Chapter

Performance Measures for Evaluating and Communicating Data Quality in Aquatic Environmental Monitoring in the U.S.

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Abstract

Quantitative data quality descriptors are important for evaluating and communicating acceptability of information used in environmental monitoring and assessment. In this chapter, we present (1) the rationale for establishing and using performance measures and MQOs in routine quality control planning and analysis, (2) field and laboratory methods for capturing input data required for performance calculations, and (3) approaches for setting data acceptability thresholds and determining the need for corrective actions. Relevant examples are available from local, regional, and national programs in the U.S. charged with monitoring and assessing aquatic biological condition, physical habitat, contaminants, and toxicity testing. We will describe techniques for calculating and determining acceptability of performance measures, such as, among other data quality indicators, precision, accuracy, sensitivity, representativeness, and completeness of field sampling, laboratory processing, and data management and analysis. Data types on which these examples will be based include benthic macroinvertebrates, fish assemblage, tissue body burden, laboratory analytical and toxicity testing, physical habitat, selected geomorphic characteristics, and algal toxins.

Keywords: precision, bias, indicators, error, corrective actions, acceptability

1. Introduction

Science is recognized as treating uncertainty and variability as information that serves as a key component of decision-making, helping formulate new questions, experimental designs, and testing and measurement procedures [1–3]. This is the essence of the scientific method; knowledge itself increases through the process of trial and error. Perhaps the most well-known effort to begin quantifying data variability as part of the decision-making process in technical endeavors led to development

of the concept of statistical process control [4]. With a focus on manufacturing, Shewhart's ideas largely originated with the desire to better understand causes of anomalous or unwanted output, and to provide clarity on what might be necessary to improve outcomes. He stated [4] "*Through the use of the scientific method…it has been found possible to set up limits within which the results of routine efforts must lie if they are to be economical. Deviations in the results of a routine process outside such limits indicate that the routine has broken down and will no longer be economical until the cause of the trouble has been removed*". Shewhart [5] further developed statistical techniques and demonstrated their application, helping to broaden the appeal of using control charts to document and track the quality of various data characteristics. The quality of data, and especially environmental data, is tracked through various quality control (QC) processes as discussed in this chapter. As Woodall [6] and others have noted, QC analyses and their interpretation are best handled by those who are knowledgeable about the field of practice.

The 1993 passing of the Government Performance and Results Act (GPRA) in the United States (US) elevated attention to documenting effectiveness, efficiency, and accountability of programs, and resulted in Federal agencies setting goals for program performance [7]. The GPRA focused the need for and use of performance characteristics and quantitative measurement quality objectives (MQO) to strengthen programs at any scale, not just Federal. The Information Quality Act (IQA) of 2000, sometimes referred to as the Data Quality Act, required Federal programs to ensure the "quality, objectivity, utility, and integrity" of publicly available information they produced [8]. It also required agencies to develop techniques for acquiring, reporting, and acting on results, where necessary.

The concept of process or QC is adaptable to any measurement system, requiring only that key points of the process are identified as providing opportunity for taking measurements, and that there is some standard or criterion for comparison. When anomalous or extreme results are detected via comparison to MQO, they would be investigated to determine what might be causing performance deviations.

Routine environmental monitoring requires consistent collection of data and information such that they are of known and acceptable quality. The purpose of this chapter is to describe data requirements, numeric structure, and interpretation thresholds for MQO related to several diverse and important indicators used in aquatic environmental monitoring throughout the US. These include biological, physical, chemical, and toxicological indicators.

2. Quality assurance and control for environmental monitoring

In the US, environmental data are collected by many federal, state, tribal, and local agencies, including the US Environmental Protection Agency (EPA), as well as non-EPA organizations supporting environmental programs on behalf of EPA in accordance with the EPA agency-wide quality system. Other federal agencies such as the US Geological Survey (USGS), the National Oceanographic and Atmospheric Administration (NOAA), and the US Fish and Wildlife Service (USFWS) collect data under different data quality frameworks but have similar requirements for known and acceptable quality. The quality assurance (QA) planning processes established by the EPA are recognized as a high standard that should be *attempted* even in non-EPA projects, such as state-, industry-, or non-profit-funded special projects. The EPA quality system is based on ANSI/ASQC E4-1994, *Specifications and Guidelines*

for Quality Systems for Environmental Data Collection and Environmental Technology Programs, a national standard for quality management practices for environmental programs involving the collection and evaluation of environmental data and the design, construction, and operation of environmental technologies [9, 10]. Quality planning documentation prepared for collection of environmental data (by or for EPA) includes descriptions of project-specific data quality objectives (DQO), quality assurance project plans (QAPP), and standard operating procedures (SOP). DQO are integral to the QA planning process. The DQO process includes identifying the decisions to be made based on the information collected, as well as the data quality and quantity acceptance criteria required to make those project decisions [11]. QAPPs are developed and implemented to ensure that data collected for a project are complete and of a quality sufficient for their intended purpose [12]. A QAPP includes a section on DQO, and SOP for relevant field collection and laboratory analysis procedures are often included as QAPP attachments. SOP are developed and followed to ensure that procedures for data collection and analysis are performed consistently within boundaries defined by MQO, thus meeting acceptance criteria.

There are different sources of error, some of which may yield uncertainty and all of which can affect variability observed in data and outcomes. This chapter discusses several commonly used indicators of aquatic environmental condition and the types of performance measures and QC processes used to ensure that data are acceptable to use in a particular environmental program.

3. Indicators of environmental condition

3.1 Biological

Field sampling, laboratory processing, and data analysis procedures for biological indicators are relatively well-established for many monitoring programs. For programs focused on community level indicators of biological integrity, such as the Index of Biological Integrity (IBI) or River Invertebrate Prediction and Classification System (RIVPACS) of observed to expected (O/E) conditions, based on consistent sampling and interpreting of taxa and individual counts. Field sampling for these indicators typically gathers composite samples from multiple habitats distributed throughout some defined area of the stream, river, lake, or estuarine/near-coastal waters. Depending on the program, the sampling area for rivers and streams can be a defined channel length, such as 100 m, or some multiple of the wetted width. Organism groups targeted by this kind of sampling includes, for example, benthic macroinvertebrates (BMI), fish, and algae/diatoms. Laboratory processing for BMI and diatoms includes sorting, subsampling, and taxonomic identifications. Estuarine and near-coastal programs sample benthic invertebrates from a surface area defined by gear type. Example methods documents are [13, 14], and several field and laboratory operations manuals from EPA National Aquatic Resource Surveys (NARS) [15–24].

Efforts to customize performance measures to biological monitoring programs have sought to use the process to isolate potential sources of variability, or error, and determine the need for and nature of corrective actions [14, 25]. A biological assessment protocol is a series of methods encompassing field sampling, laboratory processing (if necessary, and including sorting/subsampling and taxonomic identification), enumeration, data analysis, and assessment endpoints such as a regionally calibrated multimetric IBI. Community-level fish indicators typically do not involve laboratory

work as identification and counting is done in the field while on site. [14, 25] propose performance measures and MQO to cover the sequential phases of biological assessments. Key components considered are field sampling precision, and for BMI, sorting/subsampling and taxonomic identification. In the framework they propose, the ability to detect or highlight errors in these phases requires specific activities that provide data to calculate performance measures, the results of which are then compared to the MQO (**Table 1**). Descriptions below are examples of performance measures and how data are acquired for their calculation.

Field sampling precision (*requires duplicate samples*). Biological samples are taken from duplicate 100 m channel reaches that are immediately adjacent to each other. Laboratory processing and indicator calculation proceeds for each as separate samples. Comparison of results using specific performance measures (relative percent difference [RPD], coefficient of variability [CV], and confidence intervals [CIs]) (**Table 1**) reveals the precision and repeatability of the sampling method and its application.

Sorting/subsampling bias (requires sort residue rechecks). The objective of primary sorting of BMI samples is to remove all organisms from nontarget sample material, such as leaf litter, twigs, sand/silt, and other organic and inorganic detritus. The remaining sample material (sort residue) is checked for specimens missed by the primary sorter, and the performance measure, percent sorting efficiency (PSE) (**Table 1**) calculated as indicative of bias in the process.

Taxonomic precision (requires sample re-identification). Biological samples undergo identification by a primary taxonomist, then reidentification by a separate, independent taxonomist. Identification and count results are directly compared, and differences or error rates are quantified as a measure of taxonomic performance, specifically, precision. Terms calculated are percent taxonomic disagreement (PTD), percent difference in enumeration (PDE), and percent taxonomic completeness (PTC) (**Table 1**). All three terms quantify distinctly different aspects of the taxonomic identification process and relate directly to overall sample characteristics. Further, PTC indicates the proportion of the sample identified to the target hierarchical level (species, genus, tribe, family, or higher), where the absolute value of the difference between primary and QC taxonomist (|PTC|) indicates precision and consistency. Results from QC analyses can be presented in reports or associated with datasets in a straightforward manner (**Table 2**) that allows the data user to understand and move ahead with subsequent analyses.

The sites and samples for which these analyses are done use a *randomly selected* subset of sites, sort residue samples, and samples, respectively. As a rule of thumb, approximately 10% would be selected from the sample lot. The outcomes of these calculations and comparison to MQO can and should be used to (1) help detect potential problems in how the specific activity was implemented, (2) help inform the nature and need for corrective actions; and (3) summarize the overall quality of the full dataset. Subsequent values exceeding the MQO are not automatically taken to be unacceptable data points; rather, such values should receive closer scrutiny to determine reasons for the exceedance and might indicate a need for corrective actions.

The rationale for determining numeric values to be used as MQO should be based on observable data which are relevant to the monitoring program and the indicators that are being tracked as a part of it [25]. As an example, the MQO for PTD is 15 [26] and was arrived at through recognizing that taxonomic comparison (TAXCOMP) results for many samples were <20 and that there were very few <10. The 15% simply splits the difference.

Indicator category	Indicator/ group	Data	Data origin	Performance term	Source
Biological	BMI	Assemblage-level, taxonomy, count	Laboratory processing	Sample sorting: PSE Taxonomic identification: PTD, PDE, PTC, |PTC|	[14, 18, 19, 25–27]
Biological	BMI	Individual metrics, MMI	Field sampling; MMI	Precision (among sites): CV, CI90 Precision (within sites): RPD	[14, 17, 21, 22, 25–27]
Biological	Fish	Individual metrics, MMI	Field sampling; field processing; MMI	Precision (among sites): CV Precision (within sites): RPD Taxonomic identification: PTD Percent completeness: % comp.	[28, 29]
Physical	Physical habitat		Field observations	Precision (among sites): CV, CI90 Precision (within sites): RPD	[13, 14, 25]
Physical	Sediment	Sediment grain size and total organic carbon	Laboratory processing	Precision and accuracy: recovery of spikes in blanks and matrices; MDLs (calculated for lab)	[23]
Physical	Water clarity	Photosynthetically active radiation transmittance at 1 m	field measurements, calculation	Slope of least squares regression [−ln(light UW/light AMB) vs depth]; $R^2 > 0.75$	[24, 30]
Physical	Water clarity	Mean Secchi depth	Field measurements, calculation	Precision: all disappear and reappear values (3 of each) within 0.5 m	[23, 30]
Chemical	Fish	Tissue contaminant load	Laboratory processing	Sample preparation: RPD for duplicate homogenized tissue sample pairs; sample analysis: RSD for initial precision recovery, matrix spike, and matrix spike duplicate samples	[31–34, 51]
Chemical	Residuals and water quality	PFAS—16 analytes	Laboratory analysis of samples collected by facilities	Accuracy of measurements: % recovery for internal standards, LCS % recovery, MS % recovery; precision: RPD for MS/MSD and FDs	[35]
Harmful algal blooms	Algal toxins	Cylindrospermopsin, microcystins	Laboratory analysis of proficiency test (PT) samples	Accuracy of measurement: % recovery; precision among analytical laboratories: RPD	[18–20, 23, 36–40]

Indicator category	Indicator/ group	Data	Data origin	Performance term	Source
Harmful algal blooms	Algal toxins	Cylindrospermopsin, microcystins	Generally field sampling	False positive rate; false negative rate; sensitivity (detection limit); CV for precision	[41, 42]
Ecotoxicity testing	Sediment toxicity	Acute toxicity of whole sediment sample	Laboratory processing	Minimum mean control corrected % survival	[43, 44]
Ecotoxicity testing	Aquatic toxicity	Counts, weight, % survival, % fertilization	Lab testing; field exposures	Within-test variability; sensitivity to specific contaminants; control precision (CV); PMSD	[45, 46]

BMI, benthic macroinvertebrates; PSE, percent sorting efficiency; PTD, percent taxonomic disagreement; PDE, percent difference in enumeration; PTC, percent taxonomic completeness; |PTC|, absolute value of PTC difference; MMI, multimetric index; CV, coefficient of variability; RPD, relative percent difference; RSD, relative standard deviation; CI90, 90% confidence interval; UW, under water; AMB, ambient; PFAS, per- and polyfluoroalkyl substances; LCS, laboratory control sample; MS, matrix spike; MS/MSD, matrix spike/matrix spike duplicate; FD, field duplicate; MDL, method detection limit; PMSD, percent minimum significant difference.

Table 1.
Selected example performance measures for QC planning and analysis.

Performance characteristic	MQO	Observed
1. Field sampling precision (MMI)	CV < 15%	10.6
	CI90 ≤ 1.0	0.8
2. Sorting/subsampling bias	PSE ≥ 90	96.7
3. Taxonomic precision	Median PTD ≤ 15%	5.4
	Median PDE ≤ 5%	0.5
4. Taxonomic completeness	Median PTC ≥ 90%	91
	Median |PTC| ≤ 5%	1.5

Table 2.
Summary results from QC analyses BMI samples (n = 9) from the Prince George's County (Maryland, USA) biological monitoring program, 2010–2013.

Subsequent TAXCOMP results support using 15%, whether at broad national scales or smaller programs of anywhere from 10 to 50 samples. MQO are also not necessarily intended to be permanently fixed. As a monitoring program or testing procedure matures and more experience is gained, subsequent values often are observed as being consistently lower; a program may determine it would be beneficial to lower the MQO. Among all programs, PTD values are increasingly more commonly observed <10. It is advisable to use improved understanding of variability and its causes to adjust thresholds.

3.2 Physical habitat

3.2.1 Wadeable streams

One approach for characterizing the quality of stream physical habitat is a visual-based procedure [13] that assesses channel conditions in terms of stability, complexity,

and availability of habitat for stream biota. There are 10 parameters, seven of which are rated for all streams, and 3 each for low and high gradient streams (Table OS-1[1]). Parameters are graded along a continuum of conditions from the perspective that as a stream becomes physically degraded, it loses physical complexity. Each parameter is rated on a 20-point scale while the observer is on site, then the values are summed for an overall site score. The range for the overall score is 0–200, with low values indicating poor quality habitat incapable of supporting stream biota and high indicating optimal conditions.

Data for input to QC calculations are from assessments done on adjacent 100 m channel reaches, identical to those discussed above for biological sampling. Reaches for which duplicate assessments are performed are randomly selected from the full site load, and pairs of habitat assessment results are used to calculate different performance measures (**Table 1**). As an example of results from such a QC analysis, consider a project that assessed 87 wadeable stream locations in Prince George's County, Maryland USA, and thus had nine (9) pairs of habitat assessment scores (Table OS-2 cdn.intechopen.com/public/259766_osi.zip).

Even though the field technique is qualitative, these numbers demonstrate the consistency of the results, particularly the median relative percent difference (mRPD) and CV. The values of RPD range from 1.4 to 35.3, with the substantial difference at the high end of the range suggesting that either the two reaches are dramatically different in quality, or potentially a data recording error occurred. These numbers characterize quality of the physical habitat data, as well as provide a roadmap for investigating potential anomalous results.

3.2.2 Estuarine/near coastal

Environmental monitoring programs assess abiotic indicators to understand how stressors may impact organisms, as well as how the habitat may be impacted by human disturbance. For example, because light underwater diminishes with depth [47] programs such as the U.S. EPA NARS National Coastal Condition Assessment (NCCA) survey and the Chesapeake Bay Program collect *in situ* water clarity measurements to estimate the impact of cultural eutrophication on light attenuation through the water column [24]. The EPA measures water clarity as Secchi depth at Great Lakes nearshore sites (the average depth of disappearance and reappearance of a 20 cm black and white disk lowered and retrieved through the water column three times), or transmission of photosynthetically active radiation (PAR) by comparing simultaneous ambient and underwater light measurements at incremental depths for estuarine sites. Performance measures for water clarity are intended to ensure accuracy and precision, as well as repeatability and consistency across the wide array of sites encountered in the survey. Secchi depth performance checks are implemented in the field and reviewed by analysts before use. They require that all six measurements are within 0.5 m of each other. When the difference between the maximum and minimum Secchi measurements at a site exceeds 0.5 m, the field crew repeats the entire set of measurements [24]. Data analysts again check Secchi data; values exceeding the maximum difference of 0.5 m among measurements at a site are reviewed and obvious transcription errors are corrected. Final values that do not meet the quality requirement are excluded from analysis. Table OS-3 cdn.intechopen.

[1] Due to space limitations, Tables OS-1 through OS-11 are provided as Online Supporting Information cdn.intechopen.com/public/259766_osi.zip.

com/public/259766_osi.zip illustrates the decisions made when reviewing Secchi data collected at 20 sites during the NCCA 2010 field season. For PAR, light sensors and data loggers are required to have been calibrated within 2 years prior to use and NCCA analysts conduct post measurement data checks to verify data quality. To ensure that the underwater light measurements decrease with depth (that is, light attenuation increases with depth), the PAR attenuation coefficient (Kd) is first calculated as the negative of the natural log of the ratio of underwater light to ambient light [−ln(UW/AMB)]. Kd is then plotted on the *Y* axis against the measurement depth on the *X* axis. If there is a negative slope of the resulting least squares regression line, or the coefficient of determination (R^2) ≤ 0.75[2], measurements are investigated further. When specific measurements are found to be incorrect, they are excluded from regression [30]. Figure OS-1 cdn.intechopen.com/public/259766_osi.zip illustrates an example of erroneous UW PAR measurements that were excluded from analysis at a site sampled during the 2010 NCCA field season.

3.3 Chemical

3.3.1 Algal toxins

Recent NARS, including the National Lakes Assessment (NLA 2017), National Rivers and Streams Assessment (NRSA 2018/2019), and the NCCA (2020), sampled assessment locations (sites) from across the US. Locations were selected using a probability-based approach to provide representative results to estimate conditions at broad spatial scales. For purposes of discussion in this section, we will focus on water grab samples that were collected from a subset of sites representing lakes, streams and rivers, and coastal areas for analysis of cyanobacteria-produced algal toxins (microcystins and cylindrospermopsin).

As part of the effort to meet programmatic data quality requirements [18, 20, 23], EPA designed a performance analysis to document the reliability and consistency with which analytical laboratories detected the presence and concentration of the algal toxins cylindrospermopsin and microcystins. With a focus on accuracy (percent recovery), the design provided performance test (PT) samples to state and national laboratories analyzing field samples for which the nominal concentrations were known to the NARS QC administrators. The objective of the PT analysis is to allow use of the results to evaluate the quality of the analytical procedures, specifically through use of enzyme-linked immunosorbent assay (ELISA) test kits, and potentially develop recommendations for improvement in sample handling, preparation, and analytical techniques.

Sets or "waves" of PT samples were prepared and delivered to the target laboratories during the same period that primary project samples were undergoing analysis. Two waves were analyzed for the NLA (2017), and three waves of PT samples each were analyzed for the NRSA (2018/2019) and the NCCA (2020). The procedures for analyzing microcystins and cylindrospermopsin included necessary cleanup steps for samples with salinity >3.5 parts per thousand, as well as dilution steps for samples with concentrations >upper detection limit (UDL) of the ELISA test kits. The PT

[2] The protocol in [30] calls for a minimum *R* of 0.95; the minimum *R* for the NCCA is relaxed to 0.75 to allow for variability in measurement due to factors such as differing sun angles throughout the day or underwater light reflection at shallower estuarine sites.

samples were subjected to multi-temperature stability studies before shipment, and then shipped on ice packs overnight to the laboratories analyzing NARS field samples.

PT samples were prepared to specified concentrations of cyanotoxins (Table OS-4 cdn.intechopen.com/public/259766_osi.zip) and distributed to the target laboratories. We used two performance measures in evaluating the PT results. First, percent recovery was used for accuracy, and RPD or relative standard deviation (RSD) [40, 48–50] for precision. Although all PT concentrations are shown (**Table 1**), for reasons of space limitations we have selected example results to illustrate results for one round of analyses for which the most accurate % recovery results were obtained and another for the least accurate from the most recent NARS, including NLA2017, NRSA2018/2019, and NCCA2020.

Both Lab A and Lab B met the % recovery goal of 70–130% [38] for the freshwater microcystins 2018/2019 NRSA Round 1 PT samples (Table OS-5 cdn.intechopen.com/public/259766_osi.zip). In comparison, Lab A did not meet the % recovery goal for the two of the freshwater microcystins 2017 NLA Round 1 PT samples. It should be noted that the results for sample M-7 were only slightly outside the % recovery range. In addition, although the results for M-10 were lower than 70% recovery, the PT sample concentration was much higher than the test kit range and required several dilutions for analysis.

Lab A met or nearly met the % recovery goal of 70–130% [38] for the estuarine microcystins 2020 NCCA Round 3 PT samples (Table OS-6 cdn.intechopen.com/public/259766_osi.zip). In contrast, Lab D did not meet the % recovery goal for 2 of the estuarine microcystins 2020 NCCA Wave 1 PT samples. The 2020 NCCA Wave 1 estuarine microcystins % recovery results ranged from 63.0 to 131.1, excluding the two non-detect results from Lab D. The 63.0% recovery value was a calculated PT sample concentration above the upper limit of detection (20MC-9) and the 131.1 % recovery value was calculated for the lowest microcystins concentration (20MC-8). The non-detect results reported by Lab D were for concentrations at the lower end of detection (20MC-8 and 20MC-10).

Lab A met the % recovery goal of 70–130% [39] for the freshwater cylindrospermopsin 2020 NCCA Wave 3 PT sample (Table OS-7 cdn.intechopen.com/public/259766_osi.zip). In comparison, Lab A did not meet the % recovery goal for four of the freshwater cylindrospermopsin 2017 NLA Wave 1 PT samples. It should be noted that of the 2017 NLA Wave 1 PT sample concentrations with % recovery value outside the % recovery goal, only C-4 had a concentration within the detection range of the test kit.

Lab A met the % recovery goal of 70–130% [39] for the estuarine cylindrospermopsin 2020 NCCA Wave 3 PT sample (Table OS-8 cdn.intechopen.com/public/259766_osi.zip). In contrast, Lab A did not meet the % recovery goal for all five of the estuarine cylindrospermopsin 2020 NCCA Wave 1 PT samples and Lab D did not meet the % recovery goal for one of the estuarine cylindrospermopsin 2020 NCCA Round 1 PT samples. The vendor laboratory noted that the salts used to prepare the estuarine PT samples might have caused the elevated % recovery values for the lower concentrations (<1 μg/L) due to background interference. The vendor laboratory indicated that the salts would not lead to false positive results if there were no cylindrospermopsin in the sample.

The analyses and comparisons of analytical results highlighted potential issues that allowed the QC coordinators to inquire for additional information. Although these particular instances did not result in anomalous results, the evaluations did help improve understanding of the sample handling and analysis process.

3.3.2 Per- and polyfluoroalkyl substances in residuals

Entities permitted to sell or distribute wastewater residuals for land application in Massachusetts were required by the Massachusetts Department of Environmental Protection (MDEP)[3] to collect and submit quarterly samples in 2020–2021 for analyses of 16 PFAS (Table OS-9 cdn.intechopen.com/public/259766_osi.zip). In 2020–2021, no EPA-approved methods were available for testing residuals for PFAS. Laboratories used "modified" EPA Method 533 (*Determination of Per- and Polyfluoroalkyl Substances in Drinking Water by Isotope Dilution Anion Exchange Solid Phase Extraction and Liquid Chromatography/Tandem Mass Spectrometry*) [35] to analyze samples. The laboratory SOP were reviewed and approved by the MassDEP before they were used to analyze the residuals samples. In addition, a standardized data quality evaluation checklist was developed and used to consistently perform reviews of the quality of results reported in laboratory data packages. Implementing these steps allowed for evaluation of whether the analytical results met the quality requirements outlined in EPA Method 533 "modified" [35], as well as the overall analytical quality requirements in 40 CFR Part 136.7 (*Guidelines Establishing Test Procedures for the Analysis of Pollutants, Quality Assurance and Quality Control*).

In 2021, an evaluation of the analytical results was performed for quarterly residuals samples collected during the last quarter of 2020 through the third quarter of 2021 using the standardized data evaluation checklists. The method quality objectives (e.g., holding times, minimum reporting limits, RPD for laboratory or field duplicates) presented (**Table 1**) were evaluated and documented for each sample using a standardized data quality evaluation checklist. Additional issues that the laboratories encountered during analysis were also documented in these checklists. Results from these standard evaluations were used to qualify the data to enable end users to interpret the quality of results. We provide a summary of the qualifiers used (and frequency of use) for each of the reported 16 analytes from a total of 164 samples (Table OS-10 cdn.intechopen.com/public/259766_osi.zip).

Elevated reporting limits (>1 ng/g) were the most frequently used qualifier (Table OS-10 cdn.intechopen.com/public/259766_osi.zip). The R qualifier was used for at least one analyte for 79% of the samples analyzed. These elevated reporting limits were less frequently observed in samples with low moisture content, with all samples with less than 28.3% solids having elevated reporting limits for at least one analyte. It should be noted that the remaining qualifiers used for the results were only applied when the results were greater than the detection limit. The J1- qualifier, indicating that the isotopically labeled analogue recovery was below the lower acceptance limit and that the residual result is estimated (could be biased low) for the corresponding target PFAS, was used for at least one analyte for 37% of samples analyzed. The J6+ qualifier, indicating that the ratio of the quantifier ion response to qualifier ion response (i.e., primary mass transition) falls outside of the laboratory established criteria (i.e., outside ratio limits) and that results are estimated maximum concentrations, was used for at least one analyte for 37% of the samples analyzed. The J5+/− qualifier was used for at least one analyte for 34% of the samples, commonly indicating that the RPD for the field sample duplicate (or less commonly the MSD)

[3] 310 CMR 32.00: Land Application of Sludge and Septage, which states "any additional substance for which sampling and analysis is required by the Department, before or after the sludge or septage is approved by the Department pursuant to 310 CMR 32.11." Also, see URL: https://www.mass.gov/doc/required-laboratory-procedures-for-testing-pfas-in-residuals/download.

was above the upper acceptance limit or not analyzed with the residual extraction batch; this indicated that the residual PFAS results above the RL were estimated (could be biased high or low).

Results of the 2020–2021 QC evaluations were used to inform ongoing residual analyses in Massachusetts. MassDEP communicated results for individual data packages and for the overall analysis to the laboratories, contributing facilities, and their management to refine protocols and execution of the residual PFAS monitoring program. Additional analyses of the magnitudes of PFAS concentrations over time and of duplicate precision were used to recommend field sampling and duplication frequency and is a technical issue many states and other entities are beginning to address.

3.3.3 Tissue contaminants

As with biological monitoring and bioassessments, performance measures and MQOs are essential for both the field and laboratory aspects of tissue contaminant monitoring studies of aquatic biota (e.g., fish, mollusk, or crustacean tissue studies for human health or ecological risk management and communication). QA planning and implementation should focus on defining DQOs, designing a QC system to measure data quality, and assessing data quality to determine its suitability to support management decisions regarding future monitoring, risk assessment, or issuance of consumption advisories [31, 51].

Field QC procedures need to be detailed in SOPs and as noted previously, sampling practitioners need to be trained in those program-specific procedures. A primary QA concern for the field collection, handling, preservation, and shipping stages of tissue contaminant studies is the preservation of tissue sample integrity. The accuracy of analytical results depends in part on the immediate preservation (i.e., freezing) of tissues and the prevention of exposure to extraneous sources of contamination. Those sources need to be identified and avoided or eliminated. Field blanks, or rinsates of empty field sample containers have been used by some investigators to evaluate field sample packaging materials as sources of contamination, with a control limit of less than the MDL as determined for the particular analytical method or monitoring program [51]; however, immediate freezing of whole organisms in the field (and preparation of tissue in the laboratory) and the use of food-grade packaging materials reduces or even eliminates the need for field blanks. Some studies may require tissue resection in the field, but sample processing (including resections) conducted under controlled laboratory conditions reduces the potential for sample contamination. One means of evaluating the efficacy of tissue preparation cleaning and decontamination procedures is the preparation and analysis of processing blanks or rinsates of the equipment used for dissecting and homogenizing tissues. As with field contamination QC measures, the control limit for processing blanks would also be <MDL for the particular analytical method or monitoring program. Control limit exceedances require suspension of sample preparation and specific corrective action by the preparation laboratory before resection or homogenization may resume.

Overall completeness is the number of valid sample measurements relative to the number of samples planned for collection, and it may be impacted by a variety of circumstances, e.g., storm events, samples lost during shipment, etc. Completeness objectives vary by study administrators and can range from 80% to 99%, with levels <80% generally requiring corrective action such as resampling or reanalysis [33, 34, 51]. Sampling precision (or the degree of agreement among replicate measurements caused by random error) can be estimated by comparing field replicates using RSD; however,

acceptable field replicate samples require the collection of target organisms of the same species and the same sizes collected from the same location which may not always be possible. Rather than establishing acceptance limits for sampling precision, some researchers have instead used field replicate results to aid in the evaluation of study results and characterize the variability of the sampled population [32, 34]. Variability arising from tissue preparation (e.g., homogenization, compositing, and aliquoting), shipping, and laboratory analysis processes can be estimated by having the sample preparation laboratory prepare duplicate tissue homogenate or processed composite sample pairs to be analyzed as blind duplicates. [32] applied a MQO specifying that the RPD for these duplicate tissue composite pairs should be <50% for values greater than 5× the minimum level of quantification (ML) for each target contaminant and <100% for values <5× the ML.

In addition to the use of duplicate homogenate or composite sample pairs, a standard suite of laboratory QC measures including initial precision and recovery (IPR) samples, and matrix spike and matrix spike duplicate samples provides information about the precision associated with various components of the analytical process. IPR samples are used to demonstrate that a laboratory can achieve precision and accuracy using a particular analytical method prior to the analysis of any tissue study samples. They consist of a reference matrix (i.e., one that matches the study tissue matrix) that is spiked to a known level with the target contaminant. Accuracy is measured by the average recovery of the target chemical in replicate IPR samples. Precision is assessed by calculating RSD of the measured concentrations of the target chemical in the IPR samples. Matrix spike samples are field sample tissue homogenates with known amounts of a target chemical spiked into the sample to assess the effect of matrix interferences on compound identification and quantitation (measured as percent recovery of the chemical). Duplicate matrix spike samples consist of additional aliquots of matrix spike samples that are analyzed to assess the effect of tissue matrix interferences and are routinely used to assess method precision. Summarizing measurement QC limits for tissue studies is not as straightforward as identifying measurement quality indicators. Analytical QC limits vary with target chemicals and analytical methods. [51] provides general control limit recommendations and associated corrective actions for fish and shellfish tissue studies.

3.4 Ecotoxicology

Ecotoxicology tests are used in many countries and environmental programs as one of several approaches to assess environmental condition of soils, sediments, and water, toxicity of chemicals (including pesticides), and compliance with environmental regulatory statutes (e.g., the Clean Water Act in the U.S.). Toxicity testing for these various programs is largely conducted in a controlled laboratory setting according to specific test method protocols, e.g., [46, 52, 53], although mesocosm and in situ toxicity testing is also used in some cases in aquatic testing of chemicals, for example, (e.g., [54, 55]). Toxicity test results consist of two types of information: biological measurements and statistical interpretation of the observed biological data. Biological measurements are the raw data recorded when conducting toxicity tests (e.g., survival, weight, number of young produced). The statistical interpretation of a toxicity test is derived from the observed biological data.

Like other types of methods that rely on biological data, results of a toxicity test depend on the method used. Ecotoxicological testing relies on several QC procedures

and analyses to help document that the test method performs acceptably given program DQO [46, 52]. Two key QA procedures used in all ecotoxicology testing are: (1) results from testing with a reference toxicant and (2) meeting minimum test acceptability criteria.

In reference toxicant testing, test organisms are exposed to a range of concentrations of a known toxicant or positive control (e.g., a metal such as copper or a salt such as potassium chloride for aquatic testing, e.g., [56–58]). Organism response to that toxicant is compared against an acceptable range of response previously established by the laboratory for the test organism and test method. Control charts are developed based on several reference toxicant tests for a given test species and test method to document an acceptable range of response to the toxicant [46]. In practice, statistical point estimate endpoints rather than the raw data are used to document results of each test and establish an acceptable range of response for a test method and reference toxicant. Often, a series of performance measures is used with corresponding MQO to address a range of relevant concerns (Table OS-11 cdn.intechopen.com/public/259766_osi.zip). Examples of point estimate endpoints include the lethal concentration to 50% of the test organisms (LC50) and the concentration resulting in a 25% inhibition in response compared to the control organisms (IC25). Point estimate endpoints have the advantage of generating 95% CIs around the mean value so that within test variability as well as between test variability can be established. These endpoints can be compared across tests and laboratories for a given chemical because the endpoint is not dependent on the concentration series used.

The second key QA requirement is that each test method has minimum test acceptance criteria (TAC) for control organisms that should (must for some programs such as the NPDES program in the U.S.) be met in a test for the results to be considered of acceptable quality. Examples of TACs include metrics such as minimum acceptable percent survival for organisms in a clean control matrix, minimum growth, and minimum number of offspring per female that must be achieved in the controls in a test [46].

A key performance measure in ecotoxicological testing is within-test variability or precision, both in the controls alone and for the entire test. Laboratories track performance metrics for the control over time to assess within-test variability. This is accomplished by calculating the mean, standard deviation (SD), and coefficient of variation (CV) of the control replicate data for each test conducted by the laboratory for a given test method. A statistical metric that is used to calculate within-test variability for the test as a whole is percent minimum significant difference (PMSD) [59, 60], which is derived from an Analysis of Variance (ANOVA) and Dunnetts Multiple Comparison Analysis. The PMSD documents the percent effect that can be statistically distinguished as compared to the control in the test based on the within-test variability observed.

Allowable ranges of PMSD values were derived by EPA using multiple tests for a given test method [59]. Controlling both minimum as well as maximum intra-test variability in whole effluent toxicity (WET) tests is seen as an important test acceptance factor. Too much variability among control replicates reduces the ability to distinguish statistical difference in organism response among treatments. Too little variability among control replicates, on the other hand, can yield statistically significant differences among-test concentrations and the control that are *biologically meaningless*. Controlling within-test precision is key to achieving the optimal sensitivity possible using a particular test species and ecotoxicology test method.

4. Conclusions

It should be noted that there has been vigorous debate on the appropriateness of actions that should result from interpreting statistical deviation in terms of process or QC [6], including that practitioners should avoid over-interpretation. This includes suggestions that unnecessary adjustments in processes could actually increase frequency of anomalous results. The implication here is that someone interpreting and developing recommendations from QC analysis who is not knowledgeable about the field of practice or study risks having a program just working toward a number, rather than truly trying to improve a process or determine the quality of environmental data for use in assessing ecological outcomes.

