	1	0.858	0.935

Where; β is the slope, S.E is the standard error, df is the degree of freedom, Sig. is the level of significance, Exp(β) is the exponential of the slope.

In addition to identifying these critical factors, the study also gathered data on trader-recommended remedies to mitigate accuracy loss, as shown in Figure 4.1. The most common practices included cleaning the scale after use (35.0%), avoiding overloading (33.2%), and regular servicing (8.9%). These responses suggest that users are aware of the practical steps necessary to reduce degradation and maintain functional accuracy in their weighing equipment.

These results highlight the importance of adopting preventive and predictive maintenance strategies in line with best practices cited in the literature. Regular cleaning removes contaminants that interfere with sensor accuracy (Jain et al., 2014), while avoiding overloading reduces mechanical strain. Furthermore, routine servicing and recalibration by qualified technicians can address developing faults before they compromise equipment performance (Martins et al., 2020). This aligns with the approach advocated by Achouch et al. (2022), emphasizing proactive monitoring to improve operational reliability and equipment longevity (Achouch et al., 2022).

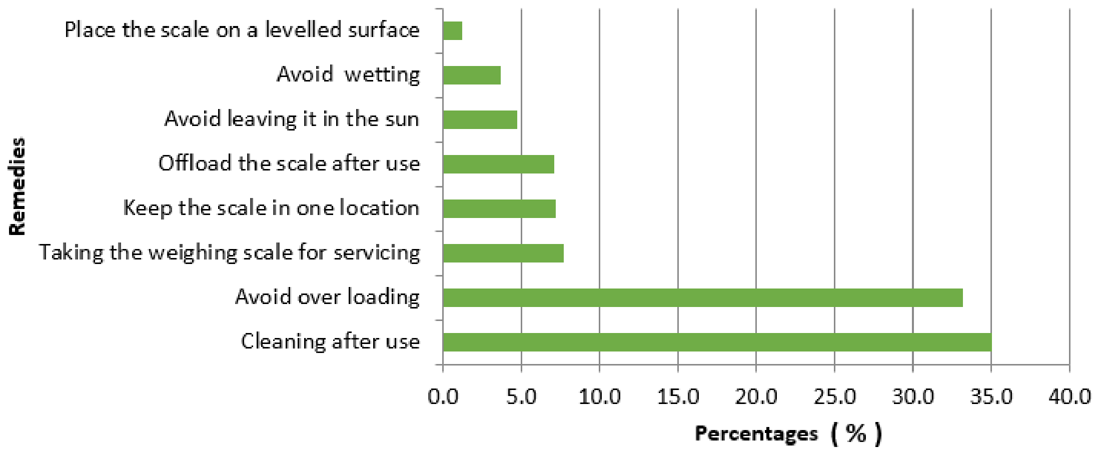

Figure 4.1:Remedies to reduce on the effect of the factors affecting accuracy of weighing equipment.

Furthermore, recognizing the impact of handling many respondents, emphasized using certified standard masses for calibration during routine use. This practice supports consistent accuracy and reflects a growing awareness among users about the role of proper handling and calibration in ensuring measurement reliability.

4.3 Determining the Level of weighing equipment degradation in stochastic environments.

A total sample of 310 mechanical counter weighing scales of market traders in the four selected markets were observed and assessed on the basis of the level of degradation. The degradation level of the weighing equipment were categorized as; significantly degraded, some indication of degradation, and no indication of degradation as shown in Table 4.3. Significantly degraded weighing equipment were those with severely deformed components, broken parts and no proper movement of the components thereby not able to weigh accurately. Weighing scales considered to be with some indication of degradation were those with defects such as cracked components, scratches and visible depreciation but still able to weigh accurately. The “no indication of degradation” referred to weighing scales that were in very sound physical and mechanical condition with no visible defects and able to weigh accurately.

Table 4.3: The level of degradation of weighing equipment

Level of degradation	Frequency	Percentage (%)
Significantly degraded	2	1
Some indication of degradation	238	76
No indication of degradation	70	23

The data was visualized using Figure 4.2 and showed that out of the 310 weighing scales examined, 238 of them fell under the second category of showing some indication of degradation. This implies that 76% of the examined weighing equipment had cracked components, scratches and visible depreciation but could still able to weigh accurately. 23% of the examined weighing equipment were still in a good physical and mechanical condition with no visible defects and therefore could give very good accurate results. However, only 1% of the examined weighing equipment were found to be significantly degraded. The smallest percentage of the significantly degraded weighing equipment is attributed to the fact that UNBS metrology officers often inspect traders' weighing equipment to ensure that their equipment comply with the existing metrology laws.