Recognition of the causes, magnitude, and effects of variability and error is attained through consistent observation and measurement and can simultaneously provide direction on the need for and types of corrective actions. Appropriately developed and implemented MQO, as part of consistent and routine measurement and monitoring programs, not only function to keep them on-track, but in the long run can also lead to more cost- and time-efficient processes.

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Chapter

Quality Impairments in Flexible Road Pavements

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Abstract

The purpose of this chapter is to present the reader with the physical processes of how flexible road pavements progressively fail and impair the quality of finished roads arising from non-adherence to roads construction quality outlines and requirements. This was achieved by investigating eight (8) roads from a sample of nineteen (19) roads based on purposive sampling. Using instruments of steel tapes, paints for failed sections, rolling rule and pictures, measurement of length, width and depth of various failed sections were taken for five (5) daily measurements at three (3) monthly visit intervals for Four Hundred and Thirty Five (435) days to show the rate of deterioration. Data obtained were analyzed for reliability of pavements using Weibull distribution statistics on ReliasoftWeibull^{++}to extrapolate pavement reliability from bathtub function. Findings showed that roads failed progressively within six (6) months after finished construction and deteriorated fast with increased failures on length, depth and width of pavements. The practical implications of this is that the process of construction did not conform with required/stipulated quality control metrics of flexible road construction especially in the areas of geomaterials compaction, temperature and density of materials laid. It was recommended that organization adhere to quality control guidelines and requirements to forestall quality impairment.

Keywords: flexible pavement, Weibull test, quality control, quality impairment, deterioration rate, reliability

1. Introduction

Issues of total quality management implementation in different construction industries around the world are well validated in studies to be at various levels of implementation between developing and developed countries [1]. Structural failures of roads before the designed lifetime are regular features especially amongst developing countries in the form of evidential failure of a small structural component, accelerative failure with visible weakness such as cracks and abrupt, sharp failures [2] etc.

Non-compliance to specification outlines of projects demand –amongst others- the use of non-standard materials, ineffective/unqualified team members of quality control rangers, fast track construction, poor detailed designs, etc. and may be regarded as are remote and immediate factors leading to failures [3]. Quality Control as a

process in road construction ensures conformity of the finished road pavement with required standards [4]. Quality defects are obtainable from the difference in the coefficient of variation of required elasticity modulus (C_v^{req}) from the standard elasticity modulus (C_v^{std}) which is based on deflection patterns of geomaterials composition and dynamic load intensity on pavements. The wider the difference between such elasticity moduli, the higher the propensity to failure of pavements [5]. Owing to such probability outlook, their reliability estimate, takes the form of

$$R_{p_t} = 0.5 + F\left[\frac{E_{eq} - E_m}{\sqrt{\sigma_{eq}^2 + \sigma_m^2}}\right] \tag{1}$$

where E_{eq} is the equivalent modulus of elasticity, E_m is the maximum modulus of elasticity, σ_{eq} is the equivalent modulus of elasticity and σ_m is the mean square deviation of the maximum modulus of elasticity.

The process of quality control in road pavements follows the examination and test of composite materials towards meeting the correct specifications and required quality. Quality control in road projects follow stratification checks by separating roads composite materials and bringing them to specialized and accredited laboratories in order to conduct a series of tests on them. However, it is worth noting at this point that specific tests may also be done on site using checklists as the construction progresses.

Absence of quality control checks has often resulted to impaired quality outputs and poor workmanship [6]. Quality impairment in road construction processes shows that finishing road surfaces, construction process, labour workforce and materials used are in need of quality review and standardization for improvement [7]. The same applies to the workforce involved. Evidences of quality failures in constructed roads is revealed in their reliability values from their mean survival time to failure time, which are consequential fall-outs of quality management principles not being implemented. Quality in the context of road construction is when functionality is at equilibrium with a construction process output based on road utilization from effective road performance, durability, conformance, reliability, uniformity and serviceability [8]. Further to this, impaired quality of constructed roads are revealing in varying forms of cracks, potholes, bulges and surface depressions that often results in poor transportation systems, and delayed economic growth [9]. Quality impairment of roads indicates an increased level of reliability failures. The aim of this paper is to parametrically estimate their durability.

2. Road construction and quality practice

Road constructions are either flexible or rigid highway pavements with most or all of the following construction materials *viz.*, soil, aggregates, admixtures, Portland cement concrete, Bituminous materials, structural steel and pavement markers [10]. All of these materials are compositely layered together in a definite mix and proportion to output a quality road carriageway [11]. Determinants of high quality roads are subjects of quality tests on the various road materials enumerated above. Test on highway materials such as, Moisture Content Value (MCV), Los Angeles Abrasion Value, Dynamic Cone Penetrometer, Flakiness Index, Penetration Test on Bitumen,

California Bearing Ratio (CBR), Softening point test on Bitumen and Ground Penetrating Radar tests are various laboratory test prerequisites for quality road [12].

Table 1 presents road construction tests for quality assured output.

Flexible road pavements construction primarily consist of 70% asphalt bitumen content that provides binder mix with aggregate to produce asphalt concrete. This is laid on a bituminous base of a binder course. Stabilization of this process is followed by the application of tack coat of 0.75 kg per sq. metre [8]. Quality control standard as required in the preparation and placing of premix material is that bitumen is heated in the temperature range of $(150–177^0)$ C within which aggregate temperature must not differ by 14°C from the binder temperature [13]. The hot mixed material of the bitumen and the aggregate together with the binder is then paved at a satisfactory temperature of not more than 163°C. This is followed for a smoother surface with a roller compaction at a speed not exceeding 5 km per hour. Preliminary or breakdown rolling uses 8 to 12 tonnes rollers and further pressurized or intermediate rolling is done using 15 to 30 tonnes fixed wheel pneumatic rollers.

During construction, the routine quality control checks carried-out to ensure quality output are often stipulated in the watch-out for resulting pavement mix, temperature at point of laying and pavement gauge or thickness. Other checks not necessarily routine but periodical are checks for aggregate grading, bitumen content grade, temperature of aggregate temperature of paving mix at mixing and compaction [14]. At every 100 tonnes of mix discharged by the hot mix plant samples are collected for the above tests. Another test for quality compliance is carried-out by implementing the Marshall test for every $100m^2$ paved and compacted [15]. This is also followed by the field density check to see if 95% of laboratory density obtained shows congruency in the field. Tolerance of 6 mm per 5 m length of paved surface is allowed for variations in depth of pavements [16]. Variations from longitudinal undulations along the straight edge at every 3.0 m check must not exceed 8.00 mm and the number of undulations higher than 6.0 mm should not exceed 10 for every 300 m of road. Near absence of quality checks in road construction projects are traceable to road failures in the form of cracks, potholes, bulge and creter depressions. A typical quality controlled road pavement construction is shown in **Figure 1**.

Failed roads maybe regarded as evidences of quality neglects. Road failures are progressive in nature with monotonic properties of lebesgue measure theory with respect to progressive road component failures. A collection of road used in a similar traffic pressured fashion normally will show propensity to fail within predictable time measures [17]. Determination of such failings owing to quality neglect is provided for in Weibull reliability analysis under the scheme of plotting the percentage of road sections that have yielded to failure over a randomized time period measurable in cycle-starts, hours of run-times, miles driven, etc. [18]. Usually, classification of quality impairment is obtainable from Weibull reliability analysis with non-linear bathtub graph having to be approximated with line of best-fit, with β describing the classification in:

$\beta < 1.0 =>$ Infant mortality $=>$ Optimum quality impairment in construction.

$\beta = 1.0 =>$ Randomized failure $=>$ Progressive quality impairment during construction.

$\beta > 1.0 =>$ Wear-Out Failure $=>$ High quality impairment during construction.

Most decent and prudent statistical inferences in Weibull test are parametrized with Time-to-Failure component of the road. This is historically accounted for by B (F) with 'F' representing the percentage of road section that have failed, while some parametrize by lifetime L(F) and 'B' representing bearing time. In the Weibull

S/N	Test type	Purpose	Test methods	Quality criterion	Expected outcome
1.	CBR – Test for Subgrade	A penetration test for the determination of mechanical fitness strength of the natural ground, subgrade and base course underweight on the carriageway	• Load bearing capacity • Moisture content • Potential for shrinkage and/or swelling	• Ease of compaction • Strength retention • Low volume response to adverse weather condition and capillary movement of ground water • Inability to compress • Bearing capability for stability	• Ability to furnish and dispense support to the finished pavements in resistance to traffic loads • Must have enough stability under inclement weather and heavy stack situation
2.	Aggregate Testing	Load transfer potentials or capability of finished pavement	• Crushing test • Abrasion test • Impact test • Soundness test • Bituminious adhesion test • Specific gravity and water absorption test	• Enabling relative offer of resistance to gradual traffic load • Ability to show hardness property of aggregate material • Ability to offer resistance to impacts on aggregate obtained as a percentage of aggregate passing sieve • Showing potential to resisting actions of weathering on aggregate under conditions of varying temperatures in sulfate solutions of sodium and magnesium. Weight loss not exceeding 12% and 18% on these solutions • Offering propensity to resist water permeability in voids on road surfaces. • Ability to show adhesion of bitumen binding to aggregate free from moisture and has no permeable water inlet	Aggregates in finished pavements must show promise of load transfer potential and capability according to test pass.
3.	Penetration test	Hardness or softness of Bitumen	• Penetration depth under the action of standard loaded needle	• Able to show penetration resistance with reference to hardness or softness of bitumen when needle load is applied under conditions of pouring temperature, size of needle and loading weight on needle	A desirable penetration value of 150 – 200 mm within 5 seconds, for cold climates or lower for hot climates
4.	Ductility test	Envisaged Bitumen deformation or elongation	• Measurement of distance to which a standard field sample of Bitumen material will be elongated without breaking at 27°C and 90 minutes rapid cooling	• Output a minimum ductility value of 75 cm under stressed condition of pulling rate, test temperature and pouring temperature	Bitumen must show ability to slow gradual deformation or elongation even at quick optimized stress and strain.

S/N	Test type	Purpose	Test methods	Quality criterion	Expected outcome
5.	Softening Point Test	To show at what temperature bitumen attains a specific point of softening	Using ring and ball apparatus where a brass ring holding sample of bitumen is placed in water or glycerin at a given temperature. Then the steel ball is placed on a bitumen sample also in the liquid medium and heated to 50°C in one minute	Output a temperature for which the softened bitumen touches the metal plate at a designated distance	Higher softening point shows lower temperature propensity and rudimentary in hot weather regions.
6.	Specific Gravity test	Determination of Bitumen binder density variation with aggregate	Specific gravity test by pycnometer or using weight of samples in air and water at 27°C.	Ensuring that mineral impurities of aromatic types are separated in the chemical composition of bitumen to keep the density at normal. With such mineral impurities, specific gravity of bitumen may increase	Obtaining a specific gravity of bitumen within 0.97 to 1.02
7.	Water content test	Prevention of bitumen foaming on heating to boiling point of water	Water distillation from a known weight of Bitumen specimen in a pure petroleum distillate, free of water. On heating, the water content in the specimen is collected from condensation and expressed as a percentage of weight of original specimen.	Water distilled is aimed at determination of allowable water content in the bitumen which it must contain to prevent foaming	Expected water content in Bitumen must be within the range of 0.2% by weight
8.	Heating loss test	Determination of volatility loss	A sample of about 50gm of bitumen is weighed and heated to 161°C for 5 hours in a specified oven. The sample is weighed again after heating and loss expressed as percent of weight of original sample.	Loss in weight of bitumen after heating shows not exceed 1% so as to retain its volatility	Relationship between Bitumen penetration value and weight loss must be 150–200 to 2% loss in weight.

Table 1.
Quality test metrics in flexible road pavements.

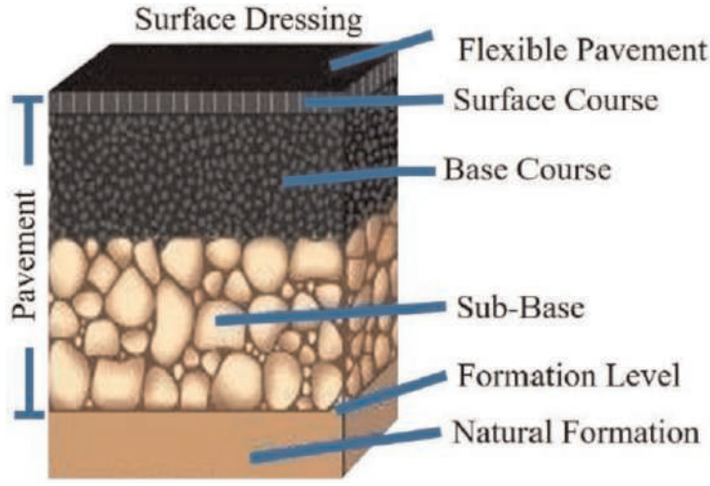

Figure 1.
Components of flexible pavements in Hassan and Sobhan [13].

statistics, the distribution shows the relationship between failed percentage with respect to time governed by constant shape factors 'β' and 'η' that determines shape and scale of distribution respectively by the function:

$$F(t) = 1 - e^{\left(\frac{-t}{\eta}\right)^{\beta}} \tag{2}$$

Summing the monotonic progressive failures over time to the point of measurement generates a probability density function (PDF) describing the frequency of failures over time estimates as:

$$f(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{3}$$

Quality control checks on compacted geomaterials such as sub-base by a more precise measuring light weight deflectometer (LWD) device in the study of Duddu and Chennarapu [19] as against density and stiffness base methods with the aim of obtaining pavement deformation modulus (E_{LWD} have shown better predictive ability of deformations). For instance LWD tests on geomaterials such as soils, aggregates, and asphalt had output of 35/60 MP_a and 120/170 MP_a. As a quality control reference, LWD tests presents the user with information on longer life cycle pavement performance and predictive failure indicator time. Confirmation of such parametric evaluations follows the regressive test between LWD and other density/stiffness methods with better coefficient of determinations (R^2). For instance, as outlined in the work of aforementioned researchers investigation of Sandy soil regression-correlation on California bearing ratio (CBR) and E_{LWD} by Dwivedi and Suman [4] gave R^2 values of 0.807 for unsoaked sand (US), 0.805 for soaked (S) sand and dry density 0.77 with the following relationship:

$$\begin{aligned} CBR_{(US)} &= 0.0009E_{LWD}{}^{2} \\ CBR_{(S)} &= 0.0001E_{LWD}{}^{2} \\ \gamma_d &= 1 \times 10^{-5}E_{LWD}{}^{2} \end{aligned} \tag{4}$$

Quality controlled output limits using their coefficient of determination (R^2) on lime based stabilized subgrade soil from correlative studies with E_{LWD} by in the literature of Bisht, Dhar and Hussain [20] for unconfined compressive strength (UCS) at R^2 = 0.99 and CBR at R^2 = 0.93 showed the following relation:

$$UCS = 4.9E_{LWD} \tag{5}$$

$$CBR = 0.15E_{LWD} \tag{6}$$

Studies by Nazzal, Abu-Farsakh, Alshibli and Mohammad [21] on crushed limestone and sandy soil geomaterials gave R^2 value of 0.83 between CBR and E_{LWD} with the following relation:

$$CBR = -14 + 0.66E_{LWD} \tag{7}$$

$$E_{v2} = (600 - 300)/(300 - E_{LWD-L_3}) \tag{8}$$

as a correlate between Static modulus of layer 2 (E_{v2}) and modulus of deformation measured by a Zorn LWD device with 300 mm diameter plate. Such stress/strain on flexible pavement layers often transfer elasticity modulus for determining pavement structural durability between layers. This is governed from the computation of road's elastic modulus (E_{gen}) based on 'g' the bearing capacity reserve of road bed and pavement in:

$$E_{gen} = \frac{E_1E_2\left[1 + \left(\frac{2h}{D}\right)^2\left(\frac{E_1}{E_2}\right)^{\frac{2}{3}}\right]^{\frac{1}{2}}}{E_1 - E_2\left\{1 - \left[1 + \left(\frac{2h}{D}\right)^2\left(\frac{E_1}{E_2}\right)^{\frac{2}{3}}\right]^{\frac{1}{2}}\right\}} \tag{9}$$

A similar correlation investigation on soil classification test between static modulus of pavement layer 1and deformation modulus using light weight deflectometer (LWD) by Alshibli, Abu-Farsakh and Seyman [22] showed a quality allowable R^2-value of 0.84. That of Rao, Shiva and Shankar [23] on subgrade geomaterials between CBR and E_{LWD} gave an R^2 value of 0.90 with the following regression result;

$$E_{v1} = 0.91E_{LWD-P_3} - 1.81 \tag{10}$$

$$CBR = -2.754 + 0.2867E_{LWD} \tag{11}$$

where E_{LWD-P_3} is the modulus of deformation measured by Prima 100 Cohesive and non-cohesive soils. Adam and Kopf [24] provided regression functions between static modulus of layer 1 (E_{vI}) and modulus of deformation from a Zorn LWD device with a 300 mm plate diameter. Deformation thresholds are predictable for quality control reasons for cohesive soils by the relationship:

$$E_{v1} = 0.833 \times E_{LWD-z3} \tag{12}$$

And for non-cohesive soils with the relation;

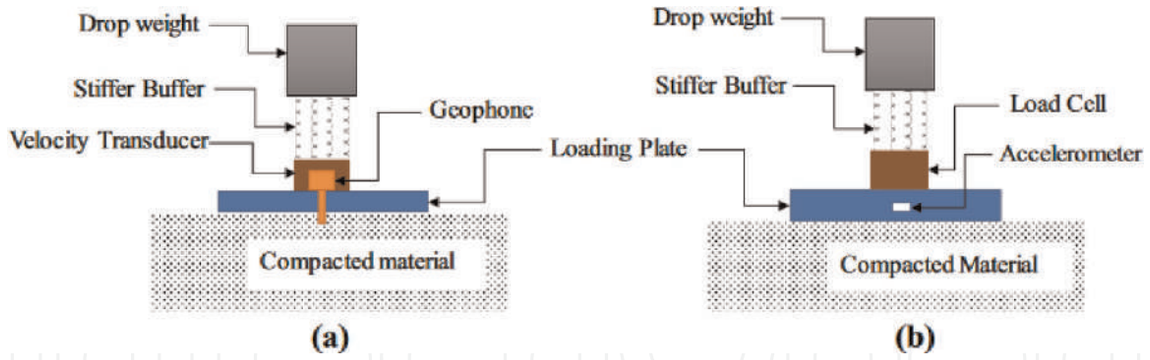

Figure 2.
*Schematic sketch of the location and type of transducer: **a** geophone measures velocity and is located on the compacted material, **b** accelerometer measures vibrations and is located in the plate. Photo credit: Duddu and Chennarapu [19].*

$$E_{v1} = 1.25 \times E_{LWD-z3} - 12.5(E_{LWD-z3}) \vee_{range} at 10 - 90MPa \tag{13}$$

Quality control checks by light weight deflection (LWD) devices are conducted by velocity tracks using geophones or vibration tracks using accelerometer which is located on the test plate (see **Figure 2** from Duddu and Chennarapu [19]).

On the basis of limit state engineering designs, there are progressive failures at retail scales to yield a point of total failure beyond which roads become unserviceable to users before their expected lifetime span. Bazhanov and Saksonova [25] and Hassan and Sobhan [13] have shown that yield point in a quality impaired constructed road is attainable after a dynamic load is applied on pavements surface originating from a plastic deformation. Forms and types of road failures are shown in the accompanying **Table 2**.

According to Gupta [26], points of statistical references in reliability of pavement estimations are marked in the pavements failure rate (hazard rate) defined by:

$$r_F(k) = \frac{P(k)}{\sum_{i=k} P^{(i)}}, \tag{14}$$

$$\frac{P(X=k)}{P(X \leq k)}, k = 0, 1, 2, \ldots$$

With $P(k) = P(X = k)$ being the mass function, cumulative distribution function $f(k) = P(X \leq k)$ and pavement survival function $\bar{F}(k) = 1 - f(k)$ respectively. The pavements' mean residual life, $(\mu_F(k)$is indicated by estimation bias as:

$$\mu_F(k) = E(X - k | X \geq k) = \frac{\sum_{x=k} \bar{F}(x)}{F(k-1)}, k = 0, 1, 2, \ldots \ldots \tag{15}$$

This estimation is premised on the deterioration force of decrement on the pavement lifespan which bears representation in plastic deformation in other to understand pavement tolerance [27]. Consequently, the pavement failure rates or hazard rates which are competing in risk value by a mortal force of decrement with mean residual life of pavement are relationally obtained by:

$$r_f(k) = \frac{1 + \mu_f(k+1) - \mu_f(k)}{1 + \mu_f(k+1)} \tag{16}$$

Quality Impairments in Flexible Road Pavements
DOI: http://dx.doi.org/10.5772/intechopen.105697

Failure Type	Figure	Description
1. Cracks		
i. Alligator cracking		Originates from inadequate structural bends, poor drains. If poorly managed can deteriorate to potholes
ii. Transverse cracking		Originates from heavy traffic and poor materials mix design
iii. Block cracking		Originates from poor unstabilized base and defective ramming. This crack enables percolation of moisture and infiltration.

Failure Type	Figure	Description
iv. Longitudinal cracking		This form of crack is traceable to unstable base and defective construction. Moisture infiltration into the bed is prevalent.
v. Slippage Cracking		This form of crack failure originate from unstable wearing course and poor drainage
2. Depression		This form of road failure is very visible with creter form of depression. Its occurrence is traceable to heavy rainfall and improper side drainage

Quality Impairments in Flexible Road Pavements
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Failure Type	Figure	Description
3. Raveling		Failure is traceable to the inability of asphalt primers, binders and tack coats to hold aggregate in place, partial compaction and wearing off or weakening of asphalt binders.
4. Potholes		Failure is attributed to the exposure of road structural members to gradual wearing by heavy vehicular loads due to accumulation of surface rain water from cracks on pavements. It produces visible three (3) dimensional failures of depth, width and length.
5. Water Bleeding		Failure is occasioned by poor mix design of structural materials and with unsuitable binder. Failures of this nature lessens car skidding resistance.

Failure Type	Figure	Description
6. Corrugation and Shoving		Failure is often associated with roughness and elevated sections of the pavement. Poor materials mix design, high traffic loads and unstable binders are most the causes of this failure

Table 2.
Types of road failure.

$$1 - \frac{\mu_f(k)}{1 + \mu_f(k+1)}, k = 0, 1, 2, \ldots..$$

The augmented pavements failure rate, mean residual life and its survival which are estimable consequences of an impaired engineering works is signified in a quality deficit index by relating the three statistical variables as:

$$\bar{F}(k) = \prod_{0 \le i \le k} \left[1 - r_f(i)\right]$$
$$\prod_{0 \le i \le k} \left[\frac{\mu_f(i)}{1 + \mu_f(i+1)}\right], \mu(0) = E(x) \tag{17}$$

Following the competing mortal forces of decrement on pavements with failure induced components yield from several real time traffic loadings, correspond to variations in the lifetime survival of pavement obtainable by:

$$\sigma_F^2(k) = Var(x - k \vee x \ge k)$$
$$k^2 + \frac{\sum_{i=k}^{\infty}(2i+1)\bar{F}(i)}{\bar{F}(k-1)} - \left(\frac{\sum_{i=k}^{\infty}\bar{F}(i)}{\bar{F}(k-1)} + k\right)^2$$
$$2\frac{\sum_{i=k}^{\infty}\bar{F}(i)}{\bar{F}(k-1)} - (2k-1)\mu_F(k) - \mu_F^2(k) \tag{18}$$

In order to idealize how quality is impaired by statistical reliability variables, the pavement's failure rate, mean residual life and variance residual life functions have causal aggregation and estimated by:

$$\sigma_F^2(k+1) - \sigma_F^2(k) = r_F(k)$$

Consequently, decreasing pavement variance residual life is X if X

$$\sigma_F^2(k+1) \le \mu_F(k)[1 + \mu_F(k+1)].$$

and it is an increasing variance residual life if

$$\sigma_F^2(k+1) \ge \mu_F(k)[1 + \mu_F(k+1)]$$

These statistical narrations in their numerical values are indicators of progressive failures with monotonicity properties for quality impairments assessment. In recent times, researches into deterioration rates of road pavements particularly in Riveros and Arredondo [28] and Al-Zahrani and Stoyanov [29] with transition probabilities indicated changes from one state to another (owing to deterioration). This illustrates precision predictability by Weibull distribution estimation. The probability density function are parametrized by $\propto$- and β- for which $(\propto > 0, \beta > 0)$ and given as:

$$F_{(t)} = \int_{\frac{\propto}{\beta}}^{o} \left(\frac{t}{\beta}\right)^{\propto - 1} exp\left[-\left(\frac{t}{\beta}\right)^{\propto}\right] \begin{matrix} fort < 0 \\ fort \ge 0 \end{matrix} \tag{19}$$

And its distribution function as:

$$F(x) = \int_1^0 exp\left[-\left(\frac{x}{\beta}\right)^{\propto}\right] \begin{matrix} forx < 0 \\ forx \geq o \end{matrix} \tag{20}$$

Under the Weibull test for pavement deterioration, expected values and variance are estimated by:

$$\mu = \beta^{-1}\left(1+\frac{1}{\propto}\right), \sigma^2 = \beta^2\left[\left(1+\frac{2}{\propto}\right) - {}^2\left(1+\frac{1}{\propto}\right)\right] \tag{21}$$

In this case, rather than Laplacian integral, the Weibull distribution is predicted on the gamma function

with:

$$((x))$$

$$(x) = \int_o^{\infty} t^{x-1}e^{-t}dtforx > 0 \tag{22}$$

This chapter deployed the use of Weibull test to obtaining the deterioration rates of selected Benin city roads in cluster from generating their deterioration model by linear regression having deterioration state as a dependent variable and pavement as an independent variable.

3. Methodology

In this research study, quality impairment in road construction was assessed by field investigation of eight (8) failing roads from a purposive sampling from 19 failed roads in the Benin city metropolis of Nigeria. Obtaining life right censored data through measurements of component failed depth, width and length with a start and end observation times were obtained. In achieving this, a seven (7) days growth rate study of failed portions in five (5) different field visitations at an interval of three (3) months for each visit was conducted to enable the capture of variation in growth rate between visits. The research team also engaged four daily undergraduate students to support obtaining measurements and controlling traffic. From the historical data gathered, mixed Weibull distribution software (Reliasoft Weibull^{++}) was used to analyze data goodness-of-fit test. Their reliability function was also tested in terms of their failure rate function and mean life function by estimating the parameters that makes the reliability function most closely fit the life data set. A review of the statistical criterion reference analytically for model fitness, shape parameters, assumed βs and graphically for fit to line, S-shape and minimum life was done from the reliability bathtub curve plot while computing their statistical function at 90% confidence bounds. **Tables 3–5** depict life data measurement of failed roads.

4. Results and discussion

Figures 3–12 and **Tables 3–5** are discussed in this section.

Figure 3.
Showing how water aids road failure.

Figure 4.
Showing how water aids road failure.

Figure 5.
Showing how failed portion of roads affects or increase journey time.

Figure 6.
Failed portion in Luckyway Road.

Figure 7.
Failed portion in Mission Road.

Figure 8.
Failed portion in New Benin Road.

5. Weibull reliability test for the deterioration of the width of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road

The shape parameter β and the 95% confidence interval of β for the data regarding the width of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road are given in

Figure 9.
Failed portion in Technical College Road.

Figure 10.
Failed portion in Textile Mill Road.

Figure 11.
Failed portion in Ogida/Upper Siluko Road.

Table 6. The road is reliable and there is not enough evidence for the deterioration of the road if the shape parameter β is close to 1 and the 95% confidence interval of β contains 1.

There is enough evidence though for the deterioration of the width of the roads in Ikpoba Hill, Lucky Way, Mission, New Benin, Ogida, Ring, Sapele and Technical College since the value of $\hat{\beta} = 22.29$ from **Table 6** is far from 1, and the approximately 95% confidence interval for $\hat{\beta}[11.45, 43.40]$ does not contain 1. The plot of the failure

Figure 12.
Failed portion in Upper Sapele Road.

rate or hazard function, which describes the likelihood of deterioration in width during the next time increment is given in **Figure 13**.

There is a steeper increase after 225 days in the hazard function in **Figure 13**. This shows that the tendency of the width of the road to deteriorate increases after the 225th day. This is due to the value of $\hat{\beta} = 22.29$ being far from 1, and the approximately 95% confidence interval for $\hat{\beta}[11.45, 43.40]$ does not contain 1. The plot of the reliability test that shows the trend of reliability (the probability of the width of the road not deteriorating at time t) with time is given in **Figure 14**. The deterioration started after the 225th day. There was a sharp rate of deterioration (decrease in the reliability status) of the width of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road after the 225th day.

6. Weibull reliability test for the deterioration of the depth of the roads in lucky way, Mission road, new Benin road, Ogida road, ring road, Sapele road, technical college road and textile mill road

The shape parameter β and the 95% confidence interval of β for the data pertaining to depth of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road are given in **Table 7**. It may be stated the road is reliable and there is not enough evidence for the deterioration of the road if the shape parameter β is close to 1 and the 95% confidence interval of β contains 1.

There is enough evidence for the deterioration of the depth of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road since the value of $\hat{\beta} = 22.50$ from **Table 7** is far from 1, and the approximately 95% confidence interval for $\hat{\beta}[10.02, 50.53]$ does not contain 1. The plot of the failure rate or hazard function, which describes the likelihood of deterioration in depth during the next time increment is given in **Figure 15**.

Routes	Serial No	1st Visit			2nd Visit			3rd Visit			4th Visit			5th Visit		
		Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)
Lucky Way	1	18	11	0.15	18.6	11	0.16	20	11	0.17	20	11	0.17	19.7	11	0.16
	2	6	2	0.23	6.8	2.2	0.23	7	4	0.24	7.3	4.2	0.24	7	3	0.24
	3	3	4	0.2	3.2	4.1	0.21	4	5	0.22	4.1	5.3	0.24	4	4.5	0.21
	4	135	11	0.1	137	11	0.11	141	11	0.12	141	11	0.12	139	11	0.11
Mission Road	1	2	3	0.1	2.3	3.7	0.11	2.5	4	0.12	2.5	4	0.12	2.4	3.9	0.11
	2	3	1	0.15	3.6	1.8	0.18	3.7	2	0.18	3.7	2	0.18	3.6	2	0.18
	3	5	2	0.089	5.3	2.3	0.1	6.2	3	0.11	6.2	3	0.11	6	2.5	0.1
	4	1	1	0.1	1.3	1.5	0.12	1.8	2	0.12	1.8	2	0.12	1.5	1.8	0.12
	5	1	1	0.076	2	1.7	0.097	2.4	2	0.1	2.4	2	0.1	2.2	1.9	0.097
	6	3	3	0.18	4	3.6	0.2	4.5	4	0.21	4.5	4	0.21	4.1	3.6	0.2
New Benin	1	2	3	0.051	2.2	3.8	0.61	2.7	3.9	0.071	2.7	3.9	0.071	2.5	3.9	0.066
	2	1	1	0.076	1.2	1.5	0.079	1.5	3	0.091	1.5	3	0.091	1.3	2.8	0.089
Ogida (Upper Siloku)	1	473	11	0.076	474	11	0.084	483	11	0.094	483	11	0.094	479	11	0.089
	2	204	8	0.051	205	8.2	0.061	208	8.5	0.066	208	8.5	0.066	208	8.3	0.061
	3	6	1	0.063	6.5	1.5	0.066	7	2	0.074	7	2	0.074	6.8	1.8	0.07
	4	5	2	0.058	5.1	2.1	0.061	6	2.5	0.074	6	2.5	0.074	5.3	2.3	0.07
	5	23	1.6	0.076	24	1.7	0.081	25	2	0.091	25	2	0.091	25	2	0.084
	6	4.7	1.5	0.089	5	2.5	0.1	5.2	3	0.1	5.2	3	0.1	5	2.8	0.1
	7	14	1.3	0.053	14.2	1.8	0.074	14.8	2	0.089	14.8	2	0.089	14.5	2	0.079

Routes	Serial No	1st Visit			2nd Visit			3rd Visit			4th Visit			5th Visit		
		Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)
Ring Road	1	1	1	0.025	1.7	2.1	0.033	2	2.5	0.041	2	2.5	0.041	2	2.2	0.038
	2	2	4	0.13	2.3	4.6	0.14	2.4	4.9	0.13	2.4	4.9	0.13	2.3	4.7	0.13
Sapele Road	1	1	1	0.051	2.5	3.6	0.069	3	4	0.076	3	4	0.076	2.8	4	0.069
	2	2	3	0.13	5.6	6.2	0.13	6.9	7	0.13	6.9	7	0.13	6	6.7	0.13
Technical College Road	1	2	5	0.051	2.6	5.3	0.056	3	5.5	0.066	3	5.5	0.066	2.9	5.4	0.058
	2	1	1	0.1	2	1.7	0.1	2.2	1.9	0.12	2.2	1.9	0.12	2	1.9	0.11
Textile Mill Road	1	1005	11	0.22	1008	11	0.23	1010	11	0.23	1010	11	0.23	1008	11	0.23
	2	258	11	0.22	259	11	0.23	262	11	0.24	262	11	0.24	261	11	0.23
	3	50	9	0.22	50	9	0.23	53	9.3	0.24	53	9.3	0.24	50	9.2	0.24

Table 3.
Life data measurement of failed road sections.

Routes	2nd and 1st Visits			3rd and 2nd Visits			4th and 3rd Visits			5th and 4th Visits		
	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)	Length (M)	Width (M)	Depth (M)
Lucky Way	0.6	0	0.01	1.1	0	0	0.3	0	0.01	0.3	0	0.01
	0.8	0.2	0	0.2	0.8	0.01	0	1	0	0	1	0
	0.2	0.1	0.01	0.8	0.4	0	0	0.5	0.01	0	0.5	0.01
	2	0	0.01	2	0	0	2		0.01	2		0.01
Mission Road	0.3	0.7	0.01	0.2	0.2	0	0.1	0.1	0.01	0.1	0.1	0.01
	0.6	0.8	0.03	0	0.2	0	0.1	0	0	0.1	0	0
	0.3	0.3	0.011	0.7	0.2	0	0.2	0.5	0.01	0.2	0.5	0.01
	0.3	0.5	0.02	0.2	0.3	0	0.3	0.2	0	0.3	0.2	0
	1	0.7	0.021	0.2	0.2	0	0.2	0.1	0.003	0.2	0.1	0.003
	1	0.6	0.02	0.1	0	0	0.4	0.4	0.01	0.4	0.4	0.01
New Benin Lagos Rd	0.2	0.8	0.01	0.3	0.1	0.005	0.2	0	0.005	0.2	0	0.005
	0.2	0.5	0	0.2	1.3	0.01	0.2	0.2	0.002	0.2	0.2	0.002
Ogida	1	0	0.008	5	0	0.005	4	0	0.005	4	0	0.005
	1	0.2	0.01	3	0.1	0.001	0	0.2	0.006	0	0.2	0.006
	0.5	0.5	0.003	0.3	0.3	0.004	0.2	0.2	0.004	0.2	0.2	0.004
	0.1	0.1	0.003	0.2	0.2	0.009	0.7	0.2	0.001	0.7	0.2	0.001
	1	0.1	0.005	1	0.3	0.003	0	0	0.007	0	0	0.007
	0.3	1	0.011	0	0.3	0	0.2	0.2	0	0.2	0.2	0
	0.2	0.5	0.021	0.3	0.2	0.005	0.3	0	0.01	0.3	0	0.01
Ring Road	0.7	1.1	0.008	0.3	0.1	0.005	0	0.3	0.003	0	0.3	0.003
	0.3	1.4	0	0	0.1	0	0.1	0.2	0	0.1	0.2	0

Routes	2nd and 1st Visits			3rd and 2nd Visits			4th and 3rd Visits			5th and 4th Visits		
Sapele	1.5	2.6	0.018	0.3	0.4	0	0.2	0	0.007	0.2	0	0.007
	3.6	3.2	0	0.4	0.5	0	0	0.3	0	0	0.3	0
Technical College Rd	0.6	0.3	0.005	0.3	0.1	0.002	0.1	0.1	0.008	0.1	0.1	0.008
	1	0.7	0	0	0.2	0.01	0.2	0	0.01	0.2	0	0.01
Textile Mill Road	3	0	0.01	0	0	0	2	0	0	2	0	0
	1	0	0.01	2	0	0	1	0	0.01	1	0	0.01
	0	0	0.01	0	0.2	0.01	3	0.1	0	3	0.1	0

Table 4.
Alternate visit comparison showing deterioration rate.