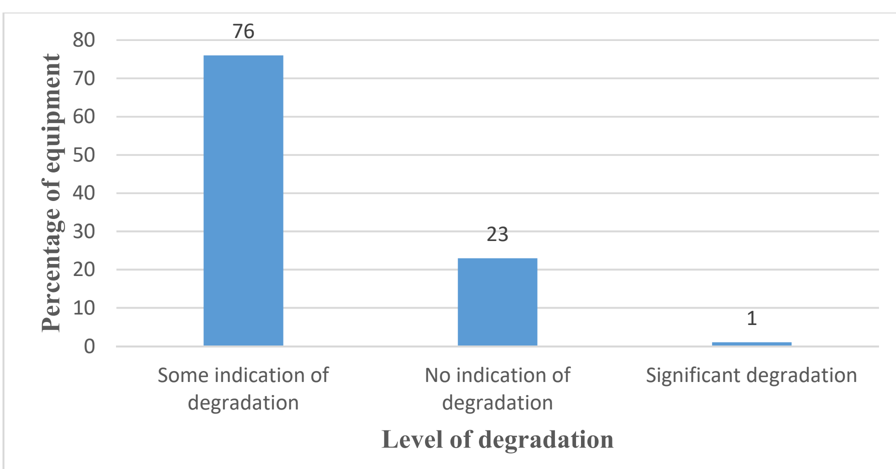

Figure 4.2: Degradation of weighing equipment by percentage

4.3.1 Factors affecting the level of degradation

To assess how various factors contribute to the degradation of mechanical weighing equipment, binary logistic regression analysis was applied, using categorized field data from inspections and perception surveys, as described in the methodology. Six predictors were examined: frequency of servicing, vibrations and shock, overloading, humidity, handling, and dirt. The regression results (Table 4.4) revealed that four factors namely; humidity ($p = 0.001$), overloading ($p = 0.001$), frequency of servicing ($p = 0.020$), and vibrations and shock ($p = 0.037$) significantly influenced degradation levels.

The odds ratios (Exp (β)) for all significant variables were above 100%, meaning each factor increased the likelihood of a weighing scale being highly degraded. For example, repeated servicing raised the odds by 267%, suggesting that frequent repairs may be associated with recurring faults or aging equipment. Overloading and humidity raised the odds by 325% and 1696%, respectively, indicating their strong impact on mechanical wear. This is consistent with prior findings by Fritsch et al., (2016), who reported that environmental exposure and mechanical strain lead to calibration drift and physical degradation.

The fact that Exp (β) values exceed 100% indicates a positive association that each unit increase in these predictors substantially raises the odds of degradation. An Exp (β) of 100% corresponds to a doubling of odds, so values above 100% show even greater influence. These results support the integration of predictive maintenance practices that use environmental and operational indicators to inform proactive servicing and timely replacement (Achouch et al., 2022).

Table 4.4: Factors influencing the level of degradation of weighing equipment

Explanatory Variable	β	S.E.	df	Sig.	Exp (β)
Frequency of servicing	0.983*	0.421	1	0.020	2.674
Contaminants	0.358	0.455	1	0.431	1.431
Vibrations and shock	0.770*	0.369	1	0.037	2.160
Overloading	1.181*	0.358	1	0.001	3.258
Temperature	0.194	0.586	1	0.740	1.215
Humidity	2.831*	0.834	1	0.001	16.967

4.3.2 Effect of weighing loads on the different levels of degradation

To further investigate the relationship between load weight and equipment degradation, an independent t-test was performed. This analysis compared the mean load weights handled by weighing equipment across three degradation levels: significant degradation, some indication of degradation, and no indication of degradation. The results, summarized in Table 4.5, revealed statistically significant differences in mean load weights among the three categories. Equipment with significant degradation had the highest mean load (3.1784 kg), followed by those with some indication of degradation (1.9712 kg). In contrast, non-degraded equipment consistently handled lower mean loads.