Routes	Ltime	Wtime	Dtime	Lstatus	Wstatus	Dstatus
Lucky Way	81	384	27	0	1	0
	39	42	165	0	0	0
	48	35	18	0	0	0
	62	380	54	0	1	0
Mission Road	68	36	58	0	0	0
	78	45	36	0	0	0
	49	85	45	0	0	0
	41	39	48	0	0	0
	40	31	75	0	0	0
	50	47	80	0	0	0
New Benin	65	49	65	0	0	0
	68	54	68	0	0	0
Ogida (Upper Siloku)	74	370	76	0	1	0
	72	62	16	0	0	0
	49	92	35	0	0	0
	68	88	65	0	0	0
	60	77	48	0	0	0
	38	74	49	0	0	0
	74	73	52	0	0	0
Ring Road	72	45	50	0	0	0
	69	65	385	0	0	1
Sapele Road	21	81	69	0	0	0
	92	70	378	0	0	1
Technical College Road	43	60	74	0	0	0
	25	42	132	0	0	0
Textile Mill Road	92	364	64	0	1	0
	88	388	63	0	1	0
	394	149	58	1	0	0

Table 5.
Road deterioration status change.

There is a steeper increase after 225 days in the hazard function in **Figure 15**. This shows that the tendency of the depth of the road to deteriorate increases after the 225th day. This is due to the value of $\hat{\beta} = 22.50$ being far from 1, and the approximately 95% confidence interval for $\hat{\beta}[10.02, 50.53]$ does not contain 1. The plot of the reliability test that shows the trend of reliability (the probability of the depth of the road not deteriorating at time t) with time is given in **Figure 16**. The deterioration started after the 225th day. There was a sharp rate of deterioration (decrease in the reliability status) of the depth of the roads Lucky Way, Mission Road, New Benin

β	LCL	UCL
22.29	11.45	43.40

Table 6.
The shape parameter β and the 95% confidence interval of β.

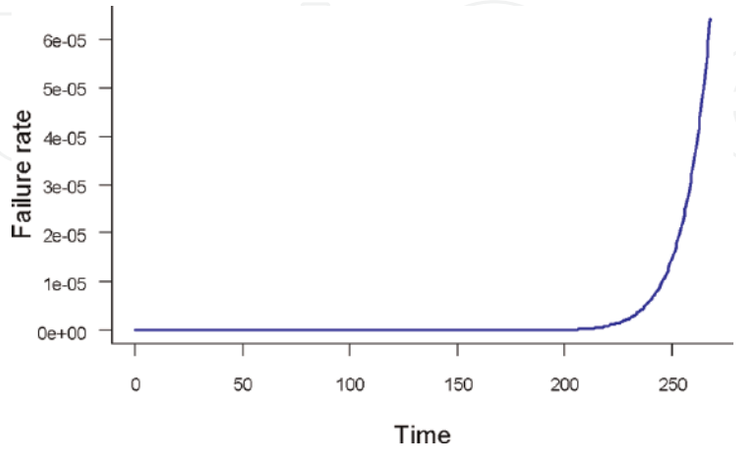

Figure 13.
The failure rate or hazard function plot for the width of the roads.

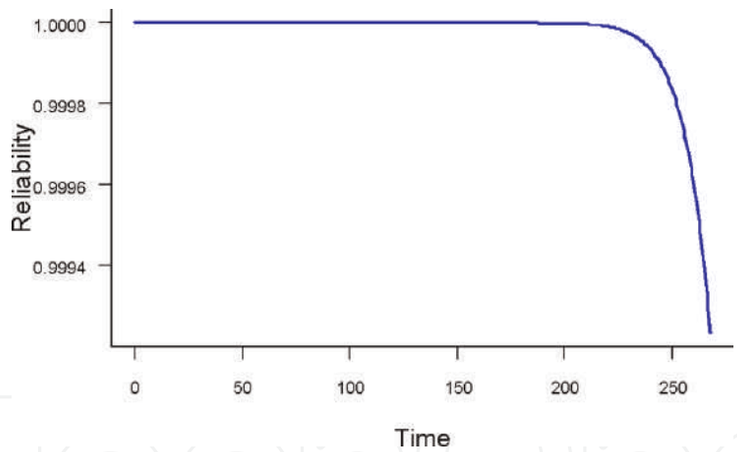

Figure 14.
The reliability test plot for the width of the roads.

β	LCL	UCL
22.50	10.02	50.53

Table 7.
The shape parameter β and the 95% confidence interval of β.

Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road after the 225th day.

Weibull Reliability Test for the Deterioration of the Length of the Roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road.

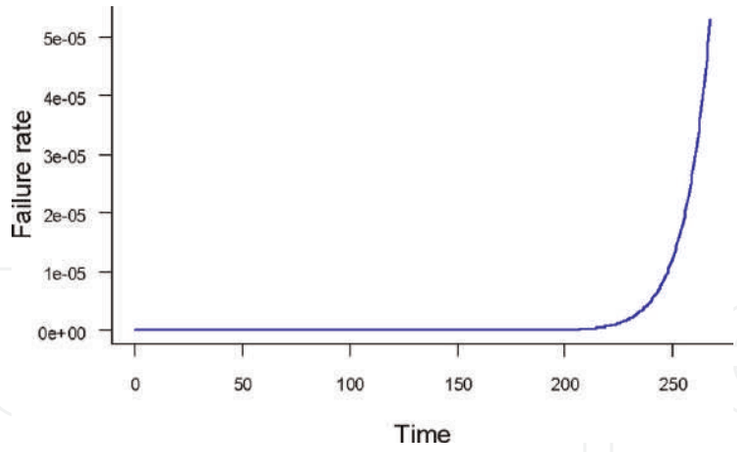

Figure 15.
The failure rate or hazard function plot for the depth of the roads.

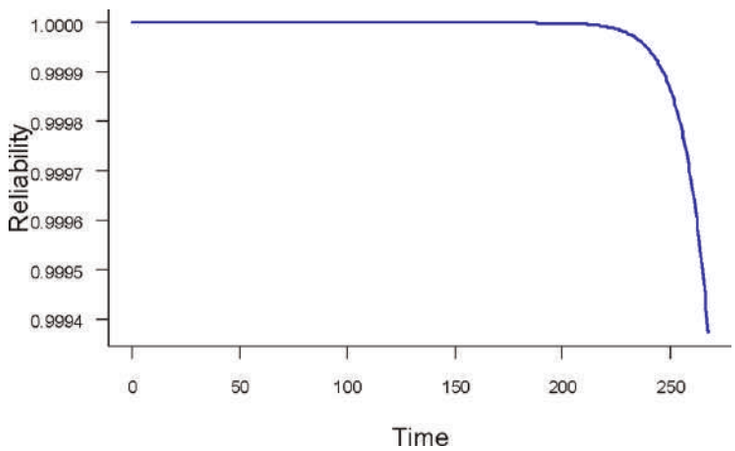

Figure 16.
The reliability test plot for the depth of the roads.

β	LCL	UCL
6.71	2.50	17.99

Table 8.
The shape parameter β and the 95% confidence interval of β.

The shape parameter β and the 95% confidence interval of β for the data on length of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road are given in **Table 8**. The road is reliable and there is not enough evidence for the deterioration of the road if the shape parameter β is close to 1 and the 95% confidence interval of β contains 1.

There is sufficient evidence for the deterioration of the length of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road since the value of $\hat{\beta} = 6.71$ from **Table 8** is far from 1, and the approximately 95% confidence interval for $\hat{\beta}[2.50, 17.99]$ does not contain 1. The plot of the failure rate or hazard function, which describes the likelihood of deterioration in length during the next time increment is given in **Figure 17**.

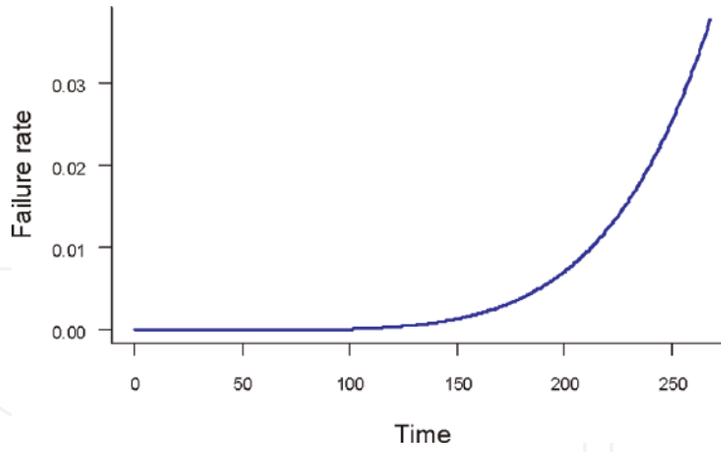

Figure 17.
The failure rate or hazard function plot for the length of the roads.

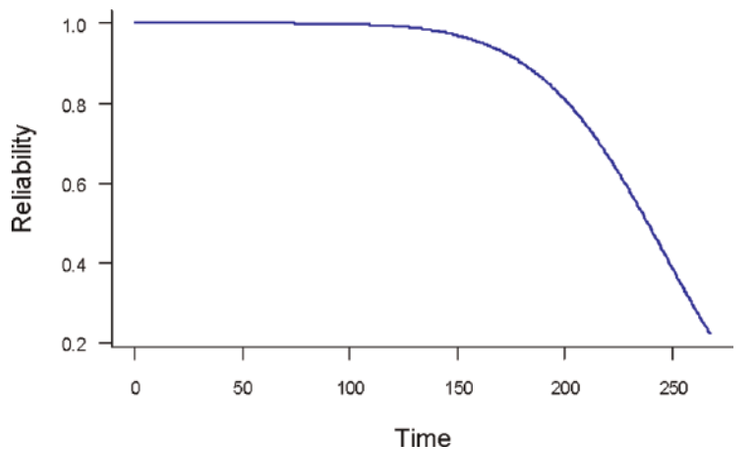

Figure 18.
The reliability test plot for the length of the roads.

There is a steeper increase after 140 days in the hazard function in **Figure 17**. This shows that the tendency of the length of the road to deteriorate increases after the 140th day. This is due to the value of $\hat{\beta} = 6.71$ being far from 1, and the approximately 95% confidence interval for $\hat{\beta}[2.50, 17.99]$ does not contain 1. The plot of the reliability test that shows the trend of reliability (the probability of the length of the road not deteriorating at time t) with time is given in **Figure 18**. The deterioration started after the 100th day. The rate of deterioration was minimal between the 100th to 150thday; after the 150thday, there was a sharp decline in the reliability status (increase in the deterioration rate) of the length of the roads in Lucky Way, Mission Road, New Benin Road, Ogida Road, Ring Road, Sapele Road, Technical College Road and Textile Mill Road.

7. Conclusion

In this study, eight (8) roads from Nineteen (19) mapped failing roads by means of purposive sampling the Benin city area of Edo state in Nigeria were assessed. Data collection follows five different routes in five (5) different field visitations at intervals of three (3) months for each visit. During visits variational failure growth in terms of

length, width and depth was obtained by tape rule measurements, rolling measuring rule, pegs, paints and photographs. Data collected were scrutinized and subjected to Weibull analysis to obtain road failure-specific sequences in reliability terms to validate and underscore quality impairments in constructed road pavements. Quality impairments originating from road component materials failure were evident in roads failing as early as six (6) months after construction. Progressive failure was noticed to be aided by further deterioration owing to lack of maintenance according to the types of road failures photographed in this paper. This is further augmented by relation to monotonicity failure theory elucidated in Gupta [26] with steady state progressive deterioration shown in the bathtub log-convexity property of the Weibull measurement count. A validation of quality impairment was deduced from a degenerating reliability Weibull analysis as corroborated in the literature of Efimenko and Moisejenko [2] and Bazhanov [5]. By undermining quality control process at construction, steep failures from a deteriorating pavement aided by the stress/strain mortal force of decrement prevailed early enough in the lifetime of the pavement to cause road failure.

8. Recommendation

Arising from the study and the observations and analysis conducted, the following recommendations are made:

1. It is recommended that quality control should be acculturated in organizations specializing in road construction and set-up procedures and instruments for quality control at points of raw materials storage including blending, mixing and placing of asphalts.

2. Deploy a quality control metrics for checking the level of quality-specific work output during the entire construction process.

3. Evolve a quality and maintenance sequence of road construction for every and any activity in the construction process.

4. Overhauling and maintaining construction equipment as required in the ISO 9002 Quality Assurance Framework. This will enable equipment work optimally especially laboratory equipment so as measurements and investigations can be precise

5. Setting site and organization's agenda around QA/AC needs at project review phase and staff meetings. This aspect of quality management encourages team building and common purpose focus towards quality objective.

6. Go round site supervision with Engineers Instruction cards to direct the rework of construction defects. This is with the aim of ensuring that site instructions for defective works are carried out without omission.

7. Allow proper physical and chemical properties limits of materials to be attained before use, in order to avoid materials failure. It will also help in quality enhancement of finished output.

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Chapter

Practicing Hypothesis Tests in Textile Engineering: Spinning Mill Exercise

Nefise Gönül Şengöz

Abstract

A novel statistical approach for multiple-stream processes is proposed in this manuscript. As important as quality control in manufacturing is, hypothesis tests are an important part of it if utilized and constructed the most logically to evaluate and decide on a special matter in a production line or a production machine. The proposed statistical approach is explained in detail in a spinning mill having 20 spinning frames. The spinning frames are adjusted according to customers' orders and to the technology of spinning frames first. Then, the result of that adjustment is controlled statistically by means of hypothesis testing, χ^2, t-test, and F statistics are used. Later, they are pooled one by one, and at the end, all 20 spinning frames are considered as one machine producing the same yarn, the same variance of yarn count, and the same yarn count. Performed literature review claims that control charts are appropriate for multiple-stream processes. But, the application of this proposed statistical approach guarantees that production starts with correct adjustments on machines, and control charts become more sensitive to the assignable causes. The application area of this proposed statistical approach is wide, leading to higher quality in products, a requirement that is in demand more every day.

Keywords: textile engineering, hypothesis tests, spinning mill, spinning frame, chi-square statistics, t-tests, F statistics, pooled estimator of sigma, pooled estimate of standard deviation, pooled estimator of variance, pooled t-Test, distribution, multiple-stream processes

1. Introduction

Quality is demanded by every customer in the products they purchase in this era of science and technology, claiming for better products and services alike. This demand produces pressure on the manufacturers to conform to customers' wishes by offering products and/or services incorporating increased quality levels, applying quality control methods, practicing statistical quality control, etc. Manufacturers intensely control and improve the quality of their products in order to make them better while also aiming at establishing a competitive edge.

Textiles are regarded as fundamental items in everyday life. They are indeed used in every field of daily life like apparel, home textiles, technical textiles (automotive, aerospace, geological, agriculture, civil, medical, sport, packaging, protective, military, art, etc.). Similar to every engineering branch, quality is the main requirement in textile engineering. The only way to achieve this is the application of quality control tools which are mostly applied in every step of textile production in order to fulfill the demands of consumers.

The main steps in textile manufacturing are yarn production, weaving, knitting, and ready-wear; besides nonwovens, texturing, finishing, dyeing, printing, etc. Yarn production is the primary step among these because if a good yarn is produced at the beginning the rest of the steps will probably end up likewise good. Good yarn provides the properties required for the next step, and for any succeeding step thereafter until the end product is reached, namely the one used in daily life. In a reverse pattern, first, the usage area of that special textile product to be manufactured has to be decided on as well as determining the requirements of properties in that special unit. Then one step backwards, weaving or knitting-specific quality properties are determined, followed by the properties of yarn to meet the properties of fabric. Finally, the latter are determined together with the fibers to be used and thus, production starts. It is very important to keep the quality properties of yarn correct and stable in order for the rest of the steps to be good. This is why quality control tools have to be applied in yarn production. Besides, technology in machinery is another grand field where huge improvements are achieved so as to manufacture products with the aimed properties. Textile machinery is an area where many technological improvements are successfully applied, yielding production of yarn with better properties.

Textile manufacturing is a multiple-stream process where one operation is usually done by more than one machine. The product of every machine is mixed into one lot. In literature, it is stated that in processes consisting of several machines producing the same material which pool their output into a common stream, control charts are appropriate to use in order to keep quality under control. In this case, machines producing the same material form a rational subgroup. Separate control charts are advised for each rational subgroup, each individual machine, or sometimes even for the different heads on the same machine. Therefore, the proper selection of samples is very important within the rational subgroup concept; the process is to be consistent and careful by extracting as much useful information as possible from the evaluation of the control charts. Even more, simultaneous monitoring of all streams is impractical when the streams are large in number, identical, and independent. Also, control charts are sensitive to assignable causes that affect the uniformity across the streams and between-stream variability [1–7].

The main concept of control charts is: Sampling the material of which the property/properties to be investigated, testing the property/properties, obtaining the results, plotting the values on the control charts, and interpreting the charts. Production is under control while the plot falls between the upper and lower control limits. If not, then the precautions needed are taken and adjustments to the machines are done. Not only one machine produces the same product but there may be more than one machine producing the same material which will be mixed and shipped into one lot, and every machine producing the same material will have to do so. The customer does not need to know which machine produced which constitutes the lot; it is the responsibility of the factory to ship a lot containing the same properties in every piece [8].

In this manuscript, it is worth noting at this point that before constructing the control charts for rational subgroups, the adjustments on the subgroups have to be

controlled statistically first. The subgroups are machines in this case. Control charts may keep the control limits after the correct adjustments on the machines are successfully done. It is thought that controlling the adjustments of the machines to produce the right material is different than keeping it under control with control charts. If the adjustments of the machines are correct at the beginning, then the purpose of the control charts will only be sensitive to assignable causes. Otherwise, it may be as if it is expected too much from the control charts; however, in this proposed novel statistical approach the purposes are separated and may help to understand processes better and keep quality under control. When quality will be set at the beginning and tested statistically then control charts will help to carry it forward in a stable manner. In this study, a different approach will be presented which is applying hypothesis tests to the adjustment of the multiple-stream machines prior to them starting production. A novel method for this kind of statistical control is proposed and explained in detail based on an example of a textile engineering spinning mill.

Hypothesis testing is a process of drawing conclusions on the collected data of statistical testing and is a specific approach for testing means or averages of that data. The purpose of statistical inference is to draw conclusions about a population on the basis of data obtained from a sample of that population. Hypothesis testing evaluates the strength of evidence from the sample and gives the basis to determine the relation to the population. Hypothesis testing equally indicates the chance about how reliably the observed results in a sample can be extrapolated to the larger population of collected samples. A specific hypothesis is formulated, the data from the sample is evaluated and if they support the specific hypothesis a statistical inference about the population is reached. Hypothesis testing is a dominant approach for data analysis in many fields of science [9].

In literature, it is discussed that there is a close connection between hypothesis testing and control charts. It is considered that if the obtained value of $\overline{x}$ is plotted and values fall in-between the control limits then it is expressed that the process mean is in control, and it is equal to a value μ_0. If $\overline{x}$ falls out of the upper or the lower control limits then it will have a value other than μ_0, it is concluded that the control chart is a kind of hypothesis testing and shows that the process is under statistical control. If the plots are in-between the control limits, this means the hypothesis is not rejected; if they are out of the control limits, this means the hypothesis is rejected [10].

On the other hand, there are some differences between hypothesis tests and control charts. The validity of assumptions, like the form of the distribution, independence, etc., are tested in hypothesis testing but not in control charts. Instead, the departures from $\overline{x}$ are seen in control charts so that the process variability may be reduced. There may be assignable causes in production and they result in different types of shifts in the process parameters. An assignable cause can result in an increase or a decrease to a new value but return quickly. It can have ups and downs in-between the control limits, and can shift to a new value but remain there; this is called a sustained shift. It is recognized in literature that only the sustained shift fits the statistical hypothesis testing model.

This chapter suggests that adjustment of the machines in a multiple-stream should be done with hypothesis testing at the beginning and then continuing production should be observed with control charts so that the quality will be under control at the beginning and will be kept stable during production. This proposed method will be done just at the beginning of production for once in order to confirm that the adjustments to produce the same lot are the same all throughout the lot, as well as considering that every centimeter of yarn will exactly be the same in the tons of guaranteed

yarn production. Then, while the production continues the control charts will monitor that quality is kept stable. This novel approach of a statistical control method will be explained in detail given in an example of a textile engineering spinning mill. In this case, the type of the yarn, the properties of the yarn, the type of fibers used to produce the yarn will not be considered except for yarn count. Yarn count property will be mentioned in the proposed hypothesis testing method. One may bear in mind that the same application can be done for every property of yarn like twist, breaking strength, breaking elongation, elasticity, abrasion resistance, hairiness, unevenness, imperfection (thick place, thin place, neps), etc.

2. Spinning mill

When yarn production is considered, regardless of the type of fiber processed, yarn production generally consists of blowroom/blending, carding, drawing, roving, and spinning steps seen in **Figure 1**, whereas an example of a spinning mill is given in **Figure 2** [11]. The same concept mentioned above is applied in yarn production. In order to produce the yarn with the aimed properties at the end, the needed adjustments have to be done starting from the very beginning of the stream until the endpoint where the yarn is obtained. In every production step there is usually more than one machine producing the same product and pouring into a common stream.

Yarn is produced on spinning frames that are ring spinning machines. Rovings come from the top to the spindles, on the way they are drafted and twisted, and the yarn forms (**Figure 3**) [12, 13]. The yarn properties, which are yarn count and yarn twist, are adjusted on the frame, but the rest of the properties listed above are the result of

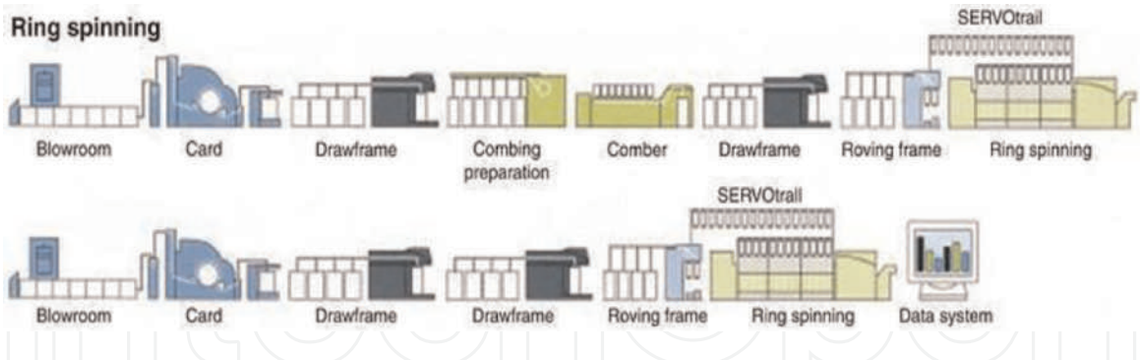

Figure 1.
Yarn production steps [11].

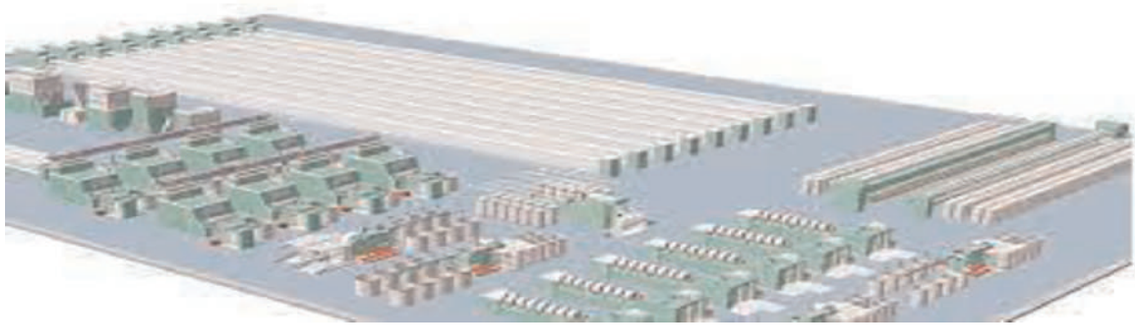

Figure 2.
An example of a spinning mill [11].

Figure 3.
Rovings, spindles, yarn [12, 13].

pressure between rollers, machine production speed, roller surfaces, delivery angles, climate, cleanness, human factor, gauge, etc. Since the yarn count is one of the adjustments done on the spinning frame, this will be considered in the rest of this chapter.

3. Reference statistical methodology in quality control

Hypothesis testing is one of the useful tools of statistical methodology in quality control and improvement. In hypothesis testing, there are the null hypothesis (H_0) and the alternative hypothesis (H_1). While the null hypothesis H_0 indicates a certain point of view of the research question, the alternative hypothesis H_1 indicates the opposite of that point of view. The opposite can be stated as not equal, greater than, or less than. Not equal is a two-sided alternative hypothesis, and the latter two are one-sided alternative hypotheses. Therefore, the determination of the parameter values in a hypothesis to be tested is very important, as they may either come from past information, a theory or model, or conformity. A statistical inference is reached with correct determination.

When working with test results, it is assumed that the obtained test results are normally distributed. If the underlying distribution of the obtained results deviate

moderately from normal distribution, t-tests perform reasonably well because of the robustness of the test. If the underlying distribution of the obtained results deviates substantially from normal distribution, when the sample size is large, because of the central limit theorem (CLT), they approximate normal distribution [14]. Especially in textile manufacturing, it is considered that the test results of properties of a product exhibit normal distribution.

In statistical inference, there may be errors, especially in hypothesis testing, wherein two kinds of errors exist. The first one is the null hypothesis is rejected even if it is true, which is the wrong decision. This is Type I Error and is symbolized by α which is also called the level of significance. In this case, the null hypothesis is unable to be rejected by $1-\alpha$ probability, or which is the right decision. The second kind of error is the null hypothesis is unable to be rejected even if it is false, which is the wrong decision. This is Type II Error and is symbolized by β. In this case, the null hypothesis is rejected by $1-\beta$ probability, or which is the right decision. Hypothesis testing errors are shown in **Table 1**. The level of significance α would take values like 0.1, 0.05, 0.01, 0.001, etc.

By designing a test procedure in hypothesis testing, a value of the probability of Type I Error α is specified so that a small value of the probability of Type II Error β is obtained. The α risk can directly be controlled or chosen; the β risk can indirectly be controlled because it is the function of sample size; consequently, the larger the sample size, the smaller it is. In textiles production, Type I Error α is sufficient. The nature of textiles production for daily usage like apparel, home textiles (rugs, curtains, bedsheets, carpets, towels, etc.), Type I Error α is satisfactory, there is no requirement for Type II Error β in such cases. The important thing is to produce yarn, fabric, ready-wear, etc. with level of significance $\alpha = 0.05$, which is usually used and is deemed enough. On the other hand, Type II Error β is strongly reasonable for technical textiles like medical, aerotextiles, geotextiles, etc.; even there are cases where 6σ is applied (such as in vivo medical textiles, aerotextiles). These special cases will not be studied in this manuscript; for the rest, only Type I Error α will be considered.

A hypothesis test can be conducted by different test statistics like the z test, t-test, χ^2 test, the appropriate one is selected in accordance with the purpose of the hypothesis test. The set of values of the test statistic which lead to the rejection of H_0 is named as the critical region or rejection region for the test.

Therefore, the procedures for a hypothesis test can be listed as:

1. To determine the null hypothesis (H_0) and the alternative hypothesis (H_1),

2. To determine the level of significance (α),

3. To determine the appropriate test statistic,

4. To determine the test statistic limit(s) leading to rejection of the null hypothesis (critical region or rejection region),

5. To calculate,

6. To conclude if the null hypothesis is rejected or it is unable to be rejected,

7. To write the conclusion sentence.

	H_0	
Decision	**True**	**False**
H_0 Unable to reject	Right decision $1-\alpha$	Wrong decision Type II Error β
H_0 Reject	Wrong decision Type I Error α	Right decision $1-\beta$

Table 1.
Hypothesis testing errors.

Sampling is very important in hypothesis testing because an inference will be reached through the parameter information the samples contain and that conclusion will be applied to all of the rest of the population.

In a hypothesis testing, if x is a random variable with unknown mean μ and known variance σ^2, then the hypothesis testing is that the mean is equal to a chosen value, μ_0. The null hypothesis (H_0) and the alternative hypothesis (H_1) are stated as:

$$\begin{aligned} H_0 &: \mu = \mu_0 \\ H_1 &: \mu \neq \mu_0 \end{aligned} \tag{1}$$

Level of significance α is determined. n samples are taken from the random variable x and the z statistic is calculated:

$$Z_0 = \frac{\overline{x} - \mu_0}{\sigma/\sqrt{n}} \tag{2}$$

If $|Z_0| \succ Z_{\alpha/2}$ then H_0 is rejected, $Z_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the standard normal distribution at a fixed significance level two-sided.

If x is a random variable with unknown mean μ and unknown variance σ^2, then the hypothesis testing is that the mean is equal to a chosen value, μ_0. The hypothesis is stated as:

$$\begin{aligned} H_0 &: \mu = \mu_0 \\ H_1 &: \mu \neq \mu_0 \end{aligned} \tag{3}$$

Since the variance is unknown, it is assumed that the x random variable has a normal distribution and deviations from normality will not affect the results much. Also, σ^2 is unknown and it is estimated by s^2. The level of significance α is determined. n samples are taken from the random variable x and the test statistic becomes a t-test:

$$t_0 = \frac{\overline{x} - \mu_0}{s/\sqrt{n}} \tag{4}$$

where instead of a normal distribution it becomes a t distribution with $n-1$ degrees of freedom.

If $|(t_0)| \succ t_{\alpha/2,n-1}$ then H_0 is rejected, $t_{\alpha/2,n-1}$ is the upper $\alpha/2$ percentage point of the t distribution with $n-1$ degrees of freedom at a fixed significance level two-sided.

Statistical tests on means are very little sensitive to normality assumptions but the tests on variances are sensitive. To test the variance of a normal distribution is equal to a chosen variance, σ_0^2, then the hypothesis is stated as:

$$H_0 : \sigma^2 = \sigma_0^2$$
$$H_1 : \sigma^2 \neq \sigma_0^2 \tag{5}$$

and the test statistic becomes a χ^2 test:

$$\chi_0^2 = \frac{(n-1)s^2}{\sigma_0^2} \tag{6}$$

where s^2 is the sample variance of n repeats. The level of significance α is determined. If $\chi_0^2 \succ \chi_{\alpha/2,n-1}^2$ or if $\chi_0^2 \prec \chi_{1-\alpha/2,n-1}^2$ then the null hypothesis H_0 is rejected for a fixed significance level, $\chi_{\alpha/2,n-1}^2$ is the upper $\alpha/2$ upper percentage point of the chi-square distribution with $n-1$ degrees of freedom and $\chi_{1-\alpha/2,n-1}^2$ is the lower $1-(\alpha/2)$ percentage. If a one-sided alternative is specified, then the hypothesis is:

$$H_0 : \sigma^2 = \sigma_0^2$$
$$H_1 : \sigma^2 \prec \sigma_0^2 \tag{7}$$

and the null hypothesis is rejected if $\chi_0^2 \prec \chi_{1-\alpha,n-1}^2$. For the other one-sided alternative, the hypothesis is:

$$H_0 : \sigma^2 = \sigma_0^2$$
$$H_1 : \sigma^2 \succ \sigma_0^2 \tag{8}$$

and the null hypothesis is rejected if $\chi_0^2 \succ \chi_{\alpha,n-1}^2$.

Chi-square testing is applied a lot in quality improvement by monitoring and control procedures. There may be a normal random variable with mean μ and variance σ^2. If $\sigma^2 \leq \sigma_0^2$, σ_0^2 being a chosen value, then the natural inherent variability of the process will be within the requirements of the design and the production will mostly be within the specification limits. But if $\sigma^2 \succ \sigma_0^2$, this means that the natural variability in the process is exceeding the specification limits. This case increases the percentage of non-conforming production items.

If there are two independent populations, as shown in **Figure 4**, then it will statistically be tested for the difference in means $\mu_1 - \mu_2$. It is assumed that μ_1, $\overline{x}_1$, σ_1^2, and n_1 are known and belonging to Population 1; whereas μ_2, $\overline{x}_2$, σ_2^2, and n_2 are known and belonging to Population 2. Both samples of the populations are random, and both populations are normally distributed; if they are not normal, the conditions of the CLT applies.

The point estimator of $\mu_1 - \mu_2$ is the difference in sample means $\overline{x}_1 - \overline{x}_2$ and from the properties of expected values:

$$E(\overline{x}_1 - \overline{x}_2) = E(\overline{x}_1) - E(\overline{x}_2) = \mu_1 - \mu_2 \tag{9}$$

is obtained and the variance of $\overline{x}_1 - \overline{x}_2$ is:

$$V(\overline{x}_1 - \overline{x}_2) = V(\overline{x}_1) + V(\overline{x}_2) = \frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2} \tag{10}$$

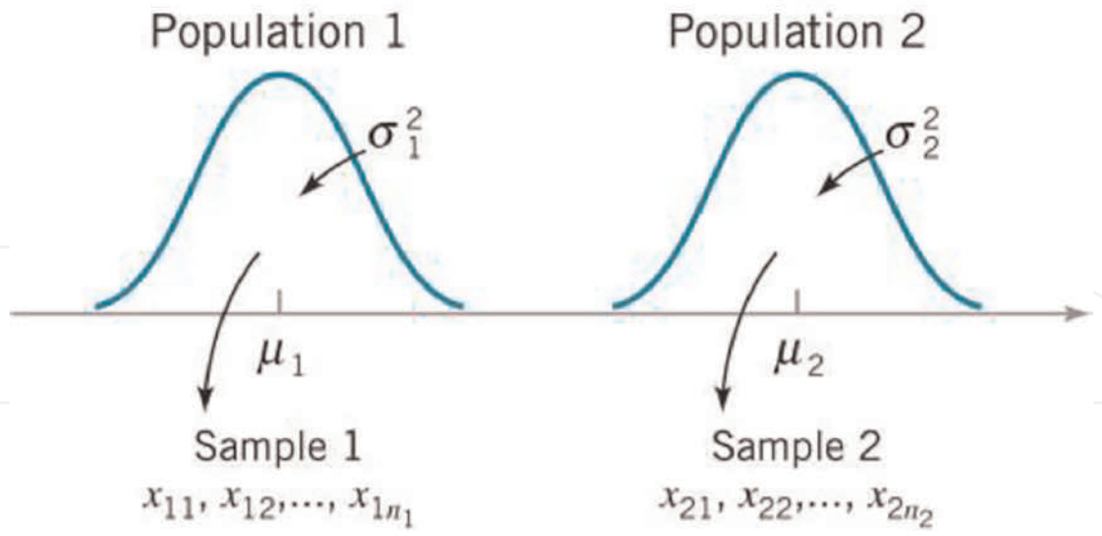

Figure 4.
Symbolization of two independent populations [1].

From the assumptions and the preceding results, the quantity Z with N(0,1) distribution can be stated as:

$$Z = \frac{\overline{x}_1 - \overline{x}_2 - (\mu_1 - \mu_2)}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{11}$$

If it is tested that the difference in means $\mu_1 - \mu_2$ is zero, that they are equal, the hypothesis is:

$$\begin{aligned} H_0 &: \mu_1 - \mu_2 = 0 \\ H_1 &: \mu_1 - \mu_2 \neq 0 \end{aligned} \tag{12}$$

Substituting 0 for $\mu_1 - \mu_2$, becomes:

$$Z_0 = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \tag{13}$$

If $|Z_0| \succ Z_{\alpha/2}$ then H_0 is rejected, $Z_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the standard normal distribution at a fixed significance level two-sided.

If there are two independent populations, then the difference in means $\mu_1 - \mu_2$ will statistically be tested. It is assumed that μ_1, $\overline{x}_1$, and n_1 are known belonging to Population 1; μ_2, $\overline{x}_2$, and n_2 are known belonging to Population 2, but σ_1^2 and σ_2^2 are unknown. Both samples of the populations are random, and both populations are normally distributed; if they are not normal, the conditions of the CLT applies. The two σ_1^2 and σ_2^2 may be equal or not. In this manuscript, the condition that they are equal will be considered, becoming $\sigma_1^2 = \sigma_2^2 = \sigma^2$. Since σ_1^2 and σ_2^2 are unknown, t-statistic will be used and sample variances of the two populations would be s_1^2, and s_2^2, respectively.

The expected value of the difference in sample means $\overline{x}_1 - \overline{x}_2$ which is an unbiased estimator of the difference in means is:

$$E(\overline{x}_1 - \overline{x}_2) = \mu_1 - \mu_2 \tag{14}$$

The variance of $\overline{x}_1 - \overline{x}_2$ is:

$$V(\overline{x}_1 - \overline{x}_2) = \frac{\sigma^2}{n_1} + \frac{\sigma^2}{n_2} = \sigma^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right) \tag{15}$$

Estimator of σ^2 is the combination of s_1^2 and s_2^2 it is the pooled estimator of σ^2, denoted by s_p^2, which is:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{16}$$

s_p^2 is the weighted average of the two sample variances s_1^2 and s_2^2.

The z test statistic for unknown σ is:

$$z = \frac{\overline{x}_1 - \overline{x}_2 - (\mu_1 - \mu_2)}{\sigma\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{17}$$

and then, for t-statistic σ is replaced by s_p.

$$t = \frac{\overline{x}_1 - \overline{x}_2 - (\mu_1 - \mu_2)}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{18}$$

a t distribution with $n_1 + n_2 - 2$ degrees of freedom, also called the pooled t-test.

If it is tested that the difference in means $\mu_1 - \mu_2$ is zero - meaning they are equal- the hypothesis is:

$$\begin{aligned} H_0 &: \mu_1 - \mu_2 = 0 \\ H_1 &: \mu_1 - \mu_2 \neq 0 \end{aligned} \tag{19}$$

Substituting 0 for $\mu_1 - \mu_2$, it becomes:

$$t_0 = \frac{\overline{x}_1 - \overline{x}_2}{s_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{20}$$

If $|t_0| \succ t_{\alpha/2, n_1+n_2-2}$ then H_0 is rejected, $t_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the t-distribution with $n_1 + n_2 - 2$ degrees of freedom at a fixed significance level two-sided.

If the variances of two independent normal distributions are tested if they are equal, σ_1^2, s_1^2 and n_1 for Population 1, and σ_2^2, s_2^2 and n_2 for Population 2, then the hypothesis is:

$$\begin{aligned} H_0 &: \sigma_1^2 = \sigma_2^2 \\ H_1 &: \sigma_1^2 \neq \sigma_2^2 \end{aligned} \tag{21}$$

F statistics is the ratio of the two sample variances:

$$F_0 = \frac{s_1^2}{s_2^2} \tag{22}$$

H_0 is rejected if $F_0 \succ F_{\alpha/2,n_1-1,n_2-1}$ or $F_0 \prec F_{1-(\alpha/2),n_1-1,n_2-1}$, which denote the upper $\alpha/2$ and lower $1-(\alpha/2)$ percentage points of the F distribution with degrees of freedom n_1-1 and n_2-1, respectively, at a fixed significance level two-sided.

4. Proposed statistical approach

In hypothesis testing, sampling is very important because an inference is reached from the values in the sample about the values in the population. Therefore sampling has to be done very carefully and samples should represent the population. Sampling is a wide subject in textile engineering. Regular sampling during production and acceptance sampling from a static lot are two grand different subjects. This broad topic of sampling in textile engineering can well be covered in a separate manuscript, so the details of sampling will not be dealt herein. Instead, the number of samples, which are repeats, will be indicated as n_i.

In ring spinning yarn production the number of spindles per spinning frame is the determining factor for sampling. As a general application, at least five bobbins per 500 spindles per spinning frame are taken randomly for the tests of yarn properties. Different frame brands have different spindle numbers such as 576, 1008, 1296, and 1824. depending on the model of the frame. For example, at least 10 bobbins have to be chosen randomly for 576 spindles per frame, at least 15 bobbins have to be chosen randomly for 1008 spindles per frame, at least 15 bobbins again for 1296 spindles per frame, or at least 20 bobbins for 1824 spindles per frame.

When sampling for hypothesis testing in this chapter, the yarn lot is the population, and statistical inference and decisions will be made about the yarn lot from the samples selected from it. In order to conclude that the machine is adjusted correctly or to make a decision about its status, samples are randomly selected as different bobbins from independent, identical, and with equal probability of being chosen spindles on a spinning frame which are adjusted to produce a special yarn. Test results of the samples will give information about the yarn population. **Figure 5** shows the relationship between a population and a sample. In textile engineering, it is assumed that the property values of a textile material have a normal distribution, consequently in yarn spinning, yarn properties also exhibit normal distribution for property values.

The constant of variation (CV%) is a frequently used value in textile engineering. Starting from fibers to the end product, say apparel, fiber (fineness, length, breaking strength – breaking elongation, etc.), yarn (count, twist, irregularity, etc.), fabric (warp and weft density, fabric thickness, etc.), and apparel (measurements, weight, etc.) properties are all tested and the results are statistically analyzed; and the mean x, standard deviation s, and CV% $\left(\frac{s}{x} \times 100\right)$ are calculated. The value of CV% indicates much information about the property it was calculated from. Furthermore, comparisons and evaluations are done making it possible to have a comprehensible understanding of how production is continuing. The constant of variation of yarn count can be expressed as $CV\%_{YarnCount}$. The value $CV\%_{YarnCount}$ has a close relationship with the technology of textile machinery. Technology of textile machinery developed considerably a lot when compared to the 1970s and 1980s. Textile machinery producers incorporate broad R&D departments and one of the main topics of their researches is

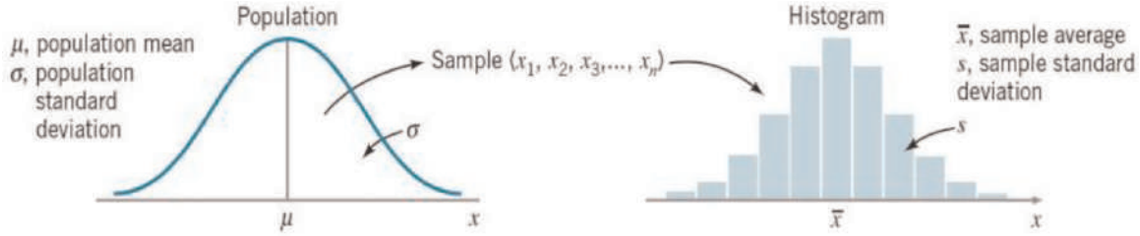

Figure 5.
Relationship between a population and a sample [1].

on $CV\%_{YarnCount}$. As a general consideration, $CV\%_{YarnCount}$ 5% was acceptable until the late 80's, whereas the $CV\%_{YarnCount}$ decreased to 3% in the mid 90's, then to 1–1.5% in the late 90s, and since 2000s this value is acceptable if it is less than 1%. In order for the $CV\%_{YarnCount}$ to be less than 1%, the variance of yarn count s has to be $\prec 1$ also. Within the context of this paper, it will be considered that the spinning frames were produced after the year 2000; therefore, the proposed statistical approach will be explained by considering s as $\prec 1$ in accordance with textile industry.

Yarn count is adjusted on the machine according to what the customer ordered. Yarn count will be indicated as μ_0 in this chapter.

The main aspect in both sampling, variation of yarn count, and yarn count is that every machine has to be adjusted to produce the yarn the customer ordered. The lot will be shipped as one and it does not make any difference for the customer which machine produced which yarn. The customer ordered the yarn lot and will regard it all the same at every single centimeter of yarn produced.

Suppose now a special yarn count of μ_0 in tex unit will be produced in twenty spinning frames in a spinning mill (**Figure 6**).

In this proposed statistical approach, the procedure starts with adjusting the Spinning Frame 1 (SF 1). The necessary adjustments to produce μ_0 tex yarn is done on the SF 1, the frame will run for a few minutes, the yarn will be produced a little bit, and n_1 bobbins from spindles are chosen as samples randomly from this normal distribution. The first thing is to test if the adjustments are correct and confront them with what the customer ordered. Since all the frames were produced after the year 2000, of the same brand, the same model, and the same technical specifications, the variance of yarn count has to be less than 1, with the latter being thus, the specified value for these hypothesis tests. In this manuscript it is argued that if the variance of yarn count is less than 1 it has to be tested before the yarn count. Then, the level of significance α is determined which is equal to 0.05 for ordinary textiles. n_1 bobbins from spindles of SF 1 are taken for yarn count tests done in the laboratory. The one-sided hypothesis is:

$$\begin{aligned} H_0 &: \sigma_1^2 = 1 \\ H_1 &: \sigma_1^2 \prec 1 \end{aligned} \tag{23}$$

and the χ^2 test statistic is:

$$\chi_1^2 = \frac{(n_1 - 1)s_1^2}{1} \tag{24}$$

s_1^2 is the sample variance of n_1 repeats from SF 1. The null hypothesis of variance of yarn count is rejected if $\chi_1^2 \prec \chi_{1-\alpha,n_1-1}^2$. If it is unable to be rejected, then the procedure

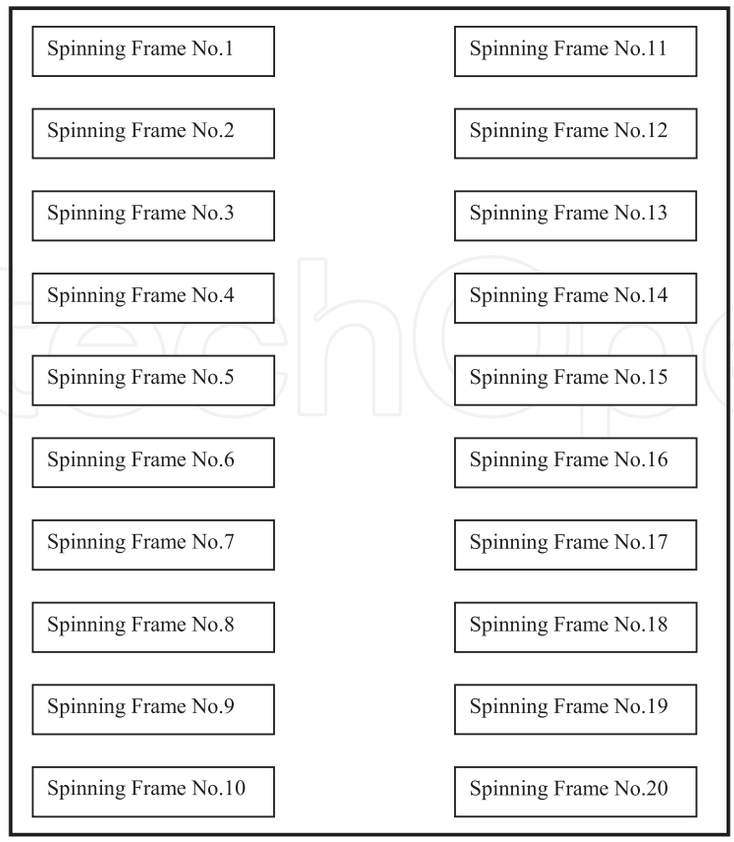

Figure 6.
Representation of spinning frames in a spinning mill.

continues by going back to the SF 1 and doing some more adjustments on the frame and repeating this test until the null hypothesis of variance of yarn count is rejected.

When it is guaranteed that the variance of yarn count is less than 1, then comes the yarn count statistics tests. The average of yarn count of SF 1 would be μ_1 and the two-sided hypothesis of yarn count is:

$$\begin{aligned} H_0 &: \mu_1 = \mu_0 \\ H_1 &: \mu_1 \neq \mu_0 \end{aligned} \tag{25}$$

Variance is estimated by s_1^2, $\overline{x}_1$ is the average of the n_1 repeats of yarn count from SF 1, the t-test statistic is:

$$t_1 = \frac{\overline{x}_1 - \mu_0}{s_1/\sqrt{n_1}} \tag{26}$$

where instead of a normal distribution it is a t distribution with $n_1 - 1$ degrees of freedom. If $|(t_1)| \succ t_{\alpha/2,n_1-1}$ then H_0 is rejected, $t_{\alpha/2,n_1-1}$ is the upper $\alpha/2$ percentage point of the t distribution with $n_1 - 1$ degrees of freedom at a fixed significance level two-sided. If the null hypothesis of yarn count is rejected, then the procedure continues by going back to the SF 1 and doing some more adjustments on the frame and repeating these tests until the null hypothesis of yarn count is unable to be rejected.

Now the SF 1 is ready to produce what the customer ordered, so the procedure will continue with the statistics to make the SF 2 to produce what the customer ordered

and also the same as SF 1. The necessary adjustments to produce μ_0 tex yarn is done on the SF 2 and n_2 bobbins from spindles of SF 2 are chosen randomly. To test if the variance of yarn count of SF 2 is less than 1, the one-sided hypothesis is:

$$\begin{aligned} H_0 &: \sigma_2^2 = 1 \\ H_1 &: \sigma_2^2 < 1 \end{aligned} \tag{27}$$

and the χ^2 test statistic is:

$$\chi_2^2 = \frac{(n_2 - 1)s_2^2}{1} \tag{28}$$

s_2^2 is the sample variance of n_2 repeats from SF 2. The null hypothesis of variance is rejected if $\chi_2^2 < \chi_{1-\alpha,n_2-1}^2$. If it is unable to be rejected, then the procedure continues by going back to the SF 2 and doing some more adjustments on the frame and repeating this test until the null hypothesis of variance of yarn count is rejected.

Both of the variances of yarn counts of SF 1 and SF 2 may be less than 1 but their equality has to be tested also. This is justified because they will all mix into one lot and it is not important from the view of point of customer which frame produced which yarn. To test their equality, the hypothesis is:

$$\begin{aligned} H_0 &: \sigma_1^2 = \sigma_2^2 \\ H_1 &: \sigma_1^2 \neq \sigma_2^2 \end{aligned} \tag{29}$$

and the F statistics is:

$$F_{(1,2)} = \frac{s_1^2}{s_2^2} \tag{30}$$

H_0 is rejected if $F_{(1,2)} > F_{\alpha/2,n_1-1,n_2-1}$ or $F_{(1,2)} < F_{1-(\alpha/2),n_1-1,n_2-1}$ which denote the upper $\alpha/2$ and lower $1-(\alpha/2)$ percentage points of the F distribution with degrees of freedom $n_1 - 1$ and $n_2 - 1$, respectively. If the null hypothesis is rejected, then the procedure continues by going back to the SF 2 and doing some more adjustments on the frame and repeating these tests until the null hypothesis of equality of variances of yarn counts is unable to be rejected.

When it is guaranteed that both the variance of yarn count is less than 1 for SF 2 and the two frames' variances are equal, then comes the yarn count statistics tests for SF 2. The average of yarn count of n_2 samples from SF 2 would be μ_2 and the two-sided hypothesis of yarn count is:

$$\begin{aligned} H_0 &: \mu_2 = \mu_0 \\ H_1 &: \mu_2 \neq \mu_0 \end{aligned} \tag{31}$$

Variance is estimated by s_2^2, $\overline{x}_2$ is the average of the n_2 repeats of yarn count from SF 2, the t-test statistic is:

$$t_2 = \frac{\overline{x}_2 - \mu_0}{s_2/\sqrt{n_2}} \tag{32}$$

where instead of a normal distribution it is a t distribution with $n_2 - 1$ degrees of freedom. If $|(t_2)| \succ t_{\alpha/2,n_2-1}$ then H_0 is rejected, $t_{\alpha/2,n_2-1}$ is the upper $\alpha/2$ percentage point of the a t distribution with $n_2 - 1$ degrees of freedom at a fixed significance level two-sided. If the null hypothesis of yarn count is rejected, then the procedure continues by going back to the SF 2 and doing some more adjustments on the frame and repeating these tests until the null hypothesis of yarn count is unable to be rejected.

Both of the yarn counts of SF 1 and SF 2 may be equal to what the customer ordered but their equality with each other has to be tested also because they will all mix into one lot and it is not important from the view of point of customer which frame produced which yarn. To test the yarn count equality of SF 1 and SF 2, even there is only one μ_0, and for ease of reference, the hypothesis is:

$$\begin{aligned} H_0 &: \mu_1 - \mu_2 = 0 \\ H_1 &: \mu_1 - \mu_2 \neq 0 \end{aligned} \tag{33}$$

and the pooled t-test statistic is:

$$t_{(1,2)} = \frac{\overline{x}_1 - \overline{x}_2}{s_{p(1,2)}\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \tag{34}$$

$$s^2_{p(1,2)} = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{35}$$

$s^2_{p(1,2)}$ is the pooled estimator of variance of SFs 1 and 2 with $(n_1 + n_2 - 2)$ degrees of freedom.

If $\left|t_{(1,2)}\right| \succ t_{\alpha/2,n_1+n_2-2}$ then H_0 is rejected, $t_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the t-distribution with $n_1 + n_2 - 2$ degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 2 and doing some more adjustments on the frame and repeating this and the above tests until the H_0 of yarn count is unable to be rejected. The operation steps can be summarized as below:

Step 1) Yarn count adjustment of SF 1.
Go to Step 1 and repeat until H_0 is unable to be rejected
Step 2) Testing the variance of yarn count of SF 1 to be less than 1.
Go to Step 1 and repeat until H_0 is unable to be rejected
Step 3) Testing the yarn count of SF 1 with μ_0.
Go to Steps 1 and 2, and repeat until H_0 is unable to be rejected
Step 4) Yarn count adjustment of SF 2.
Go to Step 4 and repeat until H_0 is unable to be rejected
Step 5) Testing the variance of yarn count of SF 2 to be less than 1.
Go to Step 4 and repeat until H_0 is unable to be rejected
Step 6) Testing the equality of variances of SF 1 and SF 2.
Go to Steps 4 and 5, and repeat until H_0 is unable to be rejected
Step 7) Testing the yarn count of SF 2 with μ_0.
Go to Steps 4, 5, and 6, and repeat until H_0 is unable to be rejected.
Step 8) Testing the equality of yarn counts of SF 1 and SF 2.
Go to Steps 4, 5, 6, and 7, and repeat until H_0 is unable to be rejected.

The same will be repeated for the rest of the spinning frames until SF 20.

Now the SFs 1 and 2 are producing the same yarn having the same yarn count and same variance of yarn count. The SFs 1 and 2 can be considered as one machine producing the same product. A representation is given in **Figure 7**.

The procedure will continue with the statistics to make the SF 3 to produce what the customer ordered and also the same as SFs 1 and 2. The necessary adjustments to produce μ_0 tex yarn is done on the SF 3 and n_3 bobbins are chosen randomly, having s_3^2 variance and $\overline{x}_3$ average yarn count. To test if the variance of yarn count of SF 3 is less than 1, the one-sided hypothesis is:

$$H_0 : \sigma_3^2 = 1$$
$$H_1 : \sigma_3^2 < 1 \tag{36}$$

and the χ^2 test statistic is:

$$\chi_3^2 = \frac{(n_3 - 1)s_3^2}{1} \tag{37}$$

s_3^2 is the sample variance of yarn count of n_3 repeats from SF 3. The null hypothesis of variance of yarn count is rejected if $\chi_3^2 < \chi_{1-\alpha,n_3-1}^2$. If it is unable to be rejected, then the procedure continues by going back to the SF 3 and doing some more adjustments on the frame and repeating this test until the H_0 of variance of yarn count is rejected.

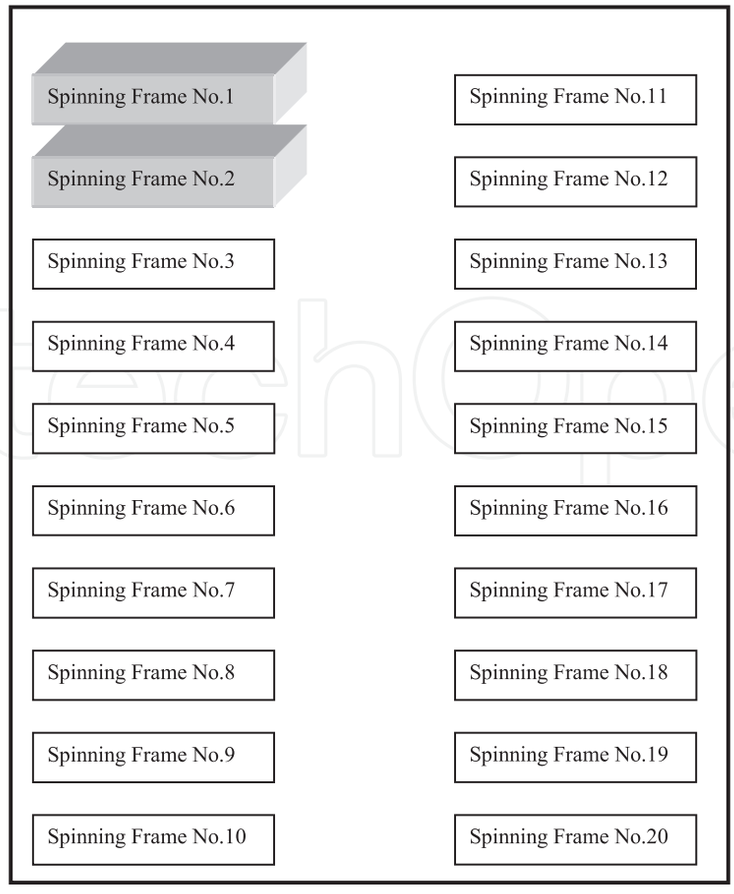

Figure 7.
Representation of SFs 1 and .2 producing the same yarn.

Both of the variances of yarn count of (SFs 1 and 2) and SF 3 may be less than 1 but their equality has to be tested also because they will all mix into one lot. To test their equality, the hypothesis is:

$$\begin{aligned} H_0 &: \sigma^2_{(1,2)} = \sigma^2_3 \\ H_1 &: \sigma^2_{(1,2)} \neq \sigma^2_3 \end{aligned} \tag{38}$$

and the F statistics is:

$$F_{(1-3)} = \frac{s^2_{p(1,2)}}{s^2_3} \tag{39}$$

H_0 is rejected if $F_{(1-3)} \succ F_{\alpha/2,n_1+n_2-2,n_3-1}$ or $F_{(1-3)} \prec F_{1-(\alpha/2),n_1+n_2-2,n_3-1}$, which denote the upper $\alpha/2$ and lower $1-(\alpha/2)$ percentage points of the F distribution with degrees of freedom n_1+n_2-2 and n_3-1, respectively. If the H_0 of variance of yarn count is rejected, then the procedure continues by going back to the SF 3 and doing some more adjustments on the frame and repeating these tests until the H_0 of variance of yarn count is unable to be rejected.

When it is guaranteed that both the variance of yarn count is less than 1 for SF 3 and it is equal with the first two frames' pooled variance of yarn count, then come the yarn count statistics tests for SF 3. The average of yarn count of SF 3 would be μ_3 and the two-sided hypothesis:

$$\begin{aligned} H_0 &: \mu_3 = \mu_0 \\ H_1 &: \mu_3 \neq \mu_0 \end{aligned} \tag{40}$$

Variance is estimated by s^2_3, $\overline{x}_3$ is the average of the n_3 repeats of yarn count from SF 3, the t-test statistic is:

$$t_3 = \frac{\overline{x}_3 - \mu_0}{s_3/\sqrt{n_3}} \tag{41}$$

where instead of a normal distribution it is a t distribution with n_3-1 degrees of freedom. If $|(t_3)| \succ t_{\alpha/2,n_3-1}$ then H_0 is rejected, $t_{\alpha/2,n_3-1}$ is the upper $\alpha/2$ percentage point of the a t distribution with n_3-1 degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 3 and doing some more adjustments on the frame and repeating these tests until the H_0 of yarn count is unable to be rejected.

Both of the yarn counts of (SFs 1 and 2) and SF 3 may be equal to what the customer ordered but their equality with each other also has to be tested because they will all mix into one lot. To test the yarn count equality of (SFs 1 and 2) and SF 3, there is only one μ_0, and for ease of reference, the hypothesis is:

$$\begin{aligned} H_0 &: \mu_{(1,2)} - \mu_3 = 0 \\ H_1 &: \mu_{(1,2)} - \mu_3 \neq 0 \end{aligned} \tag{42}$$

and the pooled t-test statistic is:

The average of yarn counts of SF 1 and SF 2 is:

$$\frac{\overline{x}_1 + \overline{x}_2}{2} = \overline{x}_{(1,2)} \tag{43}$$

then,

$$t_{(1-3)} = \frac{\overline{x}_{(1,2)} - \overline{x}_3}{s_{p(1-3)}\sqrt{\frac{1}{n_1+n_2-2} + \frac{1}{n_3}}} \tag{44}$$

$$s^2_{p(1-3)} = \frac{(n_1+n_2-2)s^2_{p(1,2)} + (n_3-1)s^2_3}{n_1+n_2+n_3-3} \tag{45}$$

$s^2_{p(1-3)}$ is the pooled estimator of variance of SFs 1−3 with (n_1+n_2-3) degrees of freedom.

If $|t_{(1-3)}| \succ t_{\alpha/2,n_1+n_2+n_3-3}$ then H_0 is rejected, $t_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the t-distribution with $n_1+n_2+n_3-3$ degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 3 and doing some more adjustments on the frame and repeating this and the above tests until the H_0 of yarn count is unable to be rejected. The operation steps can be summarized as below:

Step 1) Yarn count adjustment of SF 1.
Go to Step 1 and repeat until H_0 is unable to be rejected
Step 2) Testing the variance of yarn count of SF 1 to be less than 1.
Go to Step 1 and repeat until H_0 is unable to be rejected
Step 3) Testing the yarn count of SF 1 with μ_0.
Go to Steps 1 and 2, and repeat until H_0 is unable to be rejected
Step 4) Yarn count adjustment of SF 2.
Go to Step 4 and repeat until H_0 is unable to be rejected
Step 5) Testing the variance of yarn count of SF 2 to be less than 1.
Go to Step 4 and repeat until H_0 is unable to be rejected
Step 6) Testing the equality of variances of SF 1 and SF 2.
Go to Steps 4 and 5, and repeat until H_0 is unable to be rejected
Step 7) Testing the yarn count of SF 2 with μ_0.
Go to Steps 4, 5, and 6, and repeat until H_0 is unable to be rejected
Step 8) Testing the equality of yarn counts of SF 1 and SF 2.
Go to Steps 4, 5, 6, and 7, and repeat until H_0 is unable to be rejected.
Step 9) Yarn count adjustment of SF 3.
Go to Step 9 and repeat until H_0 is unable to be rejected
Step 10) Testing the variance of yarn count of SF 3 to be less than 1.
Go to Step 9 and repeat until H_0 is unable to be rejected
Step 11) Testing the equality of variances of (SFs 1 and 2) and SF 3.
Go to Steps 9 and 10, and repeat until H_0 is unable to be rejected
Step 12) Testing the yarn count of SF 3 with μ_0.
Go to Steps 9, 10, and 11, and repeat until H_0 is unable to be rejected
Step 13) Testing the equality of yarn counts of (SFs 1 and 2) and SF 3.
Go to Steps 9, 10, 11, and 12, and repeat until H_0 is unable to be rejected

The same will be done in a repeating pattern for the rest of the spinning frames until SF 20.

Now the SFs 1−3 are producing the same yarn having the same yarn count and the same variance of yarn count. The SFs 1−3 can be considered as one machine producing the same product. A representation is given in **Figure 8**.

The procedure will continue with the statistics to make the SF 4 to produce what the customer ordered and also the same as (SFs 1−3). The necessary adjustments to

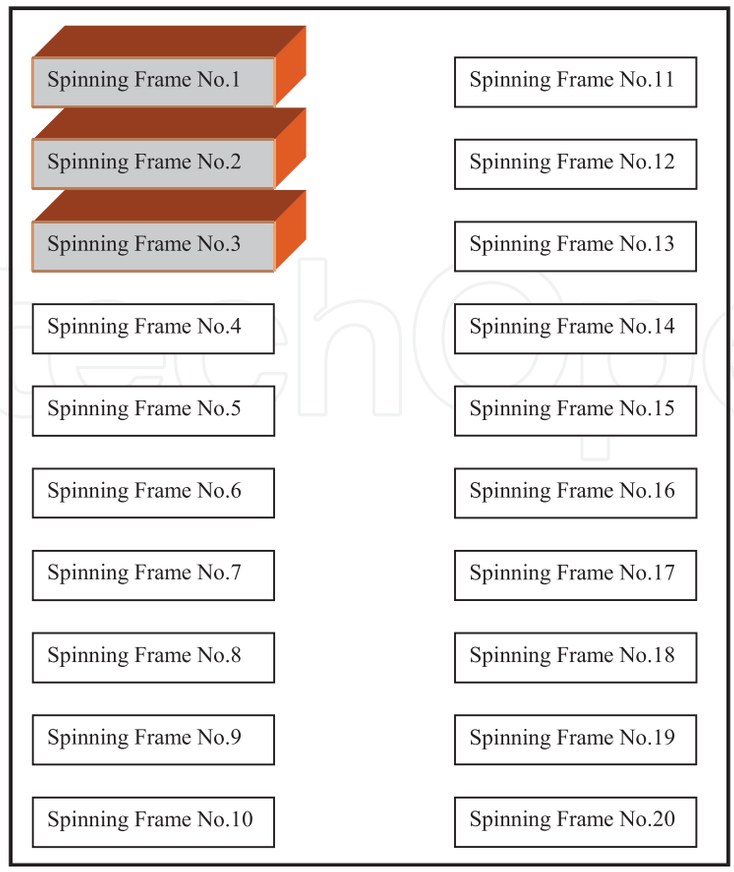

Figure 8.
Representation of SFs 1–3 producing the same yarn.

produce μ_0 tex yarn is done on the SF 4 and n_4 bobbins from spindles are chosen randomly, having s_4^2 variance of yarn count and $\overline{x}_4$ average yarn count. To test if the variance of yarn count of SF 4 is less than 1, the one-sided hypothesis is:

$$\begin{aligned} H_0 &: \sigma_4^2 = 1 \\ H_1 &: \sigma_4^2 < 1 \end{aligned} \tag{46}$$

and the χ^2 test statistic is:

$$\chi_4^2 = \frac{(n_4 - 1)s_4^2}{1} \tag{47}$$

The H_0 of variance of yarn count is rejected if $\chi_4^2 < \chi_{1-\alpha,n_4-1}^2$. If it is unable to be rejected, then the procedure continues by going back to the SF 4 and doing some more adjustments on the frame and repeating this test until the H_0 of variance of yarn count is rejected.

Both of the variances of yarn count of (SFs 1–3) and SF 4 may be less than 1 but their equality has to be tested also because they will all mix into one lot. To test their equality, the hypothesis is:

$$\begin{aligned} H_0 &: \sigma_{(1-3)}^2 = \sigma_4^2 \\ H_1 &: \sigma_{(1-3)}^2 \neq \sigma_4^2 \end{aligned} \tag{48}$$

and the F statistics is:

$$F_{(1-4)} = \frac{s^2_{p(1-3)}}{s^2_4} \tag{49}$$

H_0 is rejected if $F_{(1-4)} \succ F_{\alpha/2,n_1+n_2+n_3-3,n_4-1}$ or $F_{(1-4)} \prec F_{1-(\alpha/2),n_1+n_2+n_3-3,n_4-1}$, which denote the upper $\alpha/2$ and lower $1-(\alpha/2)$ percentage points of the F distribution with degrees of freedom $n_1+n_2+n_3-3$ and n_4-1, respectively. If the H_0 is rejected, then the procedure continues by going back to the SF 4 and doing some more adjustments on the frame and repeating these tests until the H_0 is unable to be rejected.

When it is guaranteed that both the variance of yarn count is less than 1 for SF 4 and it is equal to the first three frames' pooled variance of yarn count, then come the yarn count statistics tests. The average of yarn count of SF 4 would be μ_4 and the two-sided hypothesis is:

$$\begin{aligned} H_0 &: \mu_4 = \mu_0 \\ H_1 &: \mu_4 \neq \mu_0 \end{aligned} \tag{50}$$

Variance is estimated by s^2_4, $\overline{x}_4$ is the average of the n_4 repeats of yarn count from SF 4, the t-test statistic is:

$$t_4 = \frac{\overline{x}_4 - \mu_0}{s_4/\sqrt{n_4}} \tag{51}$$

where instead of a normal distribution it is a t distribution with n_4-1 degrees of freedom. If $|(t_4)| \succ t_{\alpha/2,n_4-1}$ then H_0 is rejected, $t_{\alpha/2,n_4-1}$ is the upper $\alpha/2$ percentage point of the t distribution with n_4-1 degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 4 and doing some more adjustments on the frame and repeating these tests until the H_0 of yarn count is unable to be rejected.

Both of the yarn counts of (SFs 1–3) and SF 4 may be equal to what the customer ordered but their equality with each other has to be tested also because they will all mix into one lot. To test the yarn count equality of (SFs 1–3) and SF 4, there is only one μ_0, the hypothesis is:

$$\begin{aligned} H_0 &: \mu_{(1-3)} - \mu_4 = 0 \\ H_1 &: \mu_{(1-3)} - \mu_4 \neq 0 \end{aligned} \tag{52}$$

and the pooled t-test statistic is:
The average of yarn counts of (SFs 1 and 2) and SF 3 is:

$$\frac{\overline{x}_{(1,2)} + \overline{x}_3}{2} = \overline{x}_{(1-3)} \tag{53}$$

then,

$$t_{(1-4)} = \frac{\overline{x}_{(1-3)} - \overline{x}_4}{s_{p(1-4)}\sqrt{\frac{1}{n_1+n_2+n_3-3} + \frac{1}{n_4}}} \tag{54}$$

$$s^2_{p(1-4)} = \frac{(n_1+n_2+n_3-3)s^2_{p(1-3)} + (n_4-1)s^2_4}{n_1 + \ldots + n_4 - 4} \tag{55}$$

$s^2_{p(1-4)}$ is the pooled estimator of variance of SFs 1–4 with (n_1+n_2-4) degrees of freedom.