These findings suggest that mechanical weighing scales exposed to heavier loads are more prone to degradation over time, supporting the hypothesis that overloading is a key factor in performance decline. This aligns with the regression results and reinforces the need for regulated load use as part of predictive maintenance planning.

Table 4.5: Mean weight of loads across the level of degradation.

Level of degradation	Mean	Std. Deviation	Std. Mean Error
Some indication of degradation	1.9712	2.02571	0.13242
No indication of degradation	1.2393	0.80918	0.09672
Significant degradation	3.1784	2.80654	0.22685

4.4 Time in use

In addition to loads, the influence of number of years the mechanical counter weighing equipment spends in service on the level of degradation was looked at. An independent t-test was used to compare the mean years of equipment in service among the three levels of degradation. The results are presented in Table 4.6 and showed that the weighing equipment that had spent more than 16 years in service had significant levels of degradations. The equipment that had spent 12 years in service showed some indication of degradation as compared to those that had spent a lower time in service. This means that the higher the number of years a weighing scale spends in service, the higher its level of degradation. A weighing scale repairer stated that ‘‘the common causes of weighing scale degradation include the frequency of servicing, vibrations during use, shock, overloading, extreme temperatures, humidity among others’’. All the aforementioned factors influence the degradation of the weighing equipment with time thereby making the equipment to transit from one level to another with time, thus, reducing its level of accuracy.

Table 4.6: Influence of the time spent in services on level of degradation.

Level of degradation	Mean	Std. Deviation	Std. Mean Error
Some indication of degradation	12.07	6.331	0.409
No indication of degradation	7.45	7.489	0.877
Significant degradation	16.32	3.179	0.296

4.5 Optimum time for weighing equipment replacement

To determine the optimum replacement time for mechanical counter weighing equipment, a Weibull distribution model was applied, as detailed in the methodology. This model analyzed the relationship between the probability of failure and time in use, allowing prediction of when equipment performance significantly declines due to degradation. The model used different shape parameters ($\beta = 1, 1.5, 2, 2.5, 3, 4$) to generate probability density curves, which showed how the likelihood of failure changes over time as shown by Figure 4.3.

The Weibull curves demonstrated a typical failure trend: the probability density increases with time, reaching a peak, and then gradually declines. This reflects the real-world behavior of weighing equipment, where failure risk rises due to wear and tear and then drops as equipment is either replaced or becomes less frequently used. Notably, with $\beta = 1$, the curve fell sharply, indicating a higher failure rate early on, typical of equipment with constant hazard over time. This behavior aligns with findings by Ma et al. (2020) and highlights how environmental conditions, mechanical stress, and usage patterns contribute to equipment degradation.

After normalization, the model identified a point where the probability density approached zero, indicating reduced failure likelihood and this was the optimum replacement time, estimated at 8.4 years. At this point, replacing the equipment prevents a significant decline in precision and accuracy, which typically follows the transition into the critical degradation phase. This result supports the use of predictive maintenance planning to optimize equipment performance and minimize operational disruptions (Wang, 2022).

Field insights also validated the model's output. Inspectors and repairers from the Legal Metrology department reported that, on average, a mechanical counter scale lasts about 9 years, though this can vary depending on user habits. Some users continue to operate equipment beyond this period, risking compromised accuracy. The 8.4-year estimate thus provides a practical and statistically supported guideline for planning timely replacements, helping stakeholders enhance measurement reliability, regulatory compliance, and resource efficiency (Ma et al., 2020; Wang, 2022).