If $|t_{(1-4)}| > t_{\alpha/2,n_1+\ldots+n_4-4}$ then H_0 is rejected, $t_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the t-distribution with $n_1 + \ldots + n_4 - 4$ degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 4 and doing some more adjustments on the frame and repeating this and the above tests until the H_0 of yarn count is unable to be rejected. The operation steps can be summarized as below:

(Continued)

Step 14) Yarn count adjustment of SF 4.
Go to Step 14 and repeat until H_0 is unable to be rejected

Step 15) Testing the variance of yarn count of SF 3 to be less than 1.
Go to Step 14 and repeat until H_0 is unable to be rejected

Step 16) Testing the equality of variances of (SFs 1−3) and SF 4.
Go to Steps 14 and 15, and repeat until H_0 is unable to be rejected

Step 17) Testing the yarn count of SF 3 with μ_0.
Go to Steps 14, 15, and 16, and repeat until H_0 is unable to be rejected

Step 18) Testing the equality of yarn counts of (SFs 1−3) and SF 4.
Go to Steps 14, 15, 16, and 17, and repeat until H_0 is unable to be rejected

The same will be repeated for the rest of the spinning frames until SF 20.

Now the SFs 1-4 are producing the same yarn having the same yarn count and same variance of yarn count. The SFs 1−4 can be considered as one machine producing the same product. A representation is given in **Figure 9**.

Suppose the same procedure is repeated for SFs 5, 6, and 7, and now the procedure will continue with the statistics to make the SF 8 to produce what the customer

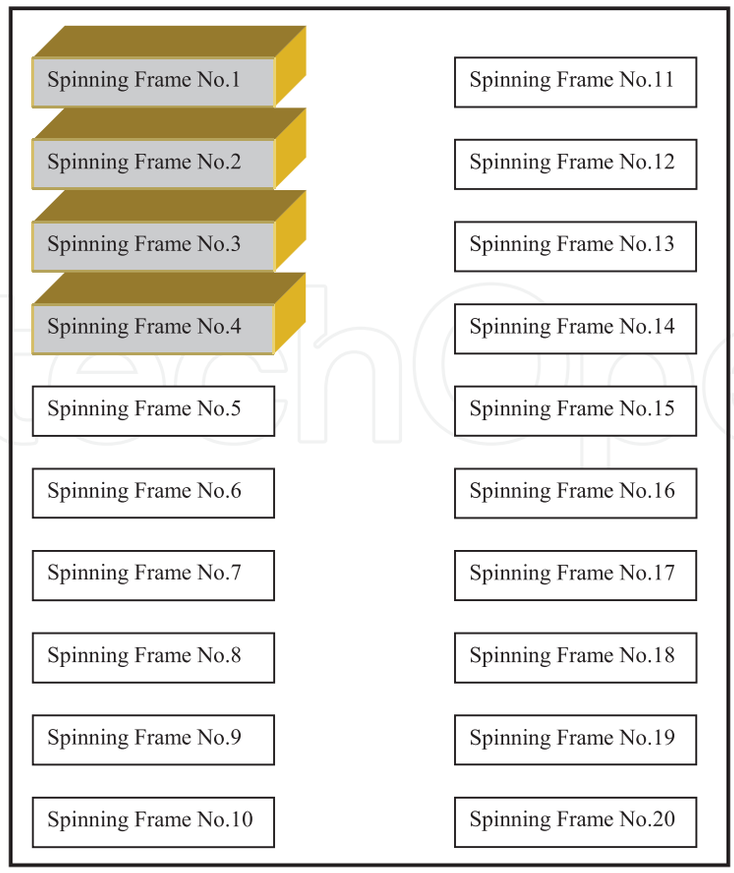

Figure 9.
Representation of SFs 1−4 producing the same yarn.

ordered and also the same as (SFs 1–7). The necessary adjustments to produce μ_0 tex yarn is done on the SF 8 and n_8 bobbins from spindles are taken randomly, having s_8^2 variance of yarn count and $\overline{x}_8$ average yarn count. To test if the variance of yarn count of SF 8 is less than 1, the one-sided hypothesis is:

$$\begin{aligned} H_0 &: \sigma_8^2 = 1 \\ H_1 &: \sigma_8^2 \prec 1 \end{aligned} \tag{56}$$

and the χ^2 test statistic is:

$$\chi_8^2 = \frac{(n_8 - 1)s_8^2}{1} \tag{57}$$

s_8^2 is the variance of yarn count of n_8 repeats from SF 8. The H_0 of variance of yarn count is rejected if $\chi_8^2 \prec \chi_{1-\alpha,n_8-1}^2$. If it is unable to be rejected, then the procedure continues by going back to the SF 8 and doing some more adjustments on the frame and repeating this test until the H_0 of variance of yarn count is rejected.

Both of the variances of yarn count of (SFs 1–7) and SF 8 may be less than 1 but their equality has to be tested also because they will all mix into one lot. To test their equality, the hypothesis is:

$$\begin{aligned} H_0 &: \sigma_{(1-7)}^2 = \sigma_8^2 \\ H_1 &: \sigma_{(1-7)}^2 \neq \sigma_8^2 \end{aligned} \tag{58}$$

and the F statistics is:

$$F_{(1-8)} = \frac{s_{p(1-7)}^2}{s_8^2} \tag{59}$$

H_0 is rejected if $F_{(1-8)} \succ F_{\alpha/2,n_1+\ldots+n_7-7,n_8-1}$ or $F_{(1-8)} \prec F_{1-(\alpha/2),n_1+\ldots+n_7-7,n_8-1}$ which denote the upper $\alpha/2$ and lower $1-(\alpha/2)$ percentage points of the F distribution with degrees of freedom $n_1 + \ldots + n_7 - 7$ and $n_8 - 1$, respectively. If the H_0 of variance of yarn count is rejected, then the procedure continues by going back to the SF 8 and doing some more adjustments on the frame and repeating these tests until the H_0 of variance of yarn count is unable to be rejected.

When it is guaranteed that both the variance of yarn count is less than 1 for SF 8 and it is equal to the first seven frames' pooled variance, then come the yarn count statistics tests for SF 8. The average of yarn count of SF 8 would be μ_8 and the two-sided hypothesis is:

$$\begin{aligned} H_0 &: \mu_8 = \mu_0 \\ H_1 &: \mu_8 \neq \mu_0 \end{aligned} \tag{60}$$

Variance is estimated by s_8^2, $\overline{x}_8$ is the average of the n_8 repeats of yarn count from SF 8, the t-test statistic is:

$$t_8 = \frac{\overline{x}_8 - \mu_0}{s_8/\sqrt{n_8}} \tag{61}$$

where instead of a normal distribution it is a t distribution with $n_8 - 1$ degrees of freedom. If $|(t_8)| \succ t_{\alpha/2,n_8-1}$ then H_0 is rejected, $t_{\alpha/2,n_8-1}$ is the upper $\alpha/2$ percentage point of the a t distribution with $n_8 - 1$ degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 8 and doing some more adjustments on the frame and repeating these tests until the H_0 of yarn count is unable to be rejected.

Both of the yarn counts of (SFs 1–7) and SF 8 may be equal to what the customer ordered but their equality with each other also has to be tested because they will all mix into one lot. To test the yarn count equality of (SFs 1–7) and SF 8, there is only one μ_0, the hypothesis is:

$$\begin{aligned} H_0 &: \mu_{(1-7)} - \mu_8 = 0 \\ H_1 &: \mu_{(1-7)} - \mu_8 \neq 0 \end{aligned} \tag{62}$$

and the pooled t-test statistic is:
The average of yarn counts of (SFs 1–6) and SF 7 is:

$$\frac{\overline{x}_{(1-6)} + \overline{x}_7}{2} = \overline{x}_{(1-7)} \tag{63}$$

then,

$$t_{(1-8)} = \frac{\overline{x}_{(1-7)} - \overline{x}_8}{s_{p(1-8)}\sqrt{\frac{1}{n_1+\ldots+n_7-7} + \frac{1}{n_8}}} \tag{64}$$

$$s^2_{p(1-8)} = \frac{(n_1 + \ldots + n_7 - 7)s^2_{p(1-7)} + (n_8 - 1)s^2_8}{n_1 + \ldots + n_8 - 8} \tag{65}$$

$s^2_{p(1-8)}$ is the pooled estimator of variance of SFs 1–8 with $(n_1 + n_2 - 8)$ degrees of freedom.

If $\left|t_{(1-8)}\right| \succ t_{\alpha/2,n_1+\ldots+n_8-8}$ then H_0 is rejected, $t_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the t-distribution with $n_1 + \ldots + n_8 - 8$ degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 8 and doing some more adjustments on the frame and repeating this and the above tests until H_0 of yarn count is unable to be rejected. The operation steps can be summarized as below:

(Continued)

Step 34) Yarn count adjustment of SF 8.
Go to Step 34 and repeat until H_0 is unable to be rejected

Step 35) Testing the variance of yarn count of SF 8 to be less than 1.
Go to Step 34 and repeat until H_0 is unable to be rejected

Step 36) Testing the equality of variances of (SFs 1–7) and SF 8.
Go to Steps 34 and 35, and repeat until H_0 is unable to be rejected

Step 37) Testing the yarn count of SF 8 with μ_0.
Go to Steps 34, 35, and 36, and repeat until H_0 is unable to be rejected

Step 38) Testing the equality of yarn counts of (SFs 1–7) and SF 8.
Go to Steps 34, 35, 36, and 37, and repeat until H_0 is unable to be rejected

The same will be done in a repeating manner for the rest of the spinning frames until SF 20.

Now the SFs 1–8 are producing the same yarn having the same yarn count and same variance of yarn count. The SFs (1–8) can be considered as a one machine producing the same product. A representation is given in **Figure 10**.

Suppose the same procedure is repeated for SFs 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19, and now the last spinning frame is the 20th one, the procedure will continue with the statistics to make the SF 20 to produce what the customer ordered and also the same as (SFs 1–19). The necessary adjustments to produce μ_0 tex yarn is done on the SF 20 and n_{20} bobbins from spindles are chosen randomly, having s_{20}^2 variance of yarn count and $\overline{x}_{20}$ average yarn count. To test if the variance of yarn count of SF 20 is less than 1, the one-sided hypothesis is:

$$\begin{aligned} H_0 &: \sigma_{20}^2 = 1 \\ H_1 &: \sigma_{20}^2 < 1 \end{aligned} \tag{66}$$

and the χ^2 test statistic is:

$$\chi_{20}^2 = \frac{(n_{20} - 1)s_{20}^2}{1} \tag{67}$$

The H_0 of variance of yarn count is rejected if $\chi_{20}^2 < \chi_{1-\alpha,n_{20}-1}^2$. If it is unable to be rejected, then the procedure continues by going back to the SF 20 and doing some more adjustments on the frame and repeating this test until the H_0 of variance of yarn count is rejected.

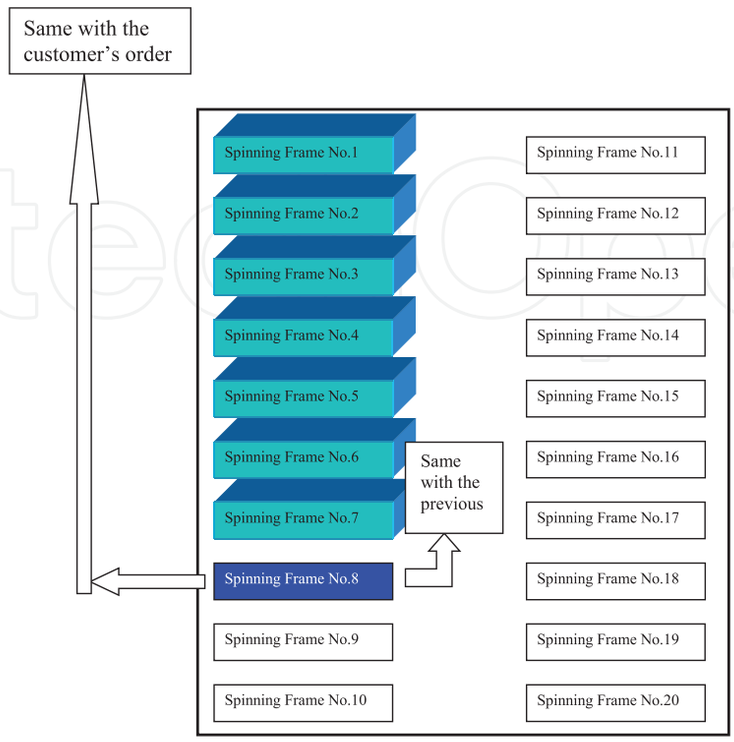

Figure 10.
Representation of SFs 1–8 producing the same yarn.

Both of the variances of yarn count of SFs (1–19) and SF 20 may be less than 1 but their equality has to be tested also because they will all mix into one lot. To test their equality, the hypothesis is:

$$\begin{aligned} H_0 &: \sigma^2_{(1-19)} = \sigma^2_{20} \\ H_1 &: \sigma^2_{(1-19)} \neq \sigma^2_{20} \end{aligned} \tag{68}$$

and the F statistics is:

$$F_{(1-20)} = \frac{s^2_{p(1-19)}}{s^2_{20}} \tag{69}$$

H_0 is rejected if $F_{20} \succ F_{\alpha/2,n_1+\ldots+n_{19}-19,n_{20}-1}$ or $F_{20} \prec F_{1-(\alpha/2),n_1+\ldots+n_{19}-19,n_{20}-1}$ which denote the upper $\alpha/2$ and lower $1-(\alpha/2)$ percentage points of the F distribution with degrees of freedom $n_1 + \ldots + n_{19} - 19$ and $n_{20} - 1$, respectively. If the H_0 is rejected, then the procedure continues by going back to the SF 20 and doing some more adjustments on the frame and repeating these tests until the H_0 is unable to be rejected.

When it is guaranteed that both the variance of yarn count is less than 1 for SF 20 and it is equal to the other nineteen frames' pooled variance of yarn count, then come the yarn count statistics tests. The average of yarn count of SF 20 would be μ_{20} and the two-sided hypothesis is:

$$\begin{aligned} H_0 &: \mu_{20} = \mu_0 \\ H_1 &: \mu_{20} \neq \mu_0 \end{aligned} \tag{70}$$

Variance of yarn count is estimated by s^2_{20}, $\overline{x}_{20}$ is the average of the n_{20} repeats of yarn count from SF 20, the t-test statistic is:

$$t_{20} = \frac{\overline{x}_{20} - \mu_0}{s_{20}/\sqrt{n_{20}}} \tag{71}$$

where instead of a normal distribution it is a t distribution with $n_{20} - 1$ degrees of freedom. If $|(t_{20})| \succ t_{\alpha/2,n_{20}-1}$ then H_0 is rejected, $t_{\alpha/2,n_{20}-1}$ is the upper $\alpha/2$ percentage point of the a t distribution with $n_{20} - 1$ degrees of freedom at a fixed significance level two-sided. If the H_0 of yarn count is rejected, then the procedure continues by going back to the SF 20 and doing some more adjustments on the frame and repeating this test until the H_0 of yarn count is unable to be rejected.

Both of the yarn counts of (SFs 1–19) and SF 20 may be equal to what the customer ordered but their equality with each other also has to be tested because they will all mix into one lot. To test the yarn count equality of SFs (1–19) and SF 20, there is only one μ_0, the hypothesis is:

$$\begin{aligned} H_0 &: \mu_{(1-19)} - \mu_{20} = 0 \\ H_1 &: \mu_{(1-19)} - \mu_{20} \neq 0 \end{aligned} \tag{72}$$

and the pooled t-test statistic is:

The average of yarn counts of (SFs 1–18) and SF 19 is:

$$\frac{\overline{x}_{(1-18)} + \overline{x}_{19}}{2} = \overline{x}_{(1-19)} \tag{73}$$

then,

$$t_{(1-20)} = \frac{\overline{x}_{(1-19)} - \overline{x}_{20}}{s_{p(1-20)}\sqrt{\frac{1}{n_1+\ldots+n_{19}-19} + \frac{1}{n_{20}}}} \tag{74}$$

$$s^2_{p(1-20)} = \frac{(n_1 + \ldots + n_{19} - 19)s^2_{p(1-19)} + (n_{20} - 1)s^2_{20}}{n_1 + \ldots + n_{20} - 20} \tag{75}$$

$s^2_{p(1-20)}$ is the pooled estimator of variance of SFs 1–20 with $(n_1 + n_2 - 20)$ degrees of freedom.

If $\left|t_{(1-20)}\right| \succ t_{\alpha/2, n_1+\ldots+n_{20}-20}$ then H_0 is rejected, $t_{\alpha/2}$ is the upper $\alpha/2$ percentage point of the t-distribution with $n_1 + \ldots + n_{20} - 20$ degrees of freedom at a fixed significance level two-sided. If the H_0 is rejected, then the procedure continues by going back to the SF 20 and doing some more adjustments on the frame and repeating this and the above tests until the H_0 of yarn count is unable to be rejected. The operation steps can be summarized as below:

(Continued)

Step 94) Yarn count adjustment of SF20.
Go to Step 94 and repeat until H_0 is unable to be rejected

Step 95) Testing the variance of yarn count of SF 20 to be less than 1.
Go to Step 94 and repeat until H_0 is unable to be rejected

Step 96) Testing the equality of variances of SFs (1–19) and SF 20.
Go to Steps 94 and 95, and repeat until H_0 is unable to be rejected

Step 97) Testing the yarn count of SF 20 with μ_0.
Go to Steps 94, 95 and 96, and repeat until H_0 is unable to be rejected

Step 98) Testing the equality of yarn counts of SFs (1–19) and SF 20.
Go to Steps 94, 95, 96 and 97, and repeat until H_0 is unable to be rejected.

Now the SFs 1–20 are producing the same yarn having the same yarn count and same variance of yarn count. The SFs (1–20) can be considered as one machine producing the same product, no difference between the yarns of twenty different spinning frames. A representation is given in **Figure 11**.

The logic in this proposed statistical approach is in a spinning mill having twenty spinning frames to adjust the first spinning frame according to what the customer ordered and to the technology of the spinning frame; take samples, statistically test them and if rejected, correct the adjustments, do the statistic tests again, and if unable to be rejected, adjust the second spinning frame according to what the customer ordered and to the technology of the spinning frame, take samples, statistically test them and if rejected, correct the adjustments, do the statistic tests again, pool the output of the first and second frames, if rejected, repeat, and if unable to be rejected, go on to the third frame, and so on until the twentieth frame. This approach pools the output of all the spinning frames in multiple-stream process of ring spinning. This will guarantee that the production starts correct and is pooled, producing yarn as per customers' order by incorporating the necessary technology and reducing variability. The whole lot will have the same yarn property at the beginning of production. During production, control charts will be performed and assignable causes will be seen if they occur, and will be

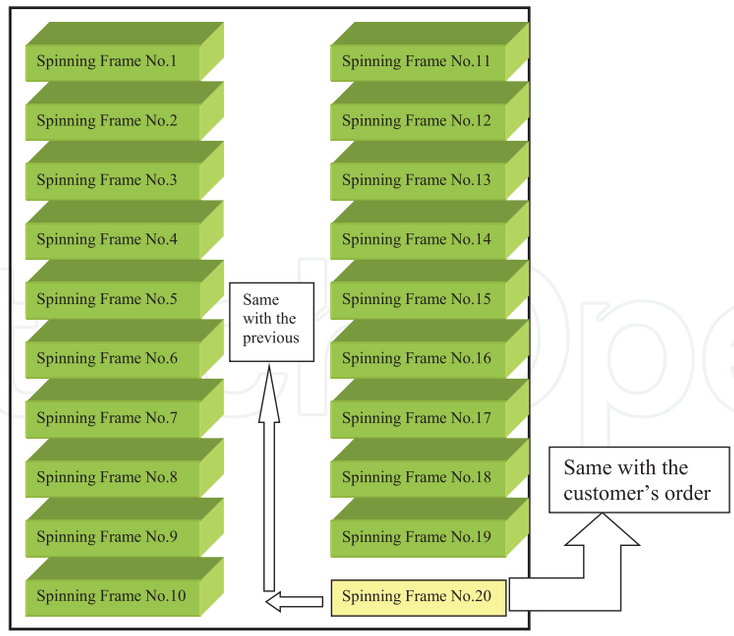

Figure 11.
Representation of SFs 1–20 producing the same yarn.

taken care of. Control charts will give much valuable information during production because it is assured that the production started correctly and all the frames are pooled. Additionally, instead of preparing separate control charts for each rational subgroup, even only one control chart for the whole lot would be enough, saving hence, time, cost, manpower, etc. This robust statistical approach can be incorporated in a statistics computer program, yielding a number of benefits for the enterprises.

On the other hand there is no restriction to employ boxplots, ANOVA, residual plots, etc. during production. These statistical methods will all add positive inferences on the data collected and support production and management. Claiming for better products and services alike will lead to new perspectives, ideas, point of views, etc.

Besides, spinning frames are not the only application area of this logic. Starting from the beginning of the stream, it can be applied to every machine in production, same two or more machines doing the same production, and so on. The first one will be adjusted at the beginning according to this logic, starting will be correct and will be pooled one by one, and continuing production will be controlled with the other statistical methods. Moreover, yarn count property is not the only application area falling under this logic. Yarn twist is also a property adjusted on the spinning frame. Other properties of textile materials adjusted on the machines can all be well worked with this proposed statistical approach.

A summary of the statistical procedures followed in this proposed statistical approach is given in **Table 2**.

5. Conclusion

This paper proposed a novel statistical approach for multiple-stream processes. Performed literature review suggests that control charts are used in multiple-stream processes but in this proposed statistical method, the expectations from the control

	SF 1		SF 2	SF 3	SF 4	... ... SF 8	... ... SF 20
Adjustment of variance of yarn count	$H_0 : \sigma_1^2 = 1$ $H_1 : \sigma_1^2 < 1$	Adjustment of variance of yarn count	$H_0 : \sigma_2^2 = 1$ $H_1 : \sigma_2^2 < 1$	$H_0 : \sigma_3^2 = 1$ $H_1 : \sigma_3^2 < 1$	$H_0 : \sigma_4^2 = 1$ $H_1 : \sigma_4^2 < 1$	$H_0 : \sigma_8^2 = 1$ $H_1 : \sigma_8^2 < 1$	$H_0 : \sigma_{20}^2 = 1$ $H_1 : \sigma_{20}^2 < 1$
	$\chi_1^2 = \frac{(n_1-1)s_1^2}{1}$		$\chi_2^2 = \frac{(n_2-1)s_2^2}{1}$	$\chi_3^2 = \frac{(n_3-1)s_3^2}{1}$	$\chi_4^2 = \frac{(n_4-1)s_4^2}{1}$	$\chi_8^2 = \frac{(n_8-1)s_8^2}{1}$	$\chi_{20}^2 = \frac{(n_{20}-1)s_{20}^2}{1}$
Rejection criteria	$\chi_1^2 < \chi_{1-\alpha,n_1-1}^2$	**Rejection criteria**	$\chi_2^2 < \chi_{1-\alpha,n_2-1}^2$	$\chi_3^2 < \chi_{1-\alpha,n_3-1}^2$	$\chi_4^2 < \chi_{1-\alpha,n_4-1}^2$	$\chi_8^2 < \chi_{1-\alpha,n_8-1}^2$	$\chi_{20}^2 < \chi_{1-\alpha,n_{20}-1}^2$
	———	Equalization of variance of yarn count with previous	$H_0 : \sigma_1^2 = \sigma_2^2$ $H_1 : \sigma_1^2 \neq \sigma_2^2$	$H_0 : \sigma_{(1,2)}^2 = \sigma_3^2$ $H_1 : \sigma_{(1,2)}^2 \neq \sigma_3^2$	$H_0 : \sigma_{(1-3)}^2 = \sigma_4^2$ $H_1 : \sigma_{(1-3)}^2 \neq \sigma_4^2$	$H_0 : \sigma_{(1-7)}^2 = \sigma_8^2$ $H_1 : \sigma_{(1-7)}^2 \neq \sigma_8^2$	$H_0 : \sigma_{(1-19)}^2 = \sigma_{20}^2$ $H_1 : \sigma_{(1-19)}^2 \neq \sigma_{20}^2$
			$F_{(1,2)} = \frac{s_1^2}{s_2^2}$	$F_{(1-3)} = \frac{s_{p(1,2)}^2}{s_3^2}$	$F_{(1-4)} = \frac{s_{p(1-3)}^2}{s_4^2}$	$F_{(1-8)} = \frac{s_{p(1-7)}^2}{s_8^2}$	$F_{(1-20)} = \frac{s_{p(1-19)}^2}{s_{20}^2}$
		Rejection criteria	$F_{(1,2)} > F_{\alpha/2,n_1-1,n_2-1}$ or $F_{(1,2)} < F_{1-(\alpha/2),n_1-1,n_2-1}$	$F_{(1-3)} > F_{\alpha/2,n_1+n_2-2,n_3-1}$ or $F_{(1-3)} < F_{1-(\alpha/2),n_1+n_2-2,n_3-1}$	$F_{(1-4)} > F_{\alpha/2,n_1+n_2+n_3-3,n_4-1}$ or $F_{(1-4)} < F_{1-(\alpha/2),n_1+n_2+n_3-3,n_4-1}$	$F_{(1-8)} > F_{\alpha/2,n_1+\ldots+n_7-7,n_8-1}$ or $F_{(1-8)} < F_{1-(\alpha/2),n_1+\ldots+n_7-7,n_8-1}$	$F_{20} > F_{\alpha/2,n_1+\ldots+n_{19}-19,n_{20}-1}$ or $F_{20} < F_{1-(\alpha/2),n_1+\ldots+n_{19}-19,n_{20}-1}$
Adjustment of yarn count	$H_0 : \mu_1 = \mu_0$ $H_1 : \mu_1 \neq \mu_0$	**Adjustment of yarn count**	$H_0 : \mu_2 = \mu_0$ $H_1 : \mu_2 \neq \mu_0$	$H_0 : \mu_3 = \mu_0$ $H_1 : \mu_3 \neq \mu_0$	$H_0 : \mu_4 = \mu_0$ $H_1 : \mu_4 \neq \mu_0$	$H_0 : \mu_8 = \mu_0$ $H_1 : \mu_8 \neq \mu_0$	$H_0 : \mu_{20} = \mu_0$ $H_1 : \mu_{20} \neq \mu_0$
	$t_1 = \frac{\overline{x}_1-\mu_0}{s_1/\sqrt{n_1}}$		$t_2 = \frac{\overline{x}_2-\mu_0}{s_2/\sqrt{n_2}}$	$t_3 = \frac{\overline{x}_3-\mu_0}{s_3/\sqrt{n_3}}$	$t_4 = \frac{\overline{x}_4-\mu_0}{s_4/\sqrt{n_4}}$	$t_8 = \frac{\overline{x}_8-\mu_0}{s_8/\sqrt{n_8}}$	$t_{20} = \frac{\overline{x}_{20}-\mu_0}{s_{20}/\sqrt{n_{20}}}$
Rejection criteria	$\lvert(t_1)\rvert > t_{\alpha/2,n_1-1}$	**Rejection criteria**	$\lvert(t_2)\rvert > t_{\alpha/2,n_2-1}$	$\lvert(t_3)\rvert > t_{\alpha/2,n_3-1}$	$\lvert(t_4)\rvert > t_{\alpha/2,n_4-1}$	$\lvert(t_8)\rvert > t_{\alpha/2,n_8-1}$	$\lvert(t_{20})\rvert > t_{\alpha/2,n_{20}-1}$
	———	Pooling of yarn count with previous	$H_0 : \mu_1 - \mu_2 = 0$ $H_1 : \mu_1 - \mu_2 \neq 0$	$H_0 : \mu_{(1,2)} - \mu_3 = 0$ $H_1 : \mu_{(1,2)} - \mu_3 \neq 0$	$H_0 : \mu_{(1-3)} - \mu_4 = 0$ $H_1 : \mu_{(1-3)} - \mu_4 \neq 0$	$H_0 : \mu_{(1-7)} - \mu_8 = 0$ $H_1 : \mu_{(1-7)} - \mu_8 \neq 0$	$H_0 : \mu_{(1-19)} - \mu_{20} = 0$ $H_1 : \mu_{(1-19)} - \mu_{20} \neq 0$
	———		———	$\frac{\overline{x}_1+\overline{x}_2}{2} = \overline{x}_{(1,2)}$	$\frac{\overline{x}_{(1,2)}+\overline{x}_3}{2} = \overline{x}_{(1-3)}$	$\frac{\overline{x}_{(1-6)}+\overline{x}_7}{2} = \overline{x}_{(1-7)}$	$\frac{\overline{x}_{(1-18)}+\overline{x}_{19}}{2} = \overline{x}_{(1-19)}$
	———		$t_{(1,2)} = \frac{\overline{x}_1-\overline{x}_2}{s_{p(1,2)}\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}}$	$t_{(1-3)} = \frac{\overline{x}_{(1,2)}-\overline{x}_3}{s_{p(1-3)}\sqrt{\frac{1}{n_1+n_2-2}+\frac{1}{n_3}}}$	$t_{(1-4)} = \frac{\overline{x}_{(1-3)}-\overline{x}_4}{s_{p(1-4)}\sqrt{\frac{1}{n_1+n_2+n_3-3}+\frac{1}{n_4}}}$	$t_{(1-8)} = \frac{\overline{x}_{(1-7)}-\overline{x}_8}{s_{p(1-8)}\sqrt{\frac{1}{n_1+\ldots+n_7-7}+\frac{1}{n_8}}}$	$t_{(1-20)} = \frac{\overline{x}_{(1-19)}-\overline{x}_{20}}{s_{p(1-20)}\sqrt{\frac{1}{n_1+\ldots+n_{19}-19}+\frac{1}{n_{20}}}}$
			$s_{p(1,2)}^2 = \frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}$	$s_{p(1-3)}^2 = \frac{(n_1+n_2-2)s_{p(1,2)}^2+(n_3-1)s_3^2}{n_1+n_2+n_3-3}$	$s_{p(1-4)}^2 = \frac{(n_1+n_2+n_3-3)s_{p(1-3)}^2+(n_4-1)s_4^2}{n_1+\ldots+n_4-4}$	$s_{p(1-8)}^2 = \frac{(n_1+\ldots+n_7-7)s_{p(1-7)}^2+(n_8-1)s_8^2}{n_1+\ldots+n_8-8}$	$s_{p(1-20)}^2 = \frac{(n_1+\ldots+n_{19}-19)s_{p(1-19)}^2+(n_{20}-1)s_{20}^2}{n_1+\ldots+n_{20}-20}$
	———	**Rejection criteria**	$\lvert t_{(1,2)}\rvert > t_{\alpha/2,n_1+n_2-2}$	$\lvert t_{(1-3)}\rvert > t_{\alpha/2,n_1+n_2+n_3-3}$	$\lvert t_{(1-4)}\rvert > t_{\alpha/2,n_1+\ldots+n_4-4}$	$\lvert t_{(1-8)}\rvert > t_{\alpha/2,n_1+\ldots+n_8-8}$	$\lvert t_{(1-20)}\rvert > t_{\alpha/2,n_1+\ldots+n_{20}-20}$

Table 2.
Summary of the statistical procedures followed in this proposed statistical approach.

charts are divided into two: First adjust the machines correctly and pool production, then use control charts for assignable causes.

In this chapter, the proposed statistical approach is explained in detail being based on a spinning mill having twenty spinning frames. When the first spinning frame is adjusted according to what the customer ordered and to the technology of the spinning frame, the results of that adjustment is controlled statistically, by means of hypothesis testing. It is the yarn count property, being μ_0, the examples are given. Yarn wrap on bobbins on the spindles, from rovings coming from the top, are drafted, and twisted to produce the yarn. n_i samples are taken from independent, identical, and with equal probability of being chosen spindles, and yarn count property have a normal distribution, as the other properties of textile materials. The adjustments on the first spinning frame are done and the variance of yarn count is hypothesis tested with less than one because of the production year of the frame. The χ^2 test statistic is applied. If rejected, the adjustments are corrected, and the same test is repeated. If unable to be rejected, then yarn count is hypothesis tested with what the customer ordered μ_0, the t-test statistic is applied; if rejected, the adjustments are corrected, and the same tests are repeated. If unable to be rejected, the second spinning frame is adjusted, the variance of yarn count is hypothesis tested with a χ^2 test statistic, and the equality of variances of yarn count of the two spinning frames is hypothesis tested with an F statistic. If rejected, the tests are repeated, if unable to be rejected, the yarn count hypothesis is tested with the t-test statistic. If rejected, adjustments on the frames are done and the tests are repeated, if both are unable to be rejected, then the yarn count of the two spinning machines are pooled. Now, the two frames are considered as one machine producing the same yarn, same variance of yarn count and same yarn count property, variability reduced the most. This statistical approach continues until the twentieth spinning frame and one by one, all the frames are considered as one machine producing the same yarn, same variance of yarn count and same yarn count property at the end.

This novel statistical approach guarantees that production starts with correct adjustments of the machines. In the performed literature review, this however has not been come across. By applying this statistical approach at the beginning of production, the correct starting will be assured and the machines will all be pooled one by one. On the other hand, during production, control charts will be applied to see the assignable causes and quick care ought to be taken. Additionally, instead of preparing separate control charts for each rational subgroup, even only one control chart for the whole lot would be enough, saving time, cost, manpower etc. This robust statistical approach can be incorporated in a statistics computer program, ending up with many benefits for the companies. Other statistical methods like boxplots, ANOVA, residual plots will all provide additional information about how the production proceeds. In addition to the above, this novel statistical approach can be applied to machines starting from the beginning of the multiple-stream like blowroom, carding, drawing, roving, examples for a spinning mill, more than one machine producing the same material. Besides, it can equally be applied to the other properties of textile materials, both adjusted directly on the machines or which result indirectly with machine settings like pressure, speed, etc. Raw materials, products, efficiency, yield, waste reduction, shift management of workers, faults, machine breakdowns, spare parts, electricity, economics, and much other application areas would emerge in due time.

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Chapter

Significance of "Quality Control" in Leather Goods and Garment Production

Abduletif Hebo

Abstract

The leather industry is one of the priority sectors that contribute to export income and economic development in the majority of African countries, in terms of creating job opportunities. Leather products need high care during manufacturing because their quality should never be compromised. Quality is a universal term used to evaluate the performance of a product or a service and the acceptance by the customer(s) in terms of customer satisfaction. As such, understanding quality concepts such as quality control (QC), quality standards, procedures, and documents related to leather goods and garment production in accordance with manufacturing company's policy is deemed useful within the context of this paper. Supervisors, quality controllers, and operators in leather products manufacturing firms need to know required quality parameters and associated control mechanisms so that defect-free products will reach the end users. In order to achieve this, quality-influencing parameters such as performance, reliability, durability, serviceability, esthetics, features, and conformance are measured so as to verify set quality levels. Furthermore, factors that affect the quality of leather goods and garments as well as methods of identifying and isolating common defects and faulty pieces especially in the finishing activities of leather production are included herein. Hence, this paper covers quality control aspects on leather goods observed within the garment manufacturing subsector.

Keywords: quality, quality control, leather goods and garment, defects

1. Introduction

The leather sector is regarded in most African countries as a major economy driver that highly contributes to a country's economic growth by means of employment opportunities and foreign cash inflow. The leather sector includes tannery, footwear, leather gloves, and leather goods and garment subsectors. Leather by itself requires high care during the different phases of production, storage, and transportation. Hence, the issue of quality in leather manufacturing process is of paramount importance as most defects in leather and leather products are irreversible. Rework or correction of incurred damages during production of leather, leather goods, and garment leads to higher labor costs and sometimes to rejection of the products.

Therefore, the implementation of quality control (QC) concepts in every production step is associated with a valuable impact on the finished products so that defect-free products reach end users.

Most of the Ethiopian companies specializing in the leather sector prefer visual inspections and simpler physical testing methods to control product quality. This preference may work for the local market as the latter may not draw too much focus on quality aspects due to it being less aware for various quality dimensions. However, for penetrating and competing on an international level, special privileges such as African Growth Opportunity Act (AGOA) from importing countries or producing goods with the required quality and at a competitive price are required. Nonetheless, consistent with descriptive statistics results, econometric findings also reveal that exporting firms were found rather less efficient compared to those which are either powerless or have totally given up looking for the international market with respect to income and market sustainability. Once basic international standards are met and market access is established through various mechanisms including participation in trade fairs, the use of the internet, and buyer contacts, exporting companies have continued to benefit from the market due to the natural superiority of Ethiopian leather in terms of fineness, thickness, flexibility, strength, and compactness of texture, according to UNCTAD (2000) [1].

But this is not true for export markets. All leather and leather products-related quality standards need to be implemented which in turn includes, but may not be limited to, physical and/or chemical testing and inspections. In a perfectly competitive market setup consisting of a high number of buyers and sellers (also referred to as a thick market), price signals would reward high quality, and hence, producers and traders of substandard quality would either be driven out of the market or would be relegated to a distinct low-quality-oriented market [2].

This chapter provides a background on quality control aspects for the production of leather products that directly reach end users. It covers quality control aspects applicable to leather products and goods and the garment manufacturing subsector.

1.1 Aims and objectives

The objective of this chapter is to provide a background on quality control aspects required in the production of leather products. In doing so, this research work aims to address the significance of quality control and quality aspects in the leather products manufacturing subsector.

2. Literature review

Quality is an absolute term. Concepts of quality and quality control with regard to the manufacture of leather goods and garments need to be viewed in accordance with the policies of the relevant specialty industries. The outcome thereof in conjunction with the application of quality control concepts listed herein will serve as the basis for supervisors, team leaders, and even operators in those companies with advanced know-how to the parameters, check points, and control mechanisms so that defect-free products will reach end users.

Most Ethiopian leather and leather products manufacturing firms had implemented various quality-related improvement tools and systems including, ISO 9001:2018, Environmental Management Systems (EMS ISO 14001:2018, Occupational

Health and Safety Management Systems ISO 45001:2018), and a plethora of other quality management systems (QMSs) in order to enhance their local and global competitions. For instance, (ELICO) Ethiopian Leather Industries Company PLC, Pittards Glove Manufacturing Factory PLC, Modern Zege leather products and footwear Industry PLC had implemented these systems [3].

Therefore, they will be able to acquire and maintain quality concepts, agreed quality standards and procedures, and introduce quality control/quality assurance (QA) to organizational staff/personnel. Furthermore, they will apply these parameters in leather goods and garment production, identify accompanied issues, and provide related documents to employees in accordance with the organization policy.

To implement quality standards, the basic conditions of the customer are (a) the purpose and (b) the selling price of the product or service.

These basic conditions can be resolved in to the following 10 detailed conditions:

- specifications of dimensions,
- operating characteristics,
- life and reliability objectives,
- safety requirements,
- relevant standard,
- engineering,
- manufacturing and quality costs,
- production conditions,
- field installation,
- maintenance and service objectives,
- energy utilization and material conservation factors,
- environmental and other side effects, and
- cost of operation or use

2.1 Concept of quality

Quality is the totality of features and characteristics of a product or service that affect its ability to satisfy the specified or implied needs of a customer. Quality consistency requires from users to concentrate on the process rather than on the product alone. Quality gurus define quality as "conformance to requirement" and "fitness for use" [4]. Good quality will automatically result in productivity improvement. It is the author's view that the best policy should be to do the things right first time.

Quality helps determine a firm's success in a number of ways:

- customer loyalty: satisfied customers return, make repeat purchases, and recommend the product or service to others,

- strong brand reputation for quality: retailers want to stock the product; improved quality leads to fewer returns and replacements which in turn lead to reduced costs attracting thus and retaining good staff.

The term "Quality" can be measured aspects such as failure or reject rates, level of product returns, customer complaints, customer satisfaction, customer loyalty, evident from repeat purchases, or renewal rates and employee health and well-being.

2.2 Quality parameters

Quality is measured in a relative manner. It depends on how the user perceives or the way he/she get satisfied with that product/service. Once a product/service is accepted to customers, it can pull more new customers and may be produced/delivered in greater numbers, affecting in turn costs that are reduced and sales which will be increased. But, as quality has no universal meaning, the way users perceive it varies. Some users may like the performance or the reliability, while others may be happy with esthetic features and so on. What is reliable for a user may not be true for another. Hence, quality is an important factor which customers look for in a product or service in order to be rewarded with total satisfaction. Some of the important quality factors/parameters that customer considers in a product or services as stated by some quality gurus are listed as follows.

2.2.1 Dimensions (parameters) of quality

Performance: it evaluates if the product does the intended (planed or proposed) job or if the service delivered meets intended objective. Potential costumers usually evaluate a product to determine if it will perform certain specific functions and how well it will do them. For example, the production of a document holder or a leather bag with multifunction pockets would fall within this category.

Reliability: it indicates a product's failure rate. Different products may need repair over their service life. The leather machineries should be also reliable so as to increase productivity, i.e. when leather garments are produced, greater attention ought to be placed during, e.g. the stitching procedure. As the needle is typically of a cutter edge type, sometimes it stitches the component by cutting the part. So, if proper stitching is not done, the product is either repaired or rejected.

Durability: it shows the duration that the product is expected to last for. This is the effective service life of the product that customer wants over a long period of time, e.g. a customer that orders a leather jacket may expect this to last for at least 5 years.

Serviceability: this parameter stands for how easy the product may be repaired. There are many industries where the customer's view of quality is directly influenced by how quickly and economically a repair or routine maintenance activity can be accomplished' in this case-study, dyeing or changing color of the leather jacket after a number of uses can be an example for this.

Esthetics: this dimension shows what the product looks like externally. This is the visual appeal of the product, often taking into account factors such as style, color, shape, packaging alternatives, and other sensory features.

Features: it means what features the product possesses. Usually, customers associate high quality with products that have added features (such as special color, design, handles, and decorations), which go beyond the basic performance of the competition.

Conformance: it is used to evaluate if the product or service conforms to the specification. This means, if it is developed based on a performance specification; will it actually perform as specified? If it is developed based on a design specification, does it possess all of the features defined?

Perceived quality: The product or service may possess adequate or even superior dimensions of quality but still fall victim to negative customer or public perceptions. As an example, a high-quality product may get the reputation for being low quality based on poor service by installation or field technicians. If the product is not installed or maintained properly, and fails as a result, the failure is often associated with the product's quality rather than the quality of the service it receives.

2.3 Quality control and quality assurance

Quality control (QC) is a procedure or a set of procedures intended to ensure that a manufactured product or performed service adheres to a defined set of quality criteria or meets the requirements of the client or customer. While quality assurance (QA) is defined as a procedure or set of procedures projected to ensure that a product or service under development (before the work is complete, as opposed to afterward) meets specified requirements. QA is sometimes expressed together with QC as a single expression. There is plenty of quality control types. The following are used in the leather-related production controls [5].

Quality control of incoming material:

- Ensuring the right materials are available in the right quantity at the right time.
- Based on quality requirements, the purchase information such as specification, packing instruction, and transportation instruction should be clearly identified.
- For example, in the garment industry for finished leather, the parameters such as color fastness, light fastness, tensile strength and softness need to be checked.
- Physical characteristics such as lining, tensile strength and color fastness need to be checked. After finalizing the parameters to be assessed for each incoming material, the standards need to be met for each parameter of each incoming material.

Process control:

Process control (PC) can be defined as any activity that adds value to the product to be supplied or the service to be rendered. The term "process" in the leather garments manufacturing industry may include – but not be limited to – unit processes such as cutting, assembling and stitching, and finishing. According to the process control steps, the parameters for each process need to be identified first. For

example, in assembling and stitching, the needle to be used, i.e. the needle number and needle point have an influence on the final product. Further, the thread used in bobbin (lower thread) and the sewing machine (top thread) also affects the quality of the final product.

Process control is carried out by the following steps:

- Identification of process control parameters,
- Establishing the standards for each parameter of each process (internal process control standard/working standard for process control),
- Fixing the limits for each parameter.

Figure 1 shows the intended process control.

- **Product control:**

Product refers to the physical output produced by supplying in the inputs or raw materials and carrying out any production process. The final product is what is dispatched to the customer or the end users. Apart from this, there are components sometimes referred to as intermittent products. For a leather garment manufacturer, these are prepared sleeves, pockets, collars, etc. Therefore, the output after each operation or process is an intermediate product. Product control generally refers to the control of the final product. Control of intermediate products is equally essential. This is due to the fact that in each stage the product quality is ensured so as to produce the final product of desired quality [6].

2.4 Quality inspection and testing

Quality inspection: Industrial activities which ensure that manufactured products, individual components, and multicomponent systems are adequate for their intended purpose. Whereas *inspection* is the activity of examining the product or its components to determine if they meet the design standards, *testing* is a procedure in which the item is observed during operation in order to determine

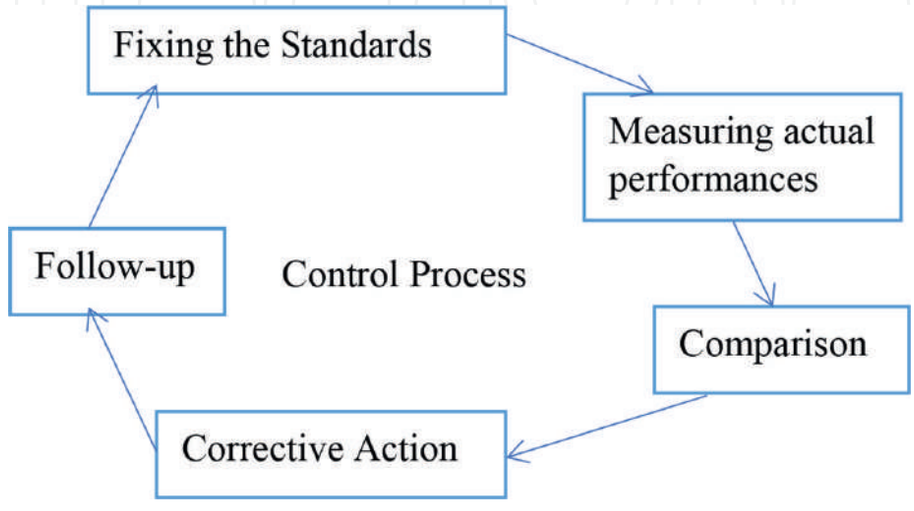

Figure 1.
Process control.

whether it functions properly for a reasonable period of time under given stress conditions. Inspection and testing are performed before, during, and after manufacturing to ensure that the quality level of the product is within acceptable design standards.

There are also various types of inspections. The following categories are used in leather goods and garment production:

- **Incoming materials inspections:** checking the quantity (finished leather, accessories, etc.), quality, rejection allowances, verification as per purchase order, lead time, etc.
- **First-article inspections:** QC inspects first-article samples prior to volume production. This verifies that product specifications are being met and avoids unnecessary re-engineering work later.
- **In-process inspections**: these on-site inspections evaluate samples of the products selected during the manufacturing process. This confirms the quality of the product and allows any necessary changes to be addressed early on reducing, hence, rework time and costs.
- **Pre-shipment inspections**: during a pre-shipment inspection, engineers verify that finished goods conform to set specifications.
- **Sample inspections**: samples are taken from inspection lots for end user evaluation, laboratory testing, or customer approval randomly, and processing QC can help for inspection. After this type of inspection, one can offer rapid service at a very affordable rate.

International standards are preferred to be used for testing leather products, especially in the garment industry. **Table 1** shows this standard.

No.	Items	Standard
1	Elastic tapes	IS 9686
2	Metal buckles	IS 96986:1980
3	Threads	IS 1376/1803
4	Leather garment sizing system	IS 10397
5	Metallic slide fastener	IS 3148:1983
6	Garment quality guide	IS 12675
7	Leather for garments	IS 12718
8	Fur leather	IS 3840/2961
9	Fusible lining	IS 12806
10	Zip fasteners	IS 8894/3184/4829

Source: Leather Industry Development Institute, Advanced Garment Production, Level IV Training Materials, June 11, 2016.

Table 1.
Standards related to leather garments industry and related items.

3. Results and analysis

3.1 Leather goods common quality parameters

In addition to the eight quality parameters of any product like durability, feature, performance, conformity, esthetics, serviceability, perceived quality, and reliability, there are also other leather goods-specific quality parameters.

3.2 Most commonly used types of testing

Leather testing: it includes wet rub fastness, dry rub fastness, tool test, stress strain test, and plaster test fastness.

Leather goods and garments testing: it encompasses handbags and small luggage, wherein the strength – say – of strap fastenings is an important consideration in the quality assessment of handbags and luggage. A large number of companies in Ethiopia are able to carry out all strength tests utilizing state-of-the-art equipment to assess the risk of strap failures, whether at fastenings (e.g. buckles) or where the strap is attached to the body of the item itself. The other one is the leather belt testing, from an assessment of the components of a belt for labeling purposes. Also, specialty companies can perform further tests in order to satisfy all clients' requirements such as the color fastness (wet and dry rub fastness test) to tarnishing of buckles and metal components, to ensure the products are fit for the purpose they are intended for.

A few examples of tests used in leather products manufacturing firms are as follows:

Smell test: the smell test is an important part of every inspection. To avoid illegal toxins, the most reliable way to check it is to perform chemical tests as per ASTM D1296 in an accredited Leather Industry Development Institute (LIDI) laboratory.

Function test: the objective is to check if the product works as designed or anticipated. In the case of the leather bag, an inspector will wear it and test the zippers' direction and strength.

Color fastness check on leather: excessive dye may be rubbed off during a color fastness check. On leather, this is a frequent problem. The test may be repeated 10 times with a dry cloth and 10 times with a wet cloth.

Abuse and fatigue tests: pulling on straps and zippers with stronger-than-usual force helps to understand the manufacturing quality of leather bags.

Seam strength test for leather bags: this test is similar to the abuse test but focuses on the seams. It uses a tension gauge to check seam strength.

Load test: the inspector loads the leather bag with weights (depending on the model between 2 and 20 kg for backpacks (bag type) most of the time. Then the bag is lifted at least 20 times and is hanged on a hook for 4 h. This is an internal company policy similar to that of color fastness check.

Zipper twisting test: this type of test is used to check both the strength of the zipper and the seams holding it in the open middle and closed position. The QC pulls the zipper sideways for 10 s in each direction. Low-quality zippers tend to open and bend beyond repair. Extensive laboratory equipment test products (e.g. opening and closing zippers 5000 times) could be used also. However, most of small and medium leather products manufacturing companies use the manual test.

Carton humidity check: This test is performed in order to assess the behavior of the product in rainy conditions, while avoiding the buildup of mold or fungus, aiming

at maintaining a humidity level below 12%. In particular, during the rainy season, the inspector should check the humidity of the export cartons with a humidity tester. As such, it ought to be ensured that sufficient desiccant (calcium oxide absorb water) is placed in the right spots.

3.3 Factors that influence the quality of leather goods and garments

Factors that influence quality aspects make bags and garments good and/or cheap. The following aspects are commonly experienced in leather products manufacture:

3.3.1 Designs and materials

The design room is where quality starts in leather goods manufacturing companies. Bag design is a system, which is not only the combination of the technique, knowledge, and the art, but also the connection of design and craft from the choice of the theme to grasp the inspiration and the accomplishment of the finished product. Through the design effect of a product, a bag or a garment should become a bridge between designers, technicians, and consumers. In that sense, it would be common language among them. The designers should identify the materials like type of leathers, accessories, colors, and hardware that will be used in the production process. A well-designed bag or a garment should include all information about its design. As an example, a good leather goods design should have at least the following information:

- leather type (color, thickness, and feeling),
- origin (cow, sheep, goat, buffalo, etc.)
- reinforcement (EVA sheet, water proof, fusing, foam, etc.),
- lining (velvet, cotton fabric, nylon, and polyester),
- accessories (eyelet and rivet),
- zipper, in terms of size (3, 5, and 8 mm), finishing (silver, gold, and bronze), and type (metallic, plastic chain, and plastic molded),
- stitching (seam type and seam length per centimeter),
- thread size (for needle thread and bobbin thread), type (cotton, nylon, polyester, silk, and polyester spun cotton), each dimension, (volume, height, and base, handling length, and width),
- edge finishing (raw edge, folded, and edge color) and hard ware's (buckle, color, and adjustable size) [7].

3.3.2 Material selection

Material selection refers to the materials selected for the manufacture of – say – a bag including the hardware and the accessories, as well as the processes involved.

3.3.3 Pattern making and cutting

The pattern making, which is also referred to as a sample making process is an important aspect and is regarded as a bridge of transforming the graphic designs into the products. The maximum permissible error (acceptable level) of pattern is 1/32 inches (1 inch error of 32 inches length), as by reference to any bag, or in accordance with international standards, such as SATRASumm, which is an industry standard package concerning the efficient cutting of leather and synthetic materials. In pattern making, usually major parts (shape and size of the bag) are made first, and then relatively smaller parts are followed and so on.

3.3.3.1 Fixing product size standards

Unlike leather garment and foot wear products, leather bags have no fixed specifications such as height, depth, and width and may therefore be easy to categorize as small bags, medium bags, and large bags. One could remember Galileo Galilei's quote: "*Measure what can be measured, and make measurable what cannot be measured*." From a quality management point of view, this means that "we cannot manage what we

Figure 2.
Pattern alignment variations: (a) and (b).

cannot measure." In short, the clearer the specification, the better the possibility of creating and delivering quality products.

3.3.3.2 Construction

Construction is the matter of how everything or patterns have been put together. **Figure 2** shows pattern alignment variations.

3.3.3.3 Technology

The manufacturing process is a key factor to leather products' quality. A different technology represents a different style of leather products. The quality of bags is as good as the people that make it. That is why the best stitchery, leather workers, and quality control technician or experts are required. In order to have best-quality products and workers, it is important to put a lot of resources into training or hiring the most qualified staff and paying them well fostering their commitment and creative minds.

3.4 Defects in goods and garments manufacturing

3.4.1 Defects and their types

Defects are deviations/nonconformities of processes, products, or materials from the requirements/standards. Causes of defects may be man-made (assignable causes) or common/natural causes. Assignable causes can be removed, while common causes can only be reduced. For example, a poorly build knife maybe a cause for cutting defects/human fault, while loose leather is a cause for less durability of the garments.

3.4.2 Methods of identifying and isolating faulty pieces

- Defects in the cutting section can be identified by various bodies operating therein that are briefly presented as follows:

  A. Cutting supervisors: they are the cutting supervisors that issue leather from raw material store where defects like loose leather, under substance, wrong color/shape, poor nap on nubuck, poor color fastness, and poor knife can be visually identified, and the leather is thereafter sorted accordingly. Only leather bundles that meet specifications are issued and allocated among cutting operators by the supervisors.

  B. Cutting operators: they can identify during cutting minor defects like grains not matched pair wise, wrong direction of cutting, cuts/flaws in component, open defect, wrong size cut, and color variations to name but a few. These operators, in addition to cutting operations, have the responsibility to take care of component quality. As such, items ought to be cut in line with the parameters stated earlier and the data be posted to the operators.

- Defects in the stitching (sewing) section can be identified by various bodies operating therein.
    - Bench workers can identify defects like notch marks not matched, edge folding inaccurate, improper alignment, wrong components placement, too much hammering, and too much glue.

C. Stitching operators: they can identify minor defects like uneven stitching length, skipped stitches, stitches not locked at the end, wrong needle/thread used, stitches too far or too close to the edge, stitches not as per the marking, broken stitches, top tension tight, and seam puckering.

Possible defects during the final inspection stage may be:

- trimming,
- thread burning,
- glue erasing,
- leaving uneven stitching length,
- pattern vs. assembly correspondence,
- measurement and alignment,
- grain structure checking,
- component checking,
- color and size matching,
- ironing dimension,
- seem puckering,
- proper feeding system,
- thread tension,
- leaving broken stitches and skipped stitches,
- stitches too far or too close to the edge,
- top tension tight, thickness, and not ±0.2 mm allowances [8].

3.5 Part five: Finishing in leather products manufacturing

Finishing is the final process given to a garment or goods in order to achieve good appearance, desirable feel and look and to impart some important, and durable and functional properties.

3.5.1 Classification of finishing

Finishing in leather products manufacturing can be classified according to the nature of the finish such as Kawabata's Evaluation System for Fabric-KES-FB and the degree of performance (ISO11644:2009). **Figure 3a** and **b** show these classifications.

3.5.2 Edge coloring

Sand edges: this is done by using emery paper to sand the edges and to arrange many belts/straps of the same size side by side on a flat table and sand simultaneously. This will ensure that all the leather layers are even and square and that any residual glues or finishes have been removed. **Figure 4** shows edge coloring in industry.

Applying color: this is done either by using *a* machine or manually. For manual operation, *the* use of dye box like Fiebing's dye will make it simpler. Keeping the dyed edge by facing up for air-drying before applying on the opposite edge is worthy. After the other side got dried, one can paint the opposite one and keep the same way one has done previously. It can also be applied during the second round if necessary. This method is used everywhere globally even though manual coloring is preferably practical in Ethiopian leather products manufacturing firms. **Figure 5** indicates the application of color with the aid of a machine.

Applying filler: the leather filler paste is a white compound that can be air- or heat-dried and requires re-coloring with a leather repair pigment after its application. The

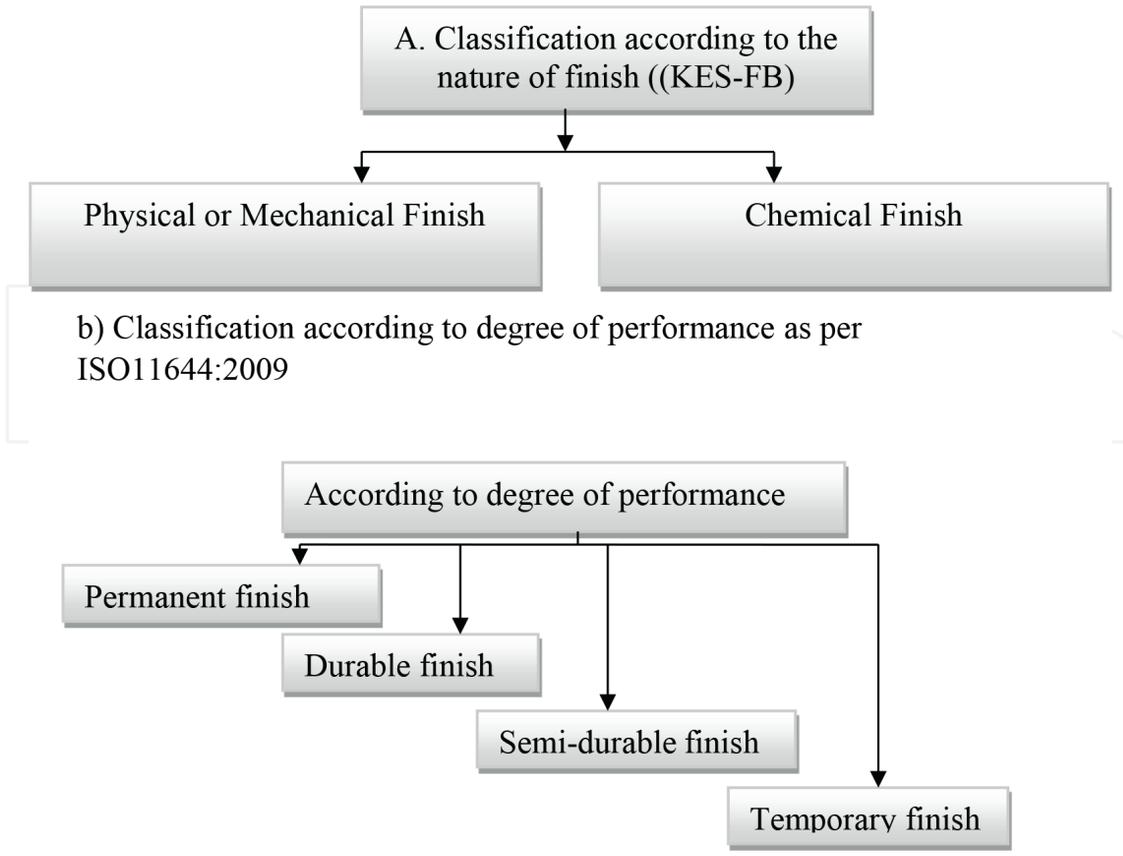

Figure 3.
Classifications based on (a) the nature of finish (KES-FB) and (b) the degree of performances as per ISO11644:2009.

leather filler remains flexible, durable, and natural to the existing leather surface. It is used to fill the edge surface and results in smoothness to the edge's surface (see **Figure 6**).

Wet and soap: the edge of the leather can be wetted using a sponge or piece of trimmed woolskin. The outcome will be a slick/polished rounded edge.

Burnishing: this is accomplished by briskly rubbing the canvas against the edge of the belt until the edge is smooth. A canvas wrapped around a motorized wood

Figure 4.
Edge coloring in practical.

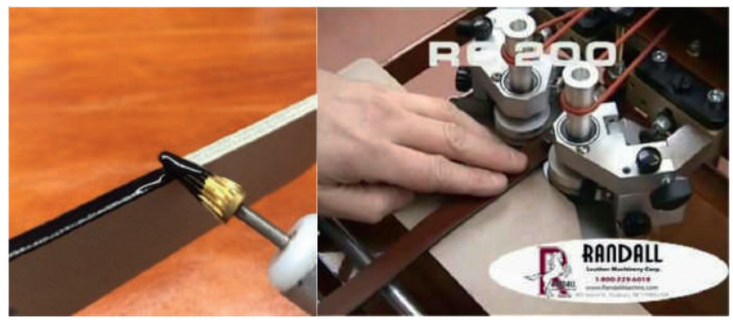

Figure 5.
Applying color with machine.

Figure 6.
Leather filler paste.

Figure 7.
Scissors for trimming.

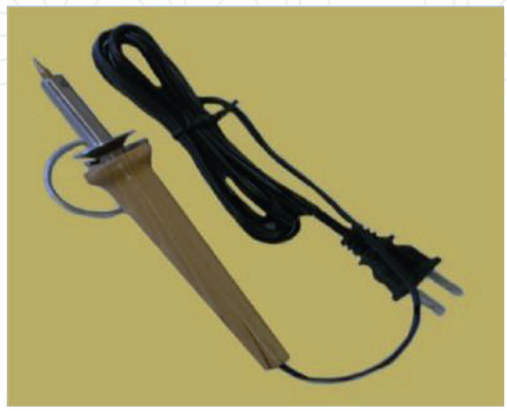

Figure 8.
Soldering iron used for thread burning.

burnishing wheel which speeds up the process could be used herein. However, care should be taken not to over-burnish, which will result in a rough edge.

Hand burnishing: this is done by means of a clean cloth that rubs the edges removing hence, any residual dye and determining thus, if the second coat is necessary.

Polish: at this point, paraffin is applied to the edge of the belt and burnished again and again. Denim works well here if burnishing is done by hand. Once one is satisfied with the finish, one can polish to a high luster with a dry cloth [9].

Finish: after the edges are polished, final finish is applied.

3.5.3 Trimming: Hand trimming and trimmer machine

It is preferred to use thread trimmer machines as it reduces trimming costs, increases production, uses unskilled help, eliminates scissor damage, keeps trimming area clean, and reduces cleanup cost. One can choose between different clipper blades and motor control for diverse material. Scissors can be used for trimming (**Figure 7**).

Thread burning: it can be manual with a candle or by means of soldering iron (**Figure 8**).

4. Discussion

The quality control concept is very useful especially for exports of branded products. Apart from the general knowledge and experience of the author in the sector, secondary sources were used from institutions such as the Ethiopian Leather Industry Development Institute (LIDI), Ethiopian Leather Industry Associations, and medium- and large-scale leather products manufacturers. The LIDI laboratory

was accredited from SANAS (South African National Accredited System) so as to support the leather sector with various laboratory testing (i.e. physical, mechanical, and chemical) services in 2012. Furthermore, the LIDI laboratory was also accredited from the Ethiopian National Accreditation Office (ENAO) in the same year.

With this responsibility, LIDI has been serving Ethiopian leather manufacturing firms by laboratory testing, technical training, quality management system (QMS), and quality control and quality assurance tools implementations. Under the Twinning program, which was made between LIDI and the Federal Democratic Republic of Ethiopia, FDRE, Ministry of Industry on Ethiopian side, and CSIR – Central Leather Research Institute-Council of Scientific and Industrial Research, India, in association with Footwear Design and Development Institute (FDDI), India, LIDI's R&D laboratory state of the art was created to meet the requirements and demands of leather and leather products in order to meet and ensure international quality standards [10].

Most of leather goods and garment manufacturing companies in Ethiopia use smell test, function test, and color fastness check on leather accepting it as internal

S.No.	Types of test	Test method
1	Determination of thickness	ISO 2589:2002
2	Determination of apparent density	ISO 2420
3	Determination of tensile strength and percentage elongation	ISO 3376
4	Determination of tearing load (single and double)	SO3377---1/3377---2
5	Determination of distension and strength of grain ball burst	ISO 3378
6	Determination of flex resistance by flexometer method	ISO 5402
7	Determination of shrinkage temperature up to 1150°C	ISO 3380
8	Water absorption (Kubelka) after 2 and 24 h	SATRA TM/ISO SLP 19
9	Determination of water resistance test for light leather	ISO 5403
10	Determination of water resistance of heavy leather	ISO 5404
11	Determination of water vapor permeability	ISO 14268
12	Determination of cold crack resistance leather finish	SLP 34
13	Determination of sole/upper adhesion tester	Internal
14	Measurement of shoe flex (walk meter)	Internal
15	Determination of dry heat resistance of leather	Internal
16	Determination of adhesion of leather finish	SLF 11
17	Color fastness to artificial light (xenon)	SLF 401
18	Determination of fastness to water spotting	ISO 11642
19	Color fastness to perspiration	ISO 11641
20	Determination of fastness of leather finish to (to and from rubbing)	ISO 11640
21	Determination of fastness to ironing (fastness to heat)	IUP 470
22	Determination of static water absorption	ISO 2417

Source: Leather Industry Development Institute's Physical Laboratory, March 23, 2016.

Table 2.
Leather physical testing.

company policy, as it matches with some of global/international standards in this aspect (ASTM D1296, ISO 11640, ISO 11641, SLF 401, IUP 470).

Apart from common quality parameters, there are also other leather goods-specific quality parameters. Items made from real leather or imitations, such as PU, which are very popular, should be treated accordingly. However, leather goods and garment manufacturing companies prefer to use simpler (by observation and manual tests) methods, whereas other manufacturers in footwear subsectors could use more test methods as per international standards in order to check, for example, grain structure, thickness, apparent density, shrinkage, flex resistance, water resistance, and so on as per ISO 2589:2002, ISO 2420, ISO 5402, ISO 3380, ISO 5403. That is because, footwear products are highly vulnerable to damage, and hence, their suitability to use needs to be assured before reaching the end users. **Table 2** provides a summary of physical testing standards for leather that could be recommended by the author to be used so as to improve productivity and reduce defect rates, rework, and waste.

Regarding the effect of human factors in product quality, it is the author's view that most quality problems are caused primarily by a lack of interest or care on the part of the worker in the production department. However, it is usually not only the worker who is responsible for this but also the conditions necessary to carry out the work correctly often do not exist. For example, instructions may be inadequate, the incoming material may be defective, the machines may not be capable of producing goods of the required quality, and proper conditions for conducting inspection of the product are not given to the workers, and so on. The study done by joint consultancy of Ethio-Indian twinning project in collaboration with the Leather Industry Development Institute (LIDI) and the Footwear Design and Development Institute (FDDI) of India approves this fact [11]. **Figure 4** (in Section 4.1) shows that inadequate instructions, which accounts for about 28% caused the rest effects. Effective understanding of the worker to the instructions in every step of production will surely lead to more pleasant effects on the product quality. However, although workers may not have control over these factors, they may though lead to defective work. **Figure 9** shows Pareto analyses of one factory.

In Japan, it is generally believed that 40% of quality problems are caused by poor product design, 30% of quality problems are due to wrong or defective materials being purchased from suppliers, and the remaining 30% are due to errors made during the manufacturing process [12]. One could argue that any other quality problems

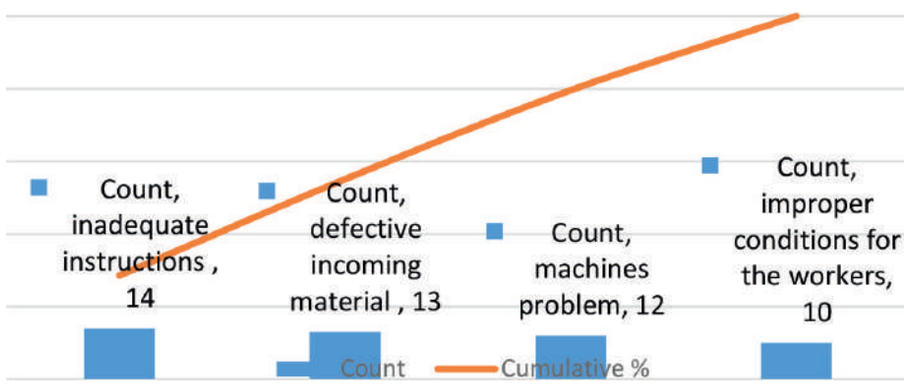

Figure 9.
Result of Pareto analysis for ELICO-universal leather products unit. Source: Twinning report [11].

in manufacturing are caused in equal proportion by managers (by not providing adequate training for workers) and by workers (by not paying adequate attention to machine settings).

Regarding defects observed in goods and in garments manufacturing listed in the following section are common examples of deficiencies in leather products manufactured in Ethiopia:

Sewing defects: open seams, wrong stitching techniques, non-matching threads and missing stitches, improper creasing of the garment, erroneous thread tension and raw edges are some of the sewing defects which can affect the garment quality adversely. Firms mitigate these types of defects by providing continuous on-the-job trainings for sewing operators.

Color defects: this category includes color variations between the sample and the final garment, wrong color combinations, and mismatching dyes' that should always be avoided. Leather issuers check this in store for every order with the help of leather sorter or in-process quality inspector.

Sizing defects: this refers to wrong gradation of sizes and difference in the measurement of various parts of garment-like sleeves of XL size for a body of L size garment that can deteriorate the garments beyond repair. Though tanneries use leather grading machine during production, Ethiopian leather goods and garment manufacturing firms usually identify and mitigate these defects by cross-checking cut components visually.

Other defects: this group entails broken or defective buttons, snaps, stitches, different shades within the same garment, dropped stitches, exposed notches and raw edges, fabric defects, holes, faulty zippers, loose or hanging sewing threads, misaligned buttons and holes, missing buttons, needle cuts or chews, pulled or loose yarn, stains, unfinished buttonhole, short zippers, inappropriate trimmings, etc. These defects, unless tackled at the very beginning, and/or quality assurance is undertaken in every step, could lead leather products manufacturing companies to be less competitive and affect in turn their existence. Due to globalization and acceptance of Ethiopian leather products to export markets, manufacturers of leather products are obliged to implement various quality improvement tools including QC/QA. Thus, respective process and final quality checking parameters have been posted in front of operators in each section along with visual defective and free cut components. This method encourages operators to think about quality issues in addition to their duties of – say – cutting, table work, sewing, and finishing.