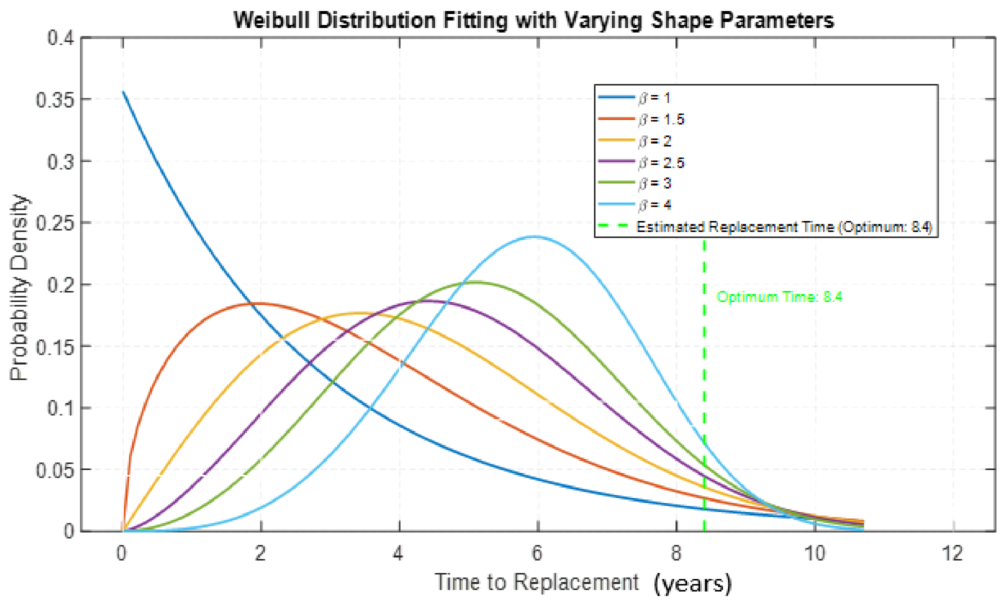

Figure 4.3: Probability Density and time to replacement.

4.6 Factors affecting the choice of weighing equipment replacement time

A linear regression model was used to test for the relationship between the demographic and operational factors with the replacement time of the weighing equipment. The influence of different factors that guided the choice of the replacement time for traders weighing equipment were assessed. The results are shown in Table 4.7.

Table 4.7: Factors affecting the replacement time of the weighing scale

Category	Explanatory Variable	Slope	Std. Error	t	P-value
Demographic	Gender (1)	0.314	0.113	2.777	0.006
	Age	0.006	0.004	1.477	0.041
	Education level (1)	0.149	0.045	3.298	0.001
Operational	Common loads used per day	-0.03	0.03	1.022	0.008
	Repairing times per year	-0.05	0.049	-1.017	0.310
	Number of enterprises	-0.017	0.119	-0.145	0.005
	Cleaning times per day	0.554	0.117	4.747	0.000

Gender (1) represents male traders; Education (1) represents formally educated traders

Out of the seven factors analyzed, six significantly influenced the weighing equipment replacement time. Gender was a significant factor, with female traders suggesting a longer service life for their equipment, indicating that their equipment maintains accuracy for a longer period compared to male traders. Age also affected replacement time, with older traders tending to keep their equipment longer, as they perceived it to maintain accuracy over time. Similarly, education level played a role, with educated traders indicating a longer replacement time, suggesting they maintain their equipment in better condition for extended periods.

The common loads used per day significantly impacted replacement time, with traders handling heavier loads opting for shorter replacement intervals, as their equipment deteriorated more quickly. The number of repairs per year did not have a significant effect on replacement time, although traders with frequent repairs tended to replace their equipment sooner. The number of enterprises using the same equipment also influenced replacement time, with traders running multiple businesses suggesting a shorter replacement time compared to those using the equipment in a single enterprise. Finally, cleaning frequency was positively correlated with replacement time, with traders who cleaned their equipment regularly recommending longer replacement intervals, likely due to better maintenance practices.

4.7 Summary of Findings

The study found that mechanical weighing equipment degrades over time due to factors such as dirt and dust, poor handling, humidity, overloading, vibrations, and frequency of servicing, all of which significantly reduce accuracy. Equipment exposed to heavier loads showed greater degradation, as confirmed by t-test analysis. Using a Weibull distribution model, the optimal replacement time was estimated at 8.4 years, aligning closely with expert views. Additionally, user related factors such as gender, age, education level, load size, number of enterprises, and cleaning frequency also influenced replacement decisions. Regular cleaning and lighter usage extended equipment life, while heavier usage and shared equipment shortened it.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study comprehensively evaluated the degradation patterns and optimal replacement timing of mechanical counter weighing equipment utilized in business transactions across four major markets: Nateete, Nakawa, Kibuye, and Kalerwe. Data collected from equipment users, repairers, and inspectors facilitated a detailed analysis of the factors influencing precision, degradation, and service life. The findings were supported by both a binary logistic regression model and a Weibull distribution failure model, which together provided robust insights into the operational reliability and maintenance scheduling of the equipment.