Concerning defect control at the finishing section, various final quality control parameters are used that include trimming, thread burning, glue erasing, pattern vs. assembly correspondence, thread tension, leaving broken stitches and skipped stitches, and stitches too far or too close to the edge.

As for Ethiopian leather products manufacturers, the defect control parameters during the final inspection stage include aspects such as:

- leaving uneven stitching length,
- measurement and alignment,
- grain structure checking,
- component checking,
- color and size matching,

- ironing dimension,
- seem puckering,
- proper feeding system,
- top tension tight and thickness, etc., are inspected prior to this stage.

5. Conclusion and further work

The leather sector's contribution is very high with respect to export incomes and economic development, especially on creating job opportunities. For instance, according to the Central Statistical Agency (CSA) of Ethiopia, export of leather and leather products, which was US $23 million in 2013, reached US$133 million in 2018. Hence, leather goods and garment to be exported need high care during all manufacturing stages in order to increase competitiveness in the global market.

This book chapter discussed quality control concepts and quality standards for leather goods and garment. In doing so, it highlighted applicable procedures and documents enabling supervisors, quality controllers, and operators in those companies to get detailed knowledge about quality parameters and control mechanisms so that defect-free products reach end users. Furthermore, it will allow readers to familiarize themselves with quality concepts in this sector. It is the author's view that this research work may prompt readers to confront themselves with quality control aspects and to research more about these aspects in this specialized manufacturing area.

Moreover, leather goods and garment quality parameters and factors that influence the quality of leather goods and garment were included. In addition to the earlier-mentioned ones, commonly occurring defects, methods of identifying and isolating faulty pieces, and some finishing types in leather products production were discussed.

Studying the application of QC/QA on the whole leather sector (leather processing, footwear industry, glove making, and other related subsectors) will be the next tasks of the researchers and book writers. This may include subsector-specific inspection and control mechanisms starting from designing, cutting, table work (preparation), sewing, inspection and testing, packing, and shipping that need to be further analyzed.

Acknowledgements

The author would like to express his gratitude to his wife for her patience and assistance.

Further reading

To get more practical explanation of quality aspects, readers are advised to read of the work of David Garvin (1988) – *Eight Dimensions of Quality*.

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Chapter

Development of a Quality Gate Reference Model for FDM Processes

Marcel Randermann, Timo Hinrichs and Roland Jochem

Abstract

Additive manufacturing (AM) enables industries to accomplish mass customization by creating complex products in small batches. For this purpose, fused deposition modeling (FDM) is widely used in 3D printing where the material is applied layer-by-layer from a digital model to form a three-dimensional object. There still exist problems in FDM processes regarding the failure rate of printed parts. Failures vary from deformed geometry, clogged nozzles, and dimensional inaccuracies to small parts not being printed that may be attributed to various process steps (e.g., poor quality CAD models, converting issues, overheating, poor quality filament, etc.). The majority of these defects are preventable and are caused by imprudent try-and-error print processes and troubleshooting quality control. The aim of this chapter is to propose a quality gate reference process with defined requirement criteria to prevent the occurrence of defects. The framework shall be applied in quality control and in-situ process monitoring to enhance overall manufacturing quality.

Keywords: additive manufacturing, fused deposition modeling, reference process, quality gates, quality control

1. Introduction

Customer demands on products and services are constantly increasing in the global and local market and the competitive conditions of companies are in constant flux. As a result, companies are faced with changing market conditions in which they have to assert themselves against increased competitive pressure, greater product complexity, and an ever-increasing variety of products [1].

Industrial 3D printing or additive manufacturing (AM) is considered the key technology for mass customization. This allows the individual production of complex components and offers various possible solutions for increasingly complex requirements [2]. Additive manufacturing is an umbrella term for manufacturing processes in which components are built up element by element or layer by layer directly from computer-aided design (CAD) data without component-specific tools [3].

Fused deposition modeling (FDM) belongs to the AM technologies, which enable incorporation of cavities in a part's design and have little changeover cost compared to conventional manufacturing processes, potentially enabling individualized production and new possibilities for light-weight products [4].

The first step of state-of-the-art FDM processes involves a so-called slicing software that is used to generate machine-executable instructions (G-code), approximating a virtual product in the form of a CAD model. The desired product geometries are decomposed (sliced) into stacked layers of equal height along a specified axis, called the build orientation. Furthermore, for each of the layers, a closed two-dimensional path is planned, incorporating print head velocities set by the user. In the production step, the FDM machine follows the defined path while extruding heat-liquified raw material threads. Starting on the build plate, for each layer, the respective trace is followed by the machine, and so the whole part is fabricated. During the process, the machine must highly accurately control the correct material flow, the build plates state, and the correct positioning and velocity of the print head [5, 6].

While the concept seems straightforward to realize, practitioners long since report that reproducibility and reliability issues persist, demanding effective quality control measures [7–9]. Achievement of the aforementioned demand requires controlling for influences from the 5M-domains during pre-process and in-process stages: man, machine, milieu, material, and method affect the success of a print [10].

To achieve a successful production result, a set of numerous interrelated process parameters must be determined, some of which have been mentioned above. Finding appropriate parameters can pose a challenge to beginners, leading to failure in almost every second print [11]. Even expert knowledge does not necessarily lead to a good print result, but their experience helps them to avoid easily preventable mistakes. Many man-hours and unnecessarily wasted material could be saved by the prevention of simple mistakes. The reason lies in the fact that there is almost no recognized or approved reference process in which defined requirements serve as a quality control measure.

As of now, there are only few works that serve as a reference process for additive manufacturing. There is a lack of standards and norms that ensure high process and product quality. A lot of previous academic literature focuses on particular printing defects such as warping or oozing. Performed research indicates that comprehensive guidelines regarding failure prevention in the overall printing process ought to be developed. Additionally, there is a lack of in-depth documented requirements to achieve high quality in process and printed products.

This paper proposes a reference process model including 10 quality gates that serve as documented requirements to prevent defects and failure prints beforehand instead of costly troubleshooting. Section 2 describes related work and shows up the gaps upon which this present scientific work further elaborates. In Section 3, various failure types are introduced and considerations to prevent them. Section 4 contains the proposed reference process model including quality gates. Section 5 summarizes the results and discusses the advantages of the proposed approach and concludes with future research potentials.

2. Related work

An extensive list of FDM print issues and their causes have been published by Loh et al. [12]. Qualitative expert knowledge has been formulated in natural language and

lacks precise arguments. Each failure is assigned to a category which is either "printer-associated," "deposition-associated," or "print quality," but no reason nor meaning for an assignment is given. Livesu et al. provide a detailed description of the main process starting with the CAD model and ending in the G-code, but they focus mainly on software issues [13]. Baş et al. describe print conditions that sufficiently lead to faults by the application of a fault tree analysis (FTA) [14]. Many faults are described and their dependencies are formally expressed. The German Norm DIN SPEC 17071 proposes a print flowchart, leaving open the actual events of quality checks [15]. Oropallo et al. name error control in a list of 10 challenges in 3D printing. A distinction is made between errors during printing and errors before printing, which is partially avoidable [16]. Bähr and Westkämper divide a print into three stages: pre-process, in-process, and post-process. The importance of cooling is emphasized and divided up into a sinter phase, crystallization phase, glass transition phase, and a shrinkage phase, which are bounded by corresponding temperature values. Additionally, a table is provided that relates process parameters to their manifestation in component properties. Martinez-Marquez et al. developed a detailed quality control procedure including 18 quality gates but tailored to the production of patient-specific medical implants [17]. The process assumes the use of a laser-based AM system and error control is only briefly described. Fu et al. provide literature research and an overview of sensor technologies for in-situ monitoring of FDM processes [18]. Their flowchart is limited to in-situ printer health and product quality monitoring. Oleff et al. do systematic literature research in order to find quality-related research gaps, giving examples for a few FDM-process errors [19]. Song and Telenko examine FDM-print failures in a university makerspace [20]. They categorize these into user errors, machine errors, and designer errors. Also, a poll has been carried out to determine failure rates dependent on the user's experience level. The results show wastage levels of about 34% of the total material and a print failure rate of 41.1%. Gibson et al. provide a rough overview starting with the CAD model, ending in the application. An in-process view, as well as defects, is not considered.

To the best of the authors' knowledge, no publication at present exists wherein a generic reference process is determined in which quality gates serve as requirements for quality control to prevent printing defects.

3. Defects in additive manufacturing

Defects that occur later in the process chain are harder to assess, as this presumes that no defect has occurred in a preceding process step.

In the following, examples of failures are explained which can either be pre-process, in-process, or post-process. Also, dependencies among failures are illustrated and research hypotheses for their assessment are formulated. Most of the enumerated defects have already been explained by Loh et al., whose work is extended in the following.

3.1 Pre-process defects

The following shows defects that may occur in the pre-process steps and are possibly preventable through quality control measures.

3.1.1 Tangled filament

If the end of the filament thread on a roll has been guided through under itself, a knot will eventually form on this roll, making proper unwinding impossible. This can

happen after a user has unloaded filament from a printer. A proper loading process of filament should therefore be examined and verified.

3.1.2 Gaps

In all instances of this kind of defect, print segments are not properly connected and small gaps are recognizable by the naked eye. Loh et al. distinguish between three kinds "walls not touching," "gaps between Infill and outline" or "gaps between thin walls." Such gap appearances are introduced by the slicing software, affected by the extrusion line width. Thus, gap defects are avoidable if slicing errors are being determined.

3.1.3 Small features not printed

This defect highlights noticeable differences between the provided CAD model and the production instructions executed by the printer. Two distinctions between affected features can be made: A vertically standing wall whose width is smaller than the extrusion line width and a feature parallel to the build plate, whose height is smaller than the layer height. Material waste can be prevented if the slicing software informs the user about deviations between the CAD model and the generated G-code.

An example part that is susceptible to these kinds of defects is given in **Figure 1**, along with G-code paths generated by a slicing software using different parameter settings. The part consists of a block, a thin wall whose depth is 0.35 mm on its top, and a thin feature whose height is 0.1 mm in parallel to the build plate and is shown in (a). If a layer height smaller than the height of the thin feature of the CAD model and a line width smaller than the wall depth is chosen, then both the wall and the thin feature are not included in the generated G-code path, as demonstrated in (b). Conversely, if the layer height is smaller than the thinnest feature and the line width is smaller than the wall depth, then the sliced result matches the expectation of the

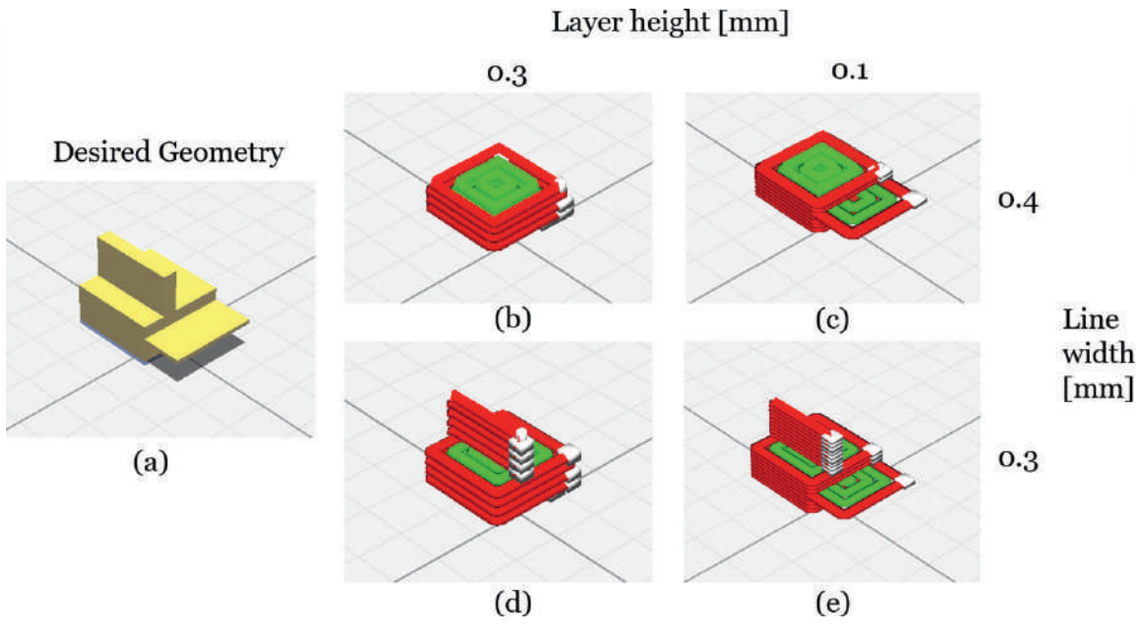

Figure 1.
Variations of parameter settings in slicing process of a complex cuboid object.

user, illustrated in (e). If either layer height or line width is not chosen appropriately, corresponding results will be sliced, as can be seen in (c) and (d), respectively.

3.2 In-process defects

3.2.1 Warping

The occurrence of warping (see **Figure 2**) manifests in an up-curl and a detachment of corners that touch the print bed at the bottom of the part in production due to tension arising from a non-uniform thermal gradient and shrinkage effects in the part. Deposition of additional layers on a corner that has already started to warp can negatively amplify the situation and may lead to an extension of the detached area. In the worst case, the part completely detaches from the bed; at this point, a print job should be canceled to avoid damage to the printer and further material waste. Scholars indeed argue that inclusion of brims or rafts or a reduction of infill percentage can help to avoid warping. As warping is irreversible, its occurrence should trigger a cancelation of the print process.

3.2.2 Detachment

The adhesion of the parts' first layer to the bed is essential for a successful result. If a part detaches from the bed, the print heads' movement will shift the part through its slight connection by the deposition strand. Thus, the material cannot be deposited at the correct location and the process should be stopped. The reason for detachment is an insufficient adhesion between the part and the build plate. Like warping, this defect is practically irreversible and the print process must be stopped.

3.2.3 Shifted layers

The path specified by the G-code must be executed accurately by the machine. Unsuccessful movement execution, for example, caused by missed-out steps of an axis motor, or a detached part creates positional deviations that lead to shifted layers if not compensated for.

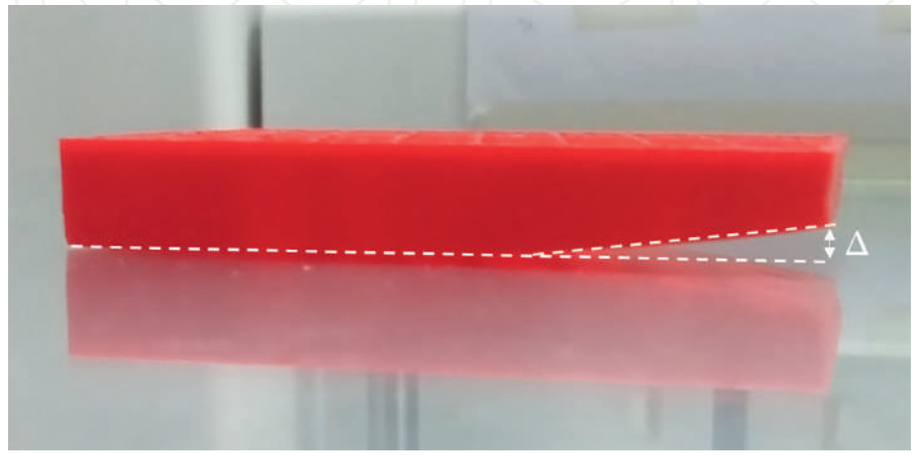

Figure 2.
Warping of a cuboid print model.

3.2.4 Clogging

Over the course of a print, all of the final parts' material must pass through the nozzle. Dust and undesired objects in the raw material can accumulate in the nozzle and lead to obstruction so that no material is deposable. Other causes could be burned residual material inside the nozzle as a result of an excessive extrusion temperature.

3.2.5 Nozzle cake/extruder blob/head flood

If material is continuously fed into the print head but cannot leave through the nozzle, then there is a risk of an occurrence of a head flood. The material sticks to material residuals that have previously been attached to the nozzle. Over time, more and more material accumulates around the nozzle. If the problem is not noticed at an early stage, the printer will likely be damaged severely. Removal of the accumulated material is time-consuming and a downtime eventuates.

3.2.6 Grinding

In FDM printers, a knurled ring drives the filament toward the hot end. If it loses grip on the filament, a small amount of material is removed from the filament's surface. If this happens for some time, then a groove forms in the filament thread, making transportation to the hot end difficult or impossible. Aggressive retraction settings can be the cause.

3.2.7 Overextrusion/underextrusion/missing extrusion

There are multiple causes for a missing extrusion: clogging, nozzle cake, or grinding. A camera, mounted at the nozzle's height, is used by many authors to monitor if the specified extrusion amount is matched.

3.2.8 Overheating

A central concept of extrusion-based 3D printing is the use of heat to extrude the raw filament. Overheating happens when a new layer is deposited on a lower layer, whose temperature has not cooled down to a certain level. Uneven printed parts may occur as a result (see **Figure 3**).

3.2.9 Curling

Another temperature-related defect caused by overheating is curling, which becomes apparent on topmost corners. This is similar to warping, but on the top instead of the bottom.

3.2.10 Pillowing

The exhibition of blisters or undesired holes in the topmost layers is termed pillowing and is caused by overheating. It can be detected the earliest after the last layer has finished and cooled down.

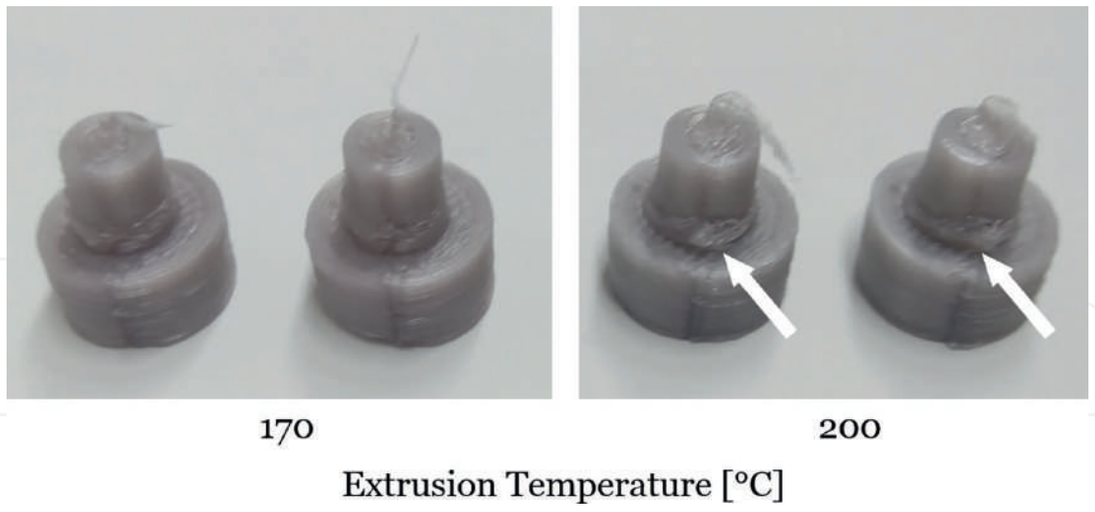

Figure 3.
Effects of overheating on print.

3.2.11 Stringing and oozing

The hot-end provides a continuous stream of liquid material whose flow is influenced by the feeder. As the hot-end consists of metal parts, rapid cooling down below the glass transition temperature of a given material to solidify inside the nozzle is infeasible. Reasons for stringing can be too high extrusion temperature or unapplied retraction settings. Once strings have appeared, there is no way to remove them during the print process. Stringing can be corrected by a post-process heat treatment.

3.3 Post-process defects and quality measures

After a successful production, the quality-related requirements may be assessed.

3.3.1 Blobs and zits

The occurrence of small bulges on the side of a part is termed blobs and zits. The interplay between start/stop position and retraction settings causes this defect. **Figure 4** shows a corresponding example, which demonstrates the development of blobs and zits that appear at the start/stop positions (right), which are marked by white dots on the left figure.

3.3.2 Porosity/voids

Due to the stacked deposition of round material beads, part-internal voids are a natural consequence. Such internal properties may be examined either by a dissection of a parts' region-of-interest or by nondestructive metrology like microcomputer tomography.

3.3.3 Vibrations and ringing

High print speeds induce vibrations that propagate through the printer's frame and cause small deviations in the head position. Hence, patterns according to these deviations appear on the parts' surface.

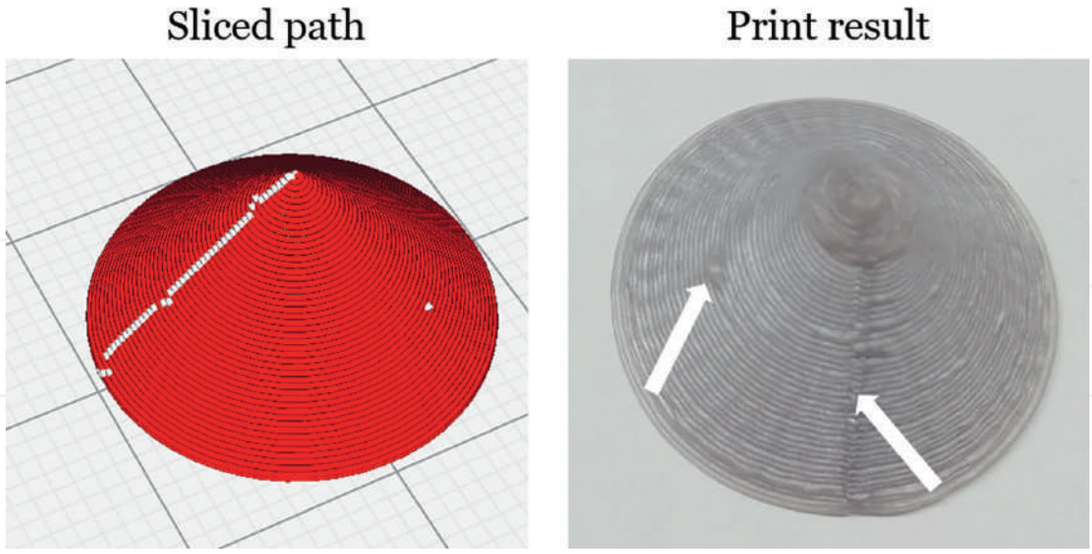

Figure 4.
Blobs and zits on a conical print object.

3.3.4 Dimensional accuracy

Overall shape deviations can be assessed by a separate measurement instrument.

3.3.5 Surface quality

The surface quality is the first aspect of an object that a customer perceives during an inspection of the object. This quality criterion can be checked independently of the actual model.

3.3.6 Mechanical properties

After quality checks of dimensional accuracy and surface quality, mechanical quality checks may be performed. Destructive assessments include tensile, shear, and compressive strengths, while part density can be measured using a scale.

4. Reference framework and quality gate process

The lack of norms and standards often leads to manufacturing processes that are defined from scratch for each individual production run, which provokes plenty of try-and-error operations. Indicative of this are numerous troubleshooting guides that help individuals cope up with problems that occur during the printing process as well as frequently discussed issues in community-based online forums (see for example [21–24]). On the other hand, there are very few references on how to plan quality and prevent easily avoidable defects beforehand. This leads to the overall conclusion that a lot of quality issues can be prevented if a reference process with criteria-based quality gates guides through the manufacturing process to ensure high process and product quality.

A reference process supports process requirements so that the process quality and resultant product quality remain consistent and reproducible at all times. This paper

proposes a generic reference process model for additive manufacturing that describes the common sequence of activities for fused deposition modeling. Furthermore, this work suggests a model that contains pre-process, in-process, and post-process steps and starts with the CAD design and ends in machine and product post-processing (see **Figure 5**). The reference process model is based on the standard DIN SPEC 17071:2019–2112 [15] that represents a process chain for additive manufacturing that can be seen in **Figure 6**.

This blueprint of an additive manufacturing process chain is further specified in the reference process model in **Figure 5** and quality gates are added. A quality gate specifies criteria in process steps as well as quality-relevant characteristics and factors that have to be met in order to continue the process flow. It enables to perform corrective and/or preventive action to ensure high quality [25].

The reference process starts with the CAD of the product that is going to be manufactured. After that, the pre-processing steps will ensure the material selection, preparation, loading, and build chamber preparation. Moreover, the build orientation and strategy, as well as the generation of support structures, will be determined. In the manufacturing process itself, the production of the first layer of the build is a crucial part and is a decisive factor for the continuous process. After the build is finished in printing, a cooldown process will harden the material. In post-processing, the build product has to be removed from the build platform and both the machine and the product itself need post-processing. The machine is cleaned-up and restored to the initial state in order to be prepared for following production runs. The support structures are removed from the printed parts and a surface finish is performed where required.

There are nine quality gates in the proposed reference process model that serve in the course of the manufacturing process as points at which a decision is made on the progression to the next process step on the basis of quality criteria clearly defined in advance. Each criterion may be checked to prevent quality issues in the succeeding process steps. **Table 1** gives an overview of all nine quality gates and the respective criteria.

In the following, an example will show how the quality gates may prevent printing issues and may ensure the overall process quality. Therefore, a 3D-printed door hinge was manufactured according to the reference process model, and after each process step the quality gate criteria are reviewed and verified.

The first quality gate is actually positioned before the pre-processing of the additive manufacturing process and verifies the CAD design of the print part (QG 0). First of all, the manufacturability in regard to printer settings and the adherence to design rules can eliminate severe quality issues that may occur during printing' as an example thereto, if the door hinge cannot be assembled after printing because of poorly placed through-hole positions.

In QG 1, storage and material validation should be performed during the material preparation to prevent material-related quality issues. Filament could be damaged because of humidity or temperature-related variations in the storage area and may provoke damage during the printing process. In addition to that, there should be sufficient filament supply for the print that has to be printed as well as a coherent diameter of filament.

After the material was loaded to the feeder of the printer, QG 2 ensures that the orientation of the filament feed is adequate and the nozzle of the printer is unclogged. Moreover, the filament tubes should be empty and the overall filament feed rate is sufficient.

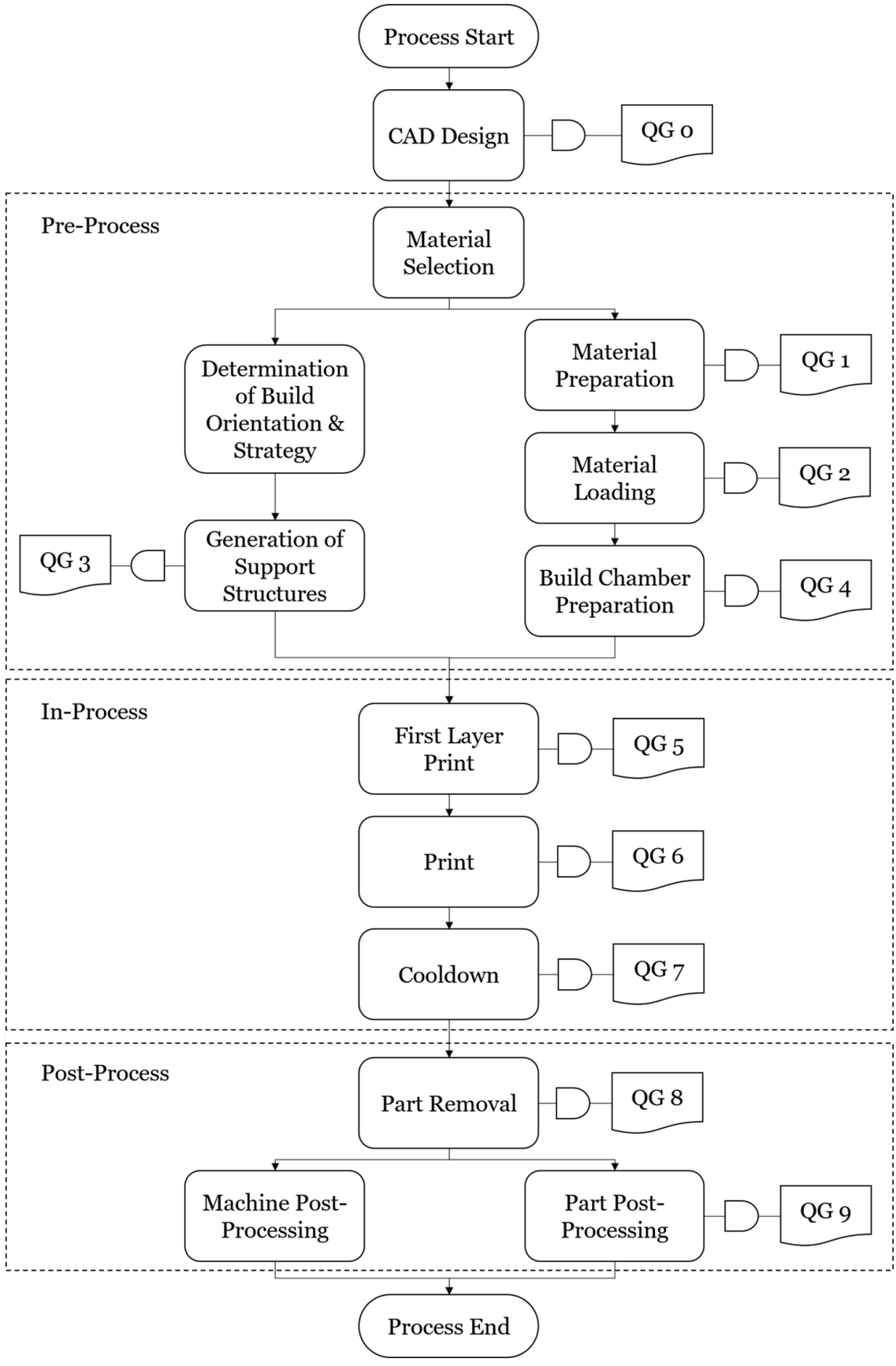

Figure 5.
Reference process for additive manufacturing.

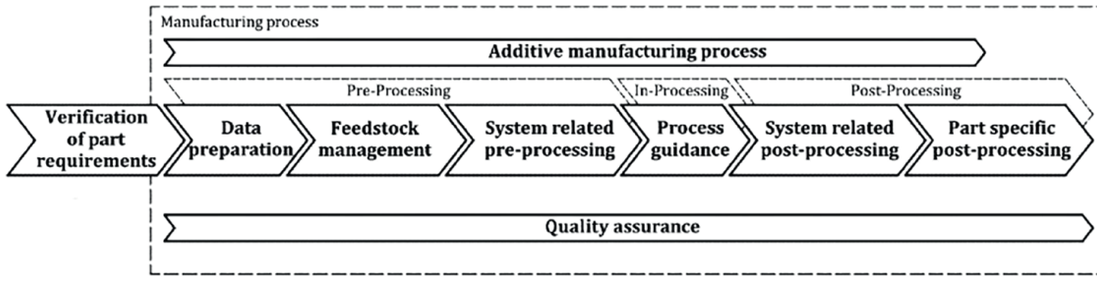

Figure 6.
DIN SPEC 17071 process standard for additive manufacturing [15].

Quality gate	Description	Criteria
QG 0	Verification of requirements and design approval	• Verification of manufacturability • Adherence to design rules • Avoidance of mass accumulation • Verification of process requirements • Verification of product requirements • Customer design approval • Wall thinness according to nozzle size • Solid bottom and support structures
QG 1	Storage and material validation	• Humidity of storage area • Temperature of storage area • No filament tangling • Age of filament according to manufacturers' instruction • Sufficient filament supply according to design • No visual material damages • Coherent diameter of filament
QG 2	Loading quality validation	• Sufficient filament feed rate • Adequate filament feed orientation • Unclogged nozzle • Empty filament tubes
QG 3	Software and file validation	• Error-free STL-files • Correct infill density • No infill overlaps • Error-free slicing process • Updated slicing software • Updated printer firmware

Quality gate	Description	Criteria
QG 4	Build chamber validation	• Free belt movement • Free extrudement wheel • Clean and dry build platform • Adequate build platform temperature • Leveled and flat build platform • Aligned rod • Fixated printer position • Adequate nozzle height from build platform • Adequate retracting settings • Adequate cooling settings • Primed nozzle
QG 5	First layer validation	• Verification of extrusion process • Adherence to build platform • Verification of geometric and dimensional proportions
QG 6	Process monitoring	• Geometric stability of build and filament • Coherent filament flow • Adherence to build platform • Adequate extrusion process • Adequate extrusion temperature • Adequate build platform temperature
QG 7	Cooldown validation	• Geometric stability (no warping or curling) • Verification of layer adhesion • Adequate part temperature • Adequate in-part temperature gradient (to avoid material stress)
QG 8	Visual inspection	• Verification of geometric stability • Verification of nondestructive detachability • Verification of transportability
QG 9	End of line quality validation	• Elimination of porosity/voids • Verification of surface quality • Verification of geometric form • Verification of tolerances • Verification of mechanical, chemical, thermal properties • Verification of density/mass

Table 1.
Quality gates for the reference process model.

QG 3 states that on the other hand, the slicing files, as well as the whole slicing process, should be error-free. Printer firmware and slicing software should load the latest update to prevent failure. The correct infill density and no infill overlap should be checked.

A lot of process failures can be associated with a build chamber that has not been calibrated for error-free printing. QG 4 examines if there is a free belt movement and a free radial movement of the extrudement wheel. Moreover, a leveled and clean build platform that has an adequate temperature can ensure a consistent printing process. The printer should have a fixed position because the printing process may cause vibrations and an unintended re-orientation of the whole system that may, in turn, interrupt the filament feed.

The first layer of printing is a crucial step for the whole printing process. Therefore, QG 5 should verify the extrusion process and the adherence to the build platform. Moreover, a visual inspection of correct geometric and dimensional proportions should be performed.

After the first layer print, the continuous layer-by-layer printing should be in-situ monitored (QG 6). The filament flow and the extrusion process should be closely monitored, as well as the geometric stability of the print. Temperature sensors may observe the extrusion temperature and build platform temperature.

When the printing process is completed, the cooldown process is also a quality-relevant aspect. To prevent warping or curling of the print due to material stress, the temperature should be lowered slowly (QG 7). In addition to that, layer adhesion should be verified.

A visual inspection can be performed as soon as the print is removed in a nondestructive manner from the build platform (QG 8). The geometric stability and the transportability should equally be verified.

Lastly, an end of line quality check should be performed after the post-processing (i.e., surface finish, removal of support structures). Verification of the surface quality as well as the geometric form including all relevant tolerances should also be performed. Finally, the mechanical, chemical, and thermal properties should be checked.

5. Conclusion and further work

The proposed reference process model including the criteria-based quality gates to prevent printing issues serves as a guideline to achieve high process and product quality. Opposed to common troubleshooting that is carried out during the occurrence of printing issues, the presented model herein allows executing corrective or preventive action. The lack of norms and standards in additive manufacturing as well as rudimentary reference processes makes it difficult to meet process and product requirements *per se* and achieve a planned quality level.

This research work has introduced a reference process including pre- and post-process activities with the aim to standardize the printing process of FDM 3D printing. These process steps are sub-divided by quality gates that ensure the fulfillment of requirements to ascertain the prevention of quality issues. There are nine quality gates that have quality descriptions in form of documented requirements that have to be met.

In view of the above, it may be stated that the proposed process model requires some effort for the verification steps in terms of an operational measuring system. Regarding the in-situ monitoring of the printing process, temperature sensors for

the extruder system as well as the build platform and a feed rate sensor need to be installed. Additionally, the calibration of the printer settings and the validation of the build chamber is a time-intensive procedure and therefore extends the printing process not inconsiderably. The availability of all required sensors is a valid difficulty.