Regarding the first objective, the study identified critical parameters affecting the precision and accuracy of weighing equipment. It was established that dirt, dust accumulation, and poor handling practices significantly compromise measurement accuracy. Specifically, traders operating in unpaved and dusty environments or those frequently relocating or mishandling their equipment exhibited higher incidences of measurement errors. Conversely, other factors such as operational errors and vibrations were found to have limited statistical significance on precision.

For the second objective, the study elucidated the key factors contributing to degradation of weighing equipment in stochastic environmental conditions. The analysis confirmed that humidity, overloading, mechanical shocks, vibrations, temperature variations, contaminant exposure, and servicing frequency are principal drivers of equipment wear and tear. Notably, the majority of equipment (76%) demonstrated some level of degradation, while only a small fraction (1%) was classified as significantly degraded. Furthermore, a positive correlation between time in service and degradation was observed, affirming that extended usage under fluctuating operational environments accelerates the deterioration process.

The third objective focused on determining the optimal replacement time for mechanical counter weighing devices. Application of the Weibull distribution model effectively characterized the failure probability over time, identifying 8.4 years as the most suitable replacement interval. This model revealed a distinct pattern in failure likelihood, highlighting a critical period wherein proactive replacement is necessary to prevent sharp declines in measurement accuracy. Importantly, this estimated replacement time aligns closely with expert assessments and observed usage trends, thereby validating the model's applicability as a predictive maintenance decision support tool.

5.2 Recommendations

With regards to the conclusion stated above about the accuracy, degradation levels, and replacement time of the mechanical counter weighing equipment, the following recommendations should be put under consideration;

(i) Users should implement regular cleaning routines to reduce dust buildup and maintain weighing accuracy.

(ii) Traders must adopt careful handling and proper calibration to minimize mechanical damage and errors.

(iii) Training programs are needed to raise awareness on correct use, maintenance, and environmental impacts on equipment.

(iv) Authorities should improve market infrastructure by paving surfaces and providing protective enclosures to reduce environmental wear.

(v) Further experimental research should be conducted to quantify factors affecting equipment degradation and inform maintenance and replacement strategies.

5.3 Areas for Future Research

Further research could explore;

(i) Experiments that quantify the specific effects of environmental factors such as humidity, temperature, and dust on the degradation of mechanical weighing equipment.

(ii) Comparative studies between mechanical and electronic weighing devices under similar conditions to provide insights into durability and cost-effectiveness.

(iii) The evaluation of the long-term impact of user training programs on equipment handling and degradation is important.

(iv) The development of advanced predictive maintenance models using machine learning alongside traditional reliability methods to optimize servicing and replacement schedules for different market environments.

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APPENDICES

Appendix -1: Interview Guide

Dear respondent, My name is Musana Raphael, a Master's student at Kyambogo University, pursuing a Master of Science in Advanced Manufacturing Systems Engineering. I am conducting a study aimed at developing a predictive model to determine the optimal time for withdrawal and replacement of weighing equipment, with the goal of enhancing consumer protection and promoting fair business transactions in Uganda.

You have been selected to participate in this study, and your responses will greatly contribute to fulfilling the requirements of my academic program. All the information you provide will be treated with the utmost confidentiality and will be used strictly for research purposes.

Guiding Interview Questions:

1. What is the most commonly used type of weighing scale among traders in this community?
2. What factors most frequently affect the **accuracy and precision** of these weighing scales?
3. How do traders in this community typically respond or react to these issues affecting scale performance?
4. In your opinion, does the **level of degradation** influence the accuracy and precision of the weighing scales? If yes, how?
5. Based on your experience, what do you consider to be an appropriate time or condition for **replacing a weighing scale**?

Appendix - 2: Questionnaire

Title of Study: *Development of a Predictive Model for Weighing Equipment Withdrawal and Replacement Time for Enhanced Consumer Protection and Competitiveness of Business Transactions in Uganda*

Dear Respondent**,** My name is Musana Raphael**,** a Master's student at Kyambogo University. I am conducting research to support the development of a predictive model for the optimal replacement time of weighing equipment. This research is aimed at improving consumer protection and enhancing business competitiveness in Uganda. Your participation is voluntary and the information provided will be kept strictly confidential.

Please respond by selecting the most appropriate option or filling in the blank spaces where applicable.

Section A: General Information

A1. Level of education

☐ Prefer not to say ☐ Primary ☐ Secondary ☐ Technical ☐ University

A2. Age of respondent: ___________

A3. Gender

☐ Male ☐ Female

A4. Trading center / town

☐ Kalerwe ☐ Kibuye ☐ Nateete ☐ Nakawa

Section B.1: Parameters Influencing Accuracy and Precision of Weighing Scales

B1.1 Do you use a weighing scale in your business?

☐ Yes ☐ No

B1.2 Type of weighing scale used:

☐ Mechanical counter scale ☐ Digital scale ☐ Other (please specify): ___________

B1.3 What weight(s) in kilograms do you most commonly measure with your scale? ___________

B1.4 On average, how often does your weighing scale drift out of accuracy per week? ___________

B1.5 Who rectifies faults when your weighing scale is inaccurate?

☐ Licensed repairer ☐ Myself ☐ Any available technician

B1.6 How many times is your weighing scale repaired annually? ___________

B1.7 Do you share your weighing scale with others?

☐ Yes ☐ No

B1.8 Does sharing your weighing scale increase its failure rate?

☐ Yes ☐ No

B1.9 If yes, what negative effects have you observed? ___________

B1.10 Do you have a designated location for your weighing scale at your premises?

☐ Yes ☐ No

B1.11 What good practices do you follow when using your weighing scale?

☐ Clean after use ☐ Avoid overloading ☐ Avoid wetting the scale ☐ Other (specify): ___________

B1.12 How many times do you clean and dust your weighing scale in a week? ___________

B1.13 Does cleaning and dusting improve accuracy/precision?

☐ Yes ☐ No

B1.14 Which of the following conditions prevail in your working environment?

☐ Dirt and dust ☐ Poor handling ☐ Operational errors ☐ Vibrations ☐ Other: ___________

B1.15 Do these conditions negatively affect the accuracy of your scale?

☐ Yes ☐ No

B1.16 Which single condition most affects accuracy and precision?

☐ Dirt and dust ☐ Poor handling ☐ Operational errors ☐ Vibrations

B1.17 How does the selected condition in B1.16 affect your scale's performance? ___________

B1.18 Can your customers detect when a scale is inaccurate?

☐ Yes ☐ No

B1.19 How do you assure customers of your scale's accuracy?

☐ Weigh in their presence ☐ Show verification mark ☐ Other (specify): ___________

B1.20 Do you think the type of weighing scale influences its accuracy and precision?

☐ Yes ☐ No

Section B.2: Environmental Factors and Degradation

B2.1 Do environmental factors affect your weighing scale's degradation?

☐ Yes ☐ No

B2.2 Which environmental factors affect your scale most?

☐ Temperature ☐ Humidity & moisture ☐ Vibrations

B2.3 Explain how the selected factor affects degradation: ___________

B2.4 How can the effects of these environmental factors be mitigated? ___________

B2.5 How does scale degradation affect accuracy/precision?

☐ Leads to lower accuracy

☐ Leads to higher accuracy

☐ Has no effect

B2.6 What is the most recurring fault in your scale?

☐ Binding error ☐ Fast beam ☐ Slow beam ☐ Missing parts

B2.7 What is the current condition of your weighing scale?

☐ No indication of degradation

☐ Some indication of degradation

☐ Significantly degraded

☐ Critically degraded

Section B.3: Estimating the Most Appropriate Replacement Time

B3.1 What do you think is the average lifespan of a good weighing scale? ___________

B3.2 How long have you used your current weighing scale? ___________

B3.3 From now, when do you expect to replace your scale? ___________

B3.4 What factors would influence your replacement decision?

☐ Level of degradation ☐ Age of scale ☐ Rate of failure ☐ Other (specify): __________

B3.5 Would you consider replacing your scale based on a recommended time interval?

☐ Yes ☐ No

Appendix -3: Introductory Letters

KYAMBOGO UNIVERSITY

P. O. BOX 1, KYAMBOGO – KAMPALA, UGANDA
TEL: 041-287341, FAX: 041-220464
www.Kyambogo.ac.ug

Department of Mechanical and Production Engineering

5th February 2024

The Chairperson,
Kalerwe Market,
Kampala Uganda,

07 FEB 2024

RCVD by [signature] 7th – FEB-2024

RE: INTRODUCTION OF MR. MUSANA RAPHAEL

Dear Sir/Madam,

and permission is granted. [signature]

This is to introduce to you the above named student with Registration number **22/U/GMEM/434/PE** pursuing a Master of Science Degree in Advance Manufacturing Systems Engineering, Department of Mechanical and Production Engineering, Kyambogo University.

He intends to carry out research on developing a Predictive mode for Weighing Equipment replacement time, in partial fulfillment of the requirements for the award of a Master of Science Degree in Advanced Manufacturing Systems Engineering.

The purpose of this letter therefore is to request you to grant him permission to carry out his study in your institution and collect data concerning types of weighing scales used by traders, the failure patterns of weighing scales, factors influencing the accuracy and precision of weighing scales among others for a period of three (3) working days.

Any assistance rendered to him will be highly appreciated.

Yours sincerely,

Dr. Maureen Nalubowa Ssempijja
Head of Department, Mechanical & Production Engineering
Email: maureenssempijja@gmail.com **Tel.**: 0752810261

HEAD OF DEPARTMENT MECHANICAL AND PRODUCTION ENGINEERING ★ KYAMBOGO UNIVERSITY P. O. BOX 1, KYAMBOGO

KYAMBOGO UNIVERSITY

P. O. BOX 1, KYAMBOGO – KAMPALA, UGANDA
TEL: 041-287341, FAX: 041-220464
www.Kyambogo.ac.ug

Department of Mechanical and Production Engineering

5th February 2024

CHAIRMAN NAKAWA MARKET
Tel: 0753 538534, 0787 762142
07 FEB 2024 KCCA
0703 243578
VENDORS WELFARE OFFICE

Received by
MUDHASI JOSEPH
C/MAN NAKAWA MARKET
0753897534

The Chairperson,
Nakawa Market,
Kampala Uganda,

RE: INTRODUCTION OF MR. MUSANA RAPHAEL

Dear Sir/Madam,

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Any assistance rendered to him will be highly appreciated.

Yours sincerely,

Dr. Maureen Nalubowa Ssempijja
Head of Department, Mechanical & Production Engineering
Email: maureenssempijja@gmail.com **Tel**.: 0752810261

HEAD OF DEPARTMENT MECHANICAL AND PRODUCTION ENGINEERING
KYAMBOGO UNIVERSITY
P.O. BOX 1, KYAMBOGO

KYAMBOGO UNIVERSITY

P. O. BOX 1, KYAMBOGO – KAMPALA, UGANDA
TEL: 041-287341, FAX: 041-220464
www.Kyambogo.ac.ug
Department of Mechanical and Production Engineering

5th February 2024

The Chairperson,
Kibuye Market,
Kampala Uganda,

REXBA LTD
KIBUYE MARKET
P. O. BOX 58, KAMPALA
Sign: 05/02/2024

RE: INTRODUCTION OF MR. MUSANA RAPHAEL

Dear Sir/Madam,

This is to introduce to you the above named student with Registration number **22/U/GMEM/434/PE** pursuing a Master of Science Degree in Advance Manufacturing Systems Engineering, Department of Mechanical and Production Engineering, Kyambogo University.

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Any assistance rendered to him will be highly appreciated.

Yours sincerely,

DEPARTMENT MECHANICAL AND PRODUCTION ENGINEERING
KYAMBOGO UNIVERSITY
05 FEB 2024
P. O. BOX 1, KYAMBOGO
HEAD OF ★

Dr. Maureen Nalubowa Ssempijja
Head of Department, Mechanical & Production Engineering
Email: maureenssempijja@gmail.com **Tel.**: 0752810261

PERMISSION GRANTED

SAVE NATEETE MKT VENDORS ASS. DATE 24/06/24

Sec/secretary

KYAMBOGO UNIVERSITY

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Department of Mechanical and Production Engineering

5th February 2024

The Chairperson,
Natete Market,
Kampala Uganda,

RE: INTRODUCTION OF MR. MUSANA RAPHAEL

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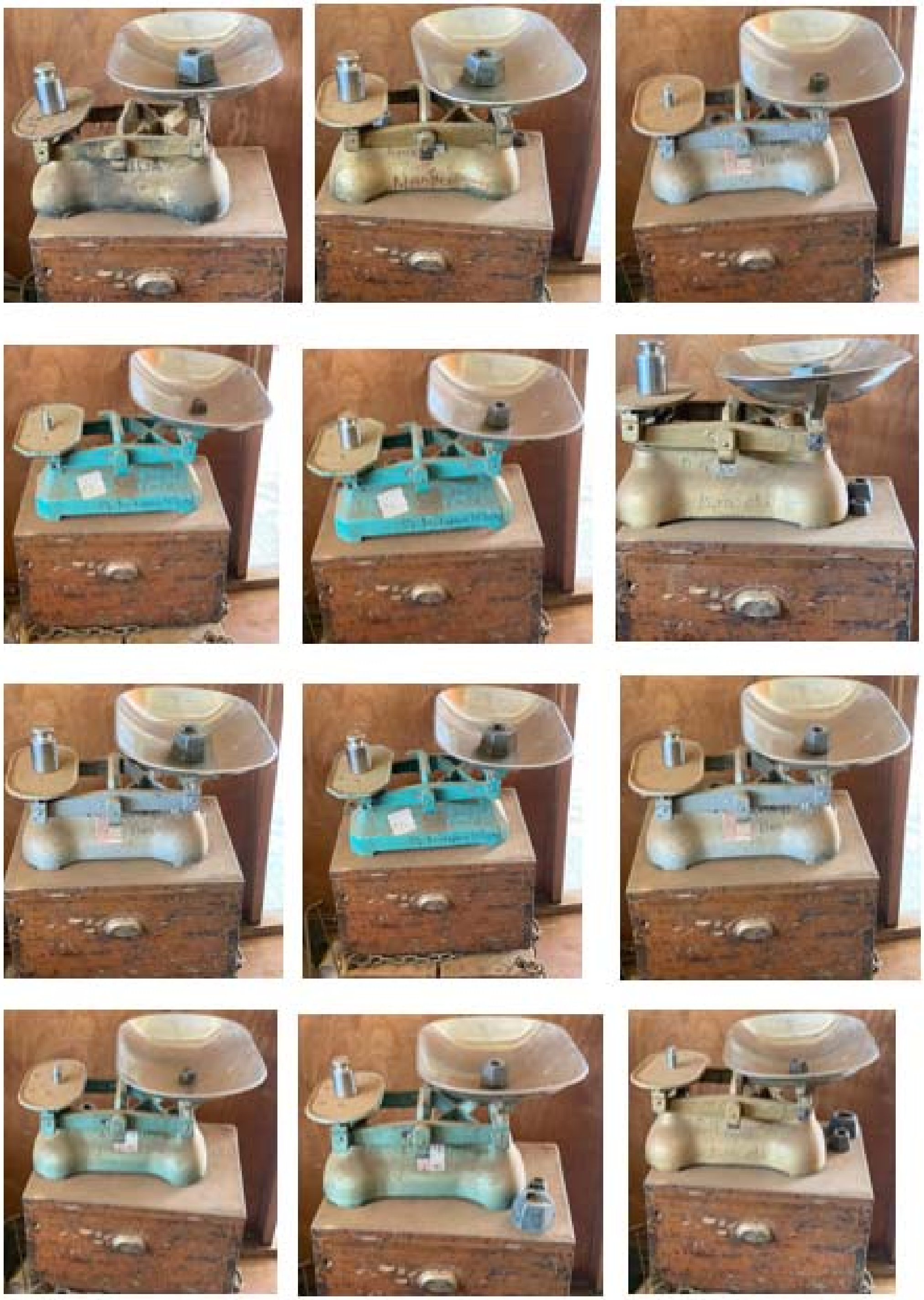
Any assistance rendered to him will be highly appreciated.

HEAD OF DEPARTMENT MECHANICAL AND PRODUCTION ENGINEERING KYAMBOGO UNIVERSITY P. O. BOX 1, KYAMBOGO

Yours sincerely,

Dr. Maureen Nalubowa Ssempijja
Head of Department, Mechanical & Production Engineering
Email: maureenssempijja@gmail.com **Tel.**: 0752810261

Appendix - 4: Traders' Weights Measured Against Standard Weights



Appendix - 5: Plagiarism Certificate and Report