There are several limitations to the introduced reference process model. First of all, it only addresses manufacturing processes that are based on thermoplastic materials. Powder bed fusion like selective laser melting is not considered in this reference process or in the quality gates. Therefore, this reference process model has to be adjusted accordingly in order to allow for these alternative additive manufacturing processes.

Further research activities have to be performed to achieve a more concise insight into how to prevent quality issues during additive manufacturing processes. First of all, this model needs further verification and validation in order to define the degree at which it can prevent relevant quality issues. Qualitative and quantitative studies may focus on what the overall benefits of this quality gate process are in terms of not aborted production runs or customer-relevant requirements. Moreover, the list of documented requirements in the quality gates is not exhaustive and quality criteria may be composed through further research to generate a complete reference model.

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Chapter

Quality Management Costs in Logistics

Marieta Stefanova

Abstract

The minimization and elimination of deviations from quality that could cause a failure in the logistics system should be identified at an early stage in order to reduce the costs for recovering the system to its normal operation. The objective of this study is to analyze the contribution of prevention costs related to quality management to the total costs by focusing on the need to undertake priority preventive actions to ensure logistics services that meet the customer's quality requirements. The methodology of the study includes the integrated application of conventional scientific methods for comparative analysis and Taguchi's design for accounting regarding the primary costs for quality management with the predominant use of qualitative analysis. By applying these methods, the following groups of costs have been analyzed: prevention and avoidance of nonconforming quality; quality evaluation and control; and covering the costs for nonconforming quality of the logistics services. The contribution of the three groups of costs has been studied. Based on the analyses, this paper comes to the conclusion that the management of those costs by groups of factors for incurring them has the potential to contribute to the improvement of the quality of logistics.

Keywords: costs, logistics, nonconformities, quality

1. Introduction

The costs for maintaining the quality of the logistics services at the level of the customer's expectation are associated with the achievement of high efficiency of the processes [1, 2], better quality of the incoming material flows [3], and performance of the equipment and inventories without failure [4, 5]. The achievement of the "Just-in-time", JIT principle for all products delivered requires targeted managerial efforts for maintaining the continuity of the logistics processes [6–10], ensuring efficient human resource management [11–13], and optimal utilization of the warehousing potential [14–17]. The identification, minimization, and elimination of deviations from set quality levels and the causes for failure of the system should be identified at the earliest possible stage in order to reduce the expenses for recovering the system to its normal operation. The level of quality has a positive impact on the implementation of the selected logistics strategy [18–21], whereas the low level of quality is an indicator of the poor efficiency of the supply chain [22]. The main objective of the quality management processes is to ensure the effective performance of the logistics services. It has been concluded that when the quality management processes are operated as a

system, they have a much more positive impact on the performance of the individual components of the system rather than the contrary. It has also been postulated that certain key areas of the logistics operations have a decisive impact on the efficiency of the logistics system, such as, for example, transportation and storage operations.

To analyze the costs for maintaining required quality levels, the components of those costs (**Figure 1**), need to be clarified:

Improvement of the logistics system efficiency is a key factor for ensuring products that meet demand and the flawless management of the organization [23–27]. Logistics operators that organize the supply chain by setting targets and results based on a limited budget manage to achieve growth in their revenues and assets, and, at the same time, reduce their operational costs [28, 29]. Due to the constantly emerging risks in the operations in the real economy where the logistics operations take place, it is often necessary to respond to the specific situation for overcoming the bottlenecks without considering the strategic guidelines for business development [30]. This is why the systems that are very flexible and capable of changing together with the market and the changes in the external environment are the most rapidly developing ones. In essence, the purpose of logistics operations can be defined as the effective and timely movement of goods to the places where the customer needs them at a reasonable price [31]. However, there are often restrictive conditions for the fulfillment of those purposes, and the appropriate equipment for loading and moving the transport vehicles is not always available when they are needed. In addition, the capacity of each logistics warehouse is strictly confined and fixed. There is competition in the sector of logistics, too. Therefore, the business needs to focus on its main competence and outsource to external contractors those services, the operation of which causes unjustified losses of resources, in order to achieve effective management of the costs for quality improvement. Actually, the main

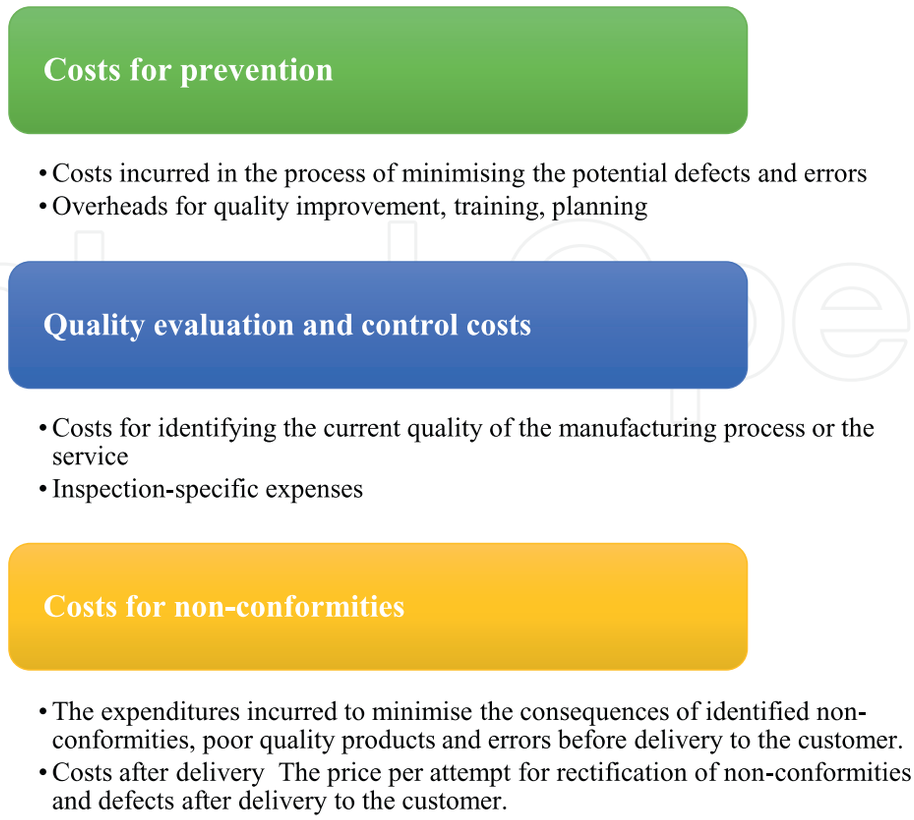


Figure 1.
Quality assurance-specific costs.

purpose of cost optimization is to practically [32, 33] satisfy the customer's requirements by reducing the time for making the delivery. The main impediment to achieving this purpose is caused by the limited possibility to transfer and receive information about the actual demand in real-time.

The main problem about minimizing the costs for achieving the logistics purposes is related to the understanding about the management of the system itself as one that distributes the cargo ("push") and one that requires distribution of the cargo where necessary and based on a customer's order ("pull") [34]. The first type of system is more appropriate in the case where no exact information about the need of goods is available. However, in this case, if demand is significantly higher than supply, distribution of scarce goods and priority servicing of selected customers is needed. The use of mathematical methods for planning routes, occupation of the warehousing facilities, and temporary hiring of workers can help to reduce costs. When accounting for the total operational overheads, the expenses for handling, storage, and transportation of the goods should be accounted for based on the main cost items. This can be done by identifying all the resources (including human resources), the packaging and repackaging operations performed, the processes, and the methods used for evaluation and control in order to ensure the overall performance of the process. In other words, the total costs for logistics are the sum of all costs incurred for the management and implementation of all processes and operations related to the logistics operations. Generally, the total costs can be divided into the following three groups:

- costs associated with the operations,
- costs related to with the management of the logistics system and,
- costs associated with the application of possible logistics risks.

There is an interesting approach in the control of quality management costs, which was developed by Taguchi [35]. This method focuses on the causes for deviations from the quality and on establishing clearer criteria for defining the critical boundary that distinguishes between conforming and nonconforming services [36]. Taguchi's contribution to quality management is related to the following principle that any variations and deviations in the function of quality are the results of random and nonrandom factors and losses are observed when the variation results in conditions where the product or service is on the exact boundary of the target conformity value [37]. This is the quadratic loss function since it is assumed that when the product or service is at its target value, the loss will be zero. According to Diallo, Khan, and Vail, the relationship between quality improvement by decreasing the variations and the costs can be analyzed by using Taguchi's function. Many researchers have also applied Taguchi's method in the field of logistics services [38–41].

The contribution to the reduction of the total operational costs for prevention of nonconforming logistics services as compared to the increase in the costs for their management and their relationship to the costs for monitoring and control in logistics services has not been studied. A number of logistics organizations have not focused on this analysis and, as a result, perform restructuring or investments which do not yield the expected positive outcome. It is the author's view that logistics service providers should draw their attention to investment in quality management related to the prevention of nonconformities. At the same time, logistics service providers should exercise more effort on the potential opportunities for the development of the actual

logistics services and the service processes. This study offers a practical solution for management and analysis for measuring these qualitative changes.

The objective of the study is to analyze the contribution to total costs of the expenses for prevention related to quality management in logistics by focusing on the need to undertake priority preventive actions to ensure the provision of logistics services that meet the customer's quality requirements. By using the applied methods, this study analyses the contribution to quality improvement of the costs attributed to the prevention and avoidance of nonconforming quality, for quality evaluation and control, and for covering the expenditures for nonconforming quality of the logistics services. The relationship between these groups of costs in quality management has been identified by means of structural modeling, which helps to establish the contribution of the costs to the achievement of sustainable quality of the logistics services.

2. Research methods

The primary method for data analysis that has been used is Taguchi's method, which defines quality from the perspective of cost minimization and the subsequent loss to society. Based on his definition about quality management, continuous, consistent, and targeted actions are required to achieve minimum variability of the logistics services offered. According to Taguchi, the efforts should focus on the following two aspects: defining the combination of factors that have the lowest impact on any deviation from quality, and adjusting those factors that are the cause for the deviation from the set target of the logistics services. Based on the results obtained from Taguchi's loss function, the contribution of the different factors that could have an effect on the deviation from the customer's expectations for high-quality logistics services can be quantified. This can be used for initiating improvements that could have a positive impact in terms of satisfying those expectations.

2.1 Stages of Taguchi's method application for this study

Taguchi's method was applied in two stages:

1. A model generation stage, which allows the selection of those controllable levels of the factors that have the greatest contribution to the achievement of the logistics services quality level expected by the customers (studied dependence) and the respective significance levels.

2. Performing the actual analysis (Taguchi's design) to identify the parameters of the analyzed factors that minimize the variation in the deviations. The calculation of the tolerances that contribute to the reduction of deviations from the expected quality level of the logistics services is performed using the software Microsoft Excel XLSTAT 2021® [42].

2.2 Method for collection of data for analysis

The proposed data to be evaluated have been taken from the annual financial statements of an operating logistics company in the food sector and have been subsequently divided into three main groups: for prevention and avoidance of nonconforming quality; for quality evaluation and control; for covering the costs for nonconforming quality

Short name	Nbr. Of categories	Period of time before implementation of the changes in the cost structure	Period of time after implementation of the changes in the cost structure
Prevention costs	2	450 (in thousand euro) (450 k€)	500 (in thousand euro)
Evaluation and control costs	2	200 (in thousand euro)	250 (in thousand euro)
Cost of nonconformities	2	100 (in thousand euro)	50 (in thousand euro)

Table 1.
Variable information.

of the logistics services. The information collected about the last two-year period has been summarized in tables in order to visually illustrate the potential impact and the actual improvement of the economic result. After the final data from the studied two-year period were collected (before and after the introduction of the changes in the cost structure), those data were summarized and presented in **Table 1**.

By observing **Table 1**, it can be seen that the costs for improvements after the introduction of the changes are two times greater than the costs for prevention and control, whereas the costs for covering losses as a result of nonconforming logistics services have decreased by half as compared to the period before the implementation of the changes. The change in the cost structure based on the pre-defined three groups has allowed for the practical application of Taguchi's principle that the nonconforming logistics service cannot be improved through the process of control or covering the losses from the nonconformity after the service has been provided. The application does not have the potential to create a conforming service, but just to identify the conforming and nonconforming services. Based on the data obtained, the experimental design was built and a questionnaire was generated.

2.3 Evaluation collection method and discussion method

The data collection for the study was performed via telephone and online meetings in focus groups by taking into account all the restrictions imposed in relation to the pandemic. All participants in the study are currently managers in organizations where the main scope of business is the provision of logistics services in the field of trade and delivery of food products to wholesalers.

The participants in the study were selected based on their management experience and, in particular, their experience in the field of logistics services quality management costs. The required criterion for participation was at least 10 years of experience. Initial informative telephone conversations about the study and its methods, including the observation of all requirements of the relevant legislation related to personal data protection, were performed with potential participants in the study. Only 5 out of a total number of 20 potential participants did not agree to participate. The participants who confirmed participation received a questionnaire. The main purpose of this questionnaire was to study the potential attitudes and evaluations of the participants regarding the need of change in the structure of quality management costs. The study was performed in two consecutive panels in online meetings with a discussion in focus groups held in-between. The evaluation of the participants' opinion was performed based on a 100-point scale ranging from 1 to 100. The questionnaire of the study is presented in **Table 2**.

By using the 100-point scale (where 1 is the lowest value and 100 is the response with the highest value), please, evaluate which, in your opinion, would be the most suitable cost structure for logistics services quality management represented in 8 different categories.				
Observations	**Prevention costs**	**Evaluation and control costs**	**Cost of nonconformities**	**Respondents' answers in the two panels**
Obs1	450	200	100	
Obs2	450	200	50	
Obs3	450	250	100	
Obs4	450	250	50	
Obs5	500	200	100	
Obs6	500	200	50	
Obs7	500	250	100	
Obs8	500	250	50	

Table 2.
Questionnaire of the study.

After the study, the participants' responses were averaged and summarized for further analyses using Taguchi's method.

The method used allows on one hand a comparison to be made, while on the other to quantify the difference between the target function (optimum ratio between the quality management costs) and its actual manifestation. The objective was to find a solution for minimizing deviations from the target function for logistics services in the food sector.

3. Results

In the course of the study, Taguchi's principles and methods for quality management were used to identify the optimum ratio between the quality management costs. The first principle that was applied is related to the statement that quality should be designed in the logistics service before offering that service on the market and, respectively, a strategy should be undertaken to increase the prevention costs (designing conforming quality) at the expense of the other costs.

Based on the experimental design, further calculations were made to find the contribution of the increased or decreased share of certain overheads to the achievement of a conforming service impacted to the lowest possible extent by the other factors. The data obtained from the two focus group sessions held were averaged and entered in **Table 3**.

Based on the results from **Table 3**, the experts have given a significantly lower number of points to the ratio of costs in the cases where there is an increase in the costs for operations associated with the rectification of problems, rather than preventive actions. It was concluded that this was the right approach; however, despite this, it is the author's view that logistics organizations practically continue using their entire potential not for the development of the types of services offered on the market, but for the rectification of problems that have occurred in the course of providing those services. The reasons for that could be related to the fact that often when designing the actual services, the processes are dragged over time, which in turn, may

Observations	*Prevention costs*	*Evaluation and control costs*	*Cost of nonconformities*	*Response 1*	*Response 2*
Obs1	450	200	100	75.000	76.000
Obs2	450	200	50	80.000	82.000
Obs3	450	250	100	78.000	80.000
Obs4	450	250	50	84.000	85.000
Obs5	500	200	100	85.000	84.000
Obs6	500	200	50	98.000	97.000
Obs7	500	250	100	88.000	96.000
Obs8	500	250	50	99.000	99.000

Table 3.
Experimental design (response 1 and 2).

lead to a delay. Therefore, this process often needs to be compensated by reducing the time limits under signed contracts and by adjusting all the details and parameters related to the negotiation of the logistics service. As a result, certain logistics operations are skipped, which are subsequently performed without actually specifying their parameters. This, on the other hand, creates more favorable conditions for customer claims and undertaking actions to increase the control in order to avoid such nonconformity in the future. The higher level of control leads to an increase in costs and does not guarantee that the services will be conforming if the conditions that lead to the presence of claims remain unchanged.

The analysis of controllable factors that create conditions for deviations in the logistics services has been studied with respect to the contribution of costs for the different operations to the total operational costs. These costs include both the costs for planning the logistics services and the costs related to the control of those services and compensations to customers related to claims and returns, replacement, or repeated implementation of the logistics operations. It is the author's view that claims could be minimized by designing logistics services that are needed by the customer rather than services that the organization is capable to provide. A number of studies have come to the conclusion that the prevention of claims is more efficient than covering the costs once a claim has been filed and, respectively, could result in greater customer satisfaction [43–47].

Based on the data collected, Taguchi's model has been created, where the ratio LS means (Signal-to-Noise ratios) has been calculated. It defines the ratio between the mean value of the share of each cost from the total costs and the standard deviation. The variability of the analyzed indicators considered significant by the experts for the provision of a conforming service, defined by their standard deviation from the average value, is presented in **Figure 2**.

The results presented in **Figure 2** show that prevention costs have been evaluated as the most significant factor with positive impact, followed by the positive impact of the costs for control. The influence of the increase in the costs for nonconforming logistics services has been assessed as negative. The multiple criteria used by the logistics operators for calculation of the services are related to the satisfaction with their expected quality and are hard to quantify. The studies performed so far show that investing in the design of services has a significantly more positive impact on the expected quality than investment in a higher level of control on the performance of those services (the prevention costs and the costs for control are equally increased by 50 units).

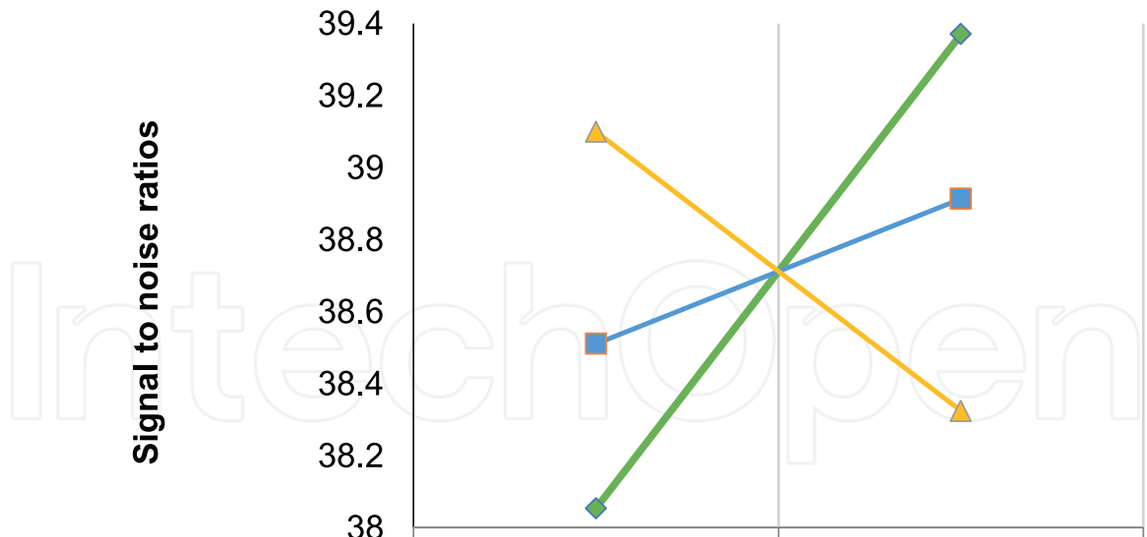


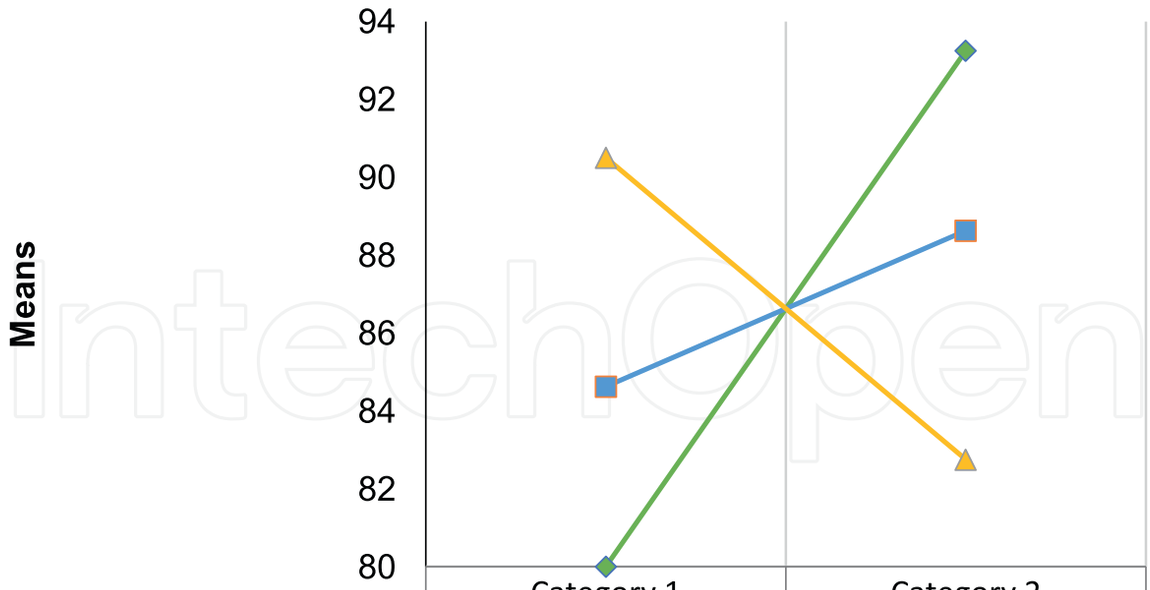
Figure 2.
Signal-to-noise ratios.

Taguchi's approach thus requires seeking an appropriate solution for reducing the variations applied to the expected quality of the logistics operations and provides an opportunity to find results for lower deviation from the target function. The model these decisions can be based on, so that the variations in the logistics services are lower than expected, is presented in **Table 4**.

The studied factors are statistically significant (at 0.05), which allows an optimum ratio to be set between the studied costs so that the deviation from the target function

Source	***Value***	***Standard error***	***t***	***Pr > |t|***	***Lower bound (95%)***	***Upper bound (95%)***
Intercept	39.184	0.136	287.649	**<0.0001**	38.805	39.562
Prevention costs-450	−1.317	0.136	−9.666	**0.001**	−1.695	−0.939
Prevention costs-500	0.000	0.000				
Evaluation and control costs-200	−0.402	0.136	−2.952	**0.042**	−0.780	−0.024
Evaluation and control costs-250	0.000	0.000				
Cost of nonconformities-50	0.775	0.136	5.690	**0.005**	0.397	1.153
Cost of nonconformities-100	0.000	0.000				

Table 4.
Model parameters (standard deviations).



	Category 1	Category 2
Prevention costs	80	93.25
Evaluation and control costs	84.625	88.625
Cost of non-conformities	90.5	82.75

Figure 3.
LS means (means prevention costs, control costs, cost of nonconformities).

is as low as possible. **Table 4** equally shows the statistical significance of each type of costs and their contribution to the achievement of an optimum combination of those costs. According to the feedback provided by the questionnaires, the most important factor in quality management is cost prevention because the absolute value of this factor is the highest. It can be stated that the prevention costs and the costs for control on the processes in the specific case that was studied were increased by the same number of units; however, the prevention costs demonstrated a much higher effect on the target function.

These results are confirmed by the main effects graphs in **Figure 3**.

Logistics organizations should invest in operations for the prevention of nonconformities in order to decrease the variability in the target function, even if the causes of the variations are not eliminated.

It has been practically demonstrated that the costs for eliminating the variation in the target function are very high. A more feasible and practical solution is to just change the structure of the costs or to control the factors that are more significant and have a greater impact on the target function. This can be achieved without increasing the total expenses or with a minimum increase resulting just from the redistribution of costs in the proper direction. Furthermore, the overheads that do not have a positive impact on the variations in the target function could be decreased and thus invested properly, in areas where their impact could be more favorable. This is what the application of Taguchi's method on the structure of quality management costs in logistics allows the user to do – to calculate the contribution of the three cost groups in order to achieve an optimum effect in the target function.

4. Conclusion

During the study, the change in the structure of quality management costs was analyzed based on the significant factors for achieving customer satisfaction defined by the experts. Data from the expenses incurred by the logistics company operating in the food sector were analyzed, which were divided into three groups of costs and described in the methodology. The road to improvement was found to be associated with the following:

- cost reduction for nonconforming services after delivery,
- keeping a relatively stable level of the expenditures for control and,
- to distribute the highest share of expenses for prevention by investing in the improvement of the processes for designing conforming logistics services.

Based on the analyses, it was concluded that even a change in the cost structure could contribute to a higher level of customer satisfaction with the studied logistics services in the food sector. Reducing the variation around the target function could not only contribute to higher customer satisfaction; moreover, it could reduce the overheads for nonconformities after delivery which are caused in particular by such a variation. Indeed, higher customer satisfaction could be achieved, if there is less variation with respect to the service wanted by the customer and delivered on time.

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Conflict of interest

The author declares no conflict of interest.

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Chapter

Managing Foodservice Quality in the Foodservice Industry

Lindiwe Julia Ncube

Abstract

Quality has become a value that enables businesses to survive and continue existing. Henceforth, food industries need to entrench quality into their business performance. Foodservice quality is characterized as a service that bears on its ability to satisfy stated or implied needs and service free of defects. Foodservice businesses are an integral part of social life, both biologically and socially, biologically as satisfying the nutrition requirements of the society and socially in terms of addressing socialization and esthetics-pleasure values. Therefore, by adopting quality approaches, food industry businesses may encourage customers' preferences for those businesses that diligently offer these services. Managing food service quality is a complex and challenging task requiring commitment, discipline, and emergent effort from everyone involved in food production processes. The task also requires the necessary management and administration techniques to continuously improve all processes (including quality control from raw material to finished product). Food industries need to be organizationally structured, establish policies and quality programs, measure customer satisfaction, use more quality tools and methodologies, embrace knowledge, apply techniques, and food safety programs to manage food quality. This chapter aims to describe the ISO 22000 system—widely used for quality management in the food industry.

Keywords: foodservice, food industry, quality management, customer satisfaction, food production

1. Introduction

Unsafe food is a risk for all, and consumers can become seriously ill; hence the food industry may face serious legal consequences. These constant problems call for additional strategies for decreasing and eradicating the risks. As food safety is a joint responsibility for all participating parties, communication and raising awareness of potential hazards through the entire food chain is crucial [1]. Recent research suggests that most microbial food contamination in the food market happens in developing countries than in developed countries. Indeed, most chemical food contamination and food adulteration occur in developing countries. Additionally, the misuse of food additives was a common problem in developing countries; and in developed and developing countries, mislabeling was a problem. Furthermore, the selling of outdated foods occurred in developing countries than in developed [2].

Food products are produced from farms or from food originating from farms. For example, food items such as bread, milk, meat, fruit, vegetables, and sugar originate from agriculture. Farmers grow, harvest, store, and transport food and food products raw materials to markets or processing plants, and transform them into various food items and products [3]. However, since the original standard was published over a decade ago, there have been substantial changes in how food is grown, transported, manufactured, and consumed. A study by [4] on food safety management systems (FSMS) performance in African food processing companies reported high microbiological and chemical contamination levels in most African food products, which exceeded the acceptable (legal) limits. In developed countries, innumerable deficiencies that affect the performance of FSMS in Africa were found at government, sectoral, retail, and organizational levels. For example, most companies (except for the exporting and large companies) hardly implemented HACCP and ISO 22000:2005.

The authors further recommended the use of measures such as the construction of risk-based legislative frameworks, strengthening of food safety authorities, and using ISO 22000:2005 for food safety management in the food industry. Indeed, consumers' food safety training was projected to be implemented by the government. The food sector had to develop sector-specific guidelines and third-party certification, while the food retailers had to develop stringent certification standards and impose product specifications. Food companies had to improve hygiene, apply strict raw material control mechanisms and production process efficacy, enhance monitoring systems assurance activities, and develop supportive administrative structures. Globally, it has been an accepted norm that food safety management systems be based on Hazard Analysis Critical Control Point (HACCP) principles, which is an internationally accepted FSMS. However, the implementation of HACCP in South Africa has been driven by the requirements of international trade—where foods are exported to developed countries such as Europe and the United States of America. A regulation requiring HACCP implementation was publicized in South Africa in the year 2003. However, the foodservice industries are not compelled to comply. According to [5], there is currently no force that pressurize the foodservice industry to implement formal food safety management systems in South Africa. Hence, the growing need for international traveling and hosting of international sports events dissected this industry.

Urbanization, consumer changes in eating habits, and travel have increased the number of people buying and eating food prepared in public places. As a result, globalization has triggered growing consumer demand for a wider variety of foods, resulting in an increasingly multifaceted and longer global food chain [6]. Food safety is becoming more critical with the demand for food to meet the rapidly growing world population. The food-to-table progression put a significant focus on food contamination prevention and maintaining good food quality standards. Each food supply chain is highly regulated by government agencies such as the FDA and the newly implemented Food Safety Modernization Act. The population growth results in increased agriculture and animal production to meet the increasing demand for food, subsequently creating opportunities and challenges for food safety. Food safety ensures that products delivered to consumers do not negatively impact their health [1]. Hence, failing to comply with the food safety regulations may result in foodborne diseases. Climate change is also influencing food safety. These challenges put greater responsibility on food producers and handlers to ensure food safety.

2. The food supply chain and food contamination

Globally, about 600 million people fall ill after eating contaminated food, and 420,000 die every year, resulting in the loss of 33 million healthy life years (DALYs). Safe food supplies support national economies, trade, and tourism, contribute to food and nutrition security, and underpin sustainable development [7]. The Centre for Disease Control, CDC, estimates that roughly 48 million people get sick, 128,000 are hospitalized, and 3000 die from foodborne diseases each year [8]. Due to the speed and product distribution range, local incidents can quickly develop into international emergencies. Severe foodborne illness outbreaks have occurred in every continent in the past decade, often augmented by globalized trade. For example, the contamination of ready-to-eat meat with listeria monocytogenes in South Africa in 2017/18, brought about 1060 cases of listeriosis and 216 deaths. At the same time, contaminated products were exported to 15 other countries in Africa, requiring an international response to implement risk management measures [9].

Food can become contaminated at any stage of the food chain including the production and distribution stages, and the primary responsibility to prevent food contamination lies with the food producers. The authors [10] reported that foods that are not prepared properly, or foods mishandled at home, in foodservice establishments, or at markets contribute to the majority of foodborne disease incidents. In addition to this, most consumers and food handlers may lack knowledge and understanding of the practice of basic hygiene measures when buying, selling, and preparing food items hence, their health and that of the wider community may be at risk of foodborne illnesses. Tracking food through all the supply chain stages has become more complex and difficult as consumers are distant from the farm. Therefore, farmers must ensure food safety when growing and processing food, and during food preservation and transportation. Due to the fact that food items travel long distances, food products are exposed to a greater possibility of contamination or spoilage [11]. **Figure 1** below shows the flow of food and services that begin at the input and farm production sector and extend along the food supply chain until they reach the consumer.

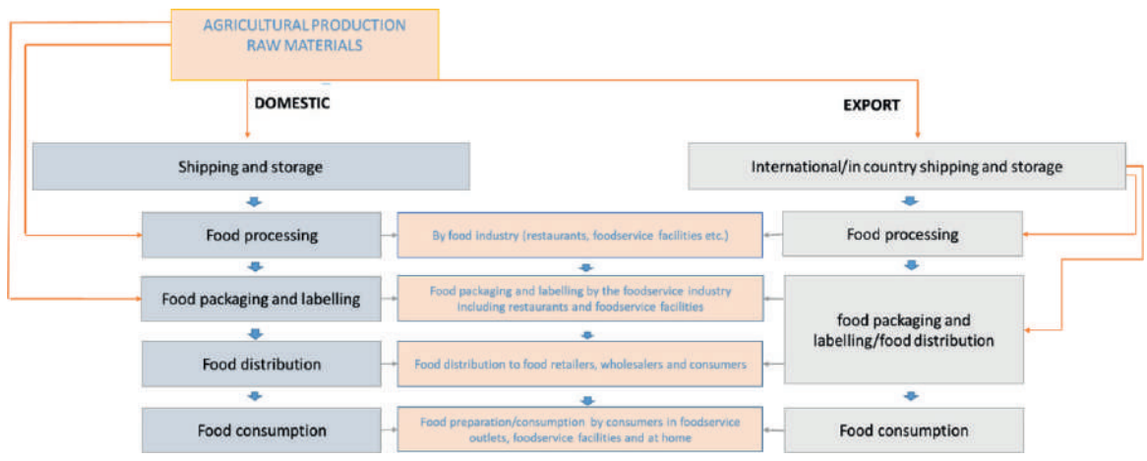

Figure 1.
The food supply chain.

2.1 The ISO 22000:2018 food safety management system

The ISO Food Safety Management System is malleable and can be utilized by all organizations involved in the food chain. Resulting from the usage, the food industry

organizations may share common food safety language, thus reducing the risk of critical errors and maximizing the use of resources. Enterprises such as growers, transporters, packagers, processors, retailers, public and private catering companies, public and private food production and services units, bottlers, and restaurants can implement this standard [12].

The ISO 22000 was first published in 2005 to overcome the food crisis and facilitate harmonizing international food safety rules and regulations. The food industry has received the standard well, however the new food safety risks impelled for an updated version. Therefore, the latest edition was published on 19th June 2018 and upholds a concrete association with the Codex Alimentarius standards. The standard also addresses evolving food safety challenges and supports the organizational strategic direction with its Food Safety Management objectives.

The ISO 22000: 2018 is an internationally recognized food safety management system that can be used in any organization in the food chain. The latest ISO 22000:2018 is the newest food safety management standard bringing a common framework to all management systems. The ISO 22000:2018's framework can assist in aligning the different food safety management system standards, helps to keep uniformity, offer corresponding sub-clauses against the top-level structure and apply communal language through all standards. Also, the new standard in place, makes it easier for organizations to incorporate their food safety management system into the fundamental business processes and attract more participation from senior management [13]. The ISO 22000:2018 is more focused on top management to demonstrate leadership and commitment to the FSMS and food safety policies. Additionally, top management needs to ensure the consignment, communication, and understanding of all the responsibilities, across the organization. Also, top management has a responsibility to ensure that the adequate food safety importance is communicated and understood by all parties and that the FSMS achieves its intended outcomes.

2.1.1 Key changes of the ISO 22000 standard

The following critical changes of the IS0 22000 standard were identified by [14].

1. Organizational context: clause four (4)

This clause intends to provide a high-level, strategic understanding of the essential issues that can positively or negatively affect organizational food safety management. It countenances the organization to identify and understand factors and parties that affect the intended outcome(s) of the FSMS. It addresses the concept of preventive action, where organizations need to determine external and internal issues, problems, and risks relevant to their purpose. The issues should also include conditions that affect the organization, such as those highlighted in the general guidance on "issues" in Clause 5.3 of ISO 31000:2009.

The organization needs to identify the interested parties relevant to the FSMS. For example, these groups could include customers, consumers, suppliers, and non-government organizations. Determining their relevant needs and expectations is currently part of establishing the context for a FSMS. After the context has been established, the FSMS scope must be determined with various additional factors.

Finally, Clause 4 requirement is to establish, implement, maintain and continually improve the FSMS. This clause requires adopting a process approach. Although each

organization may be different, documented information such as process diagrams or written procedures can be used to support this.

2. Clause eight (8): operation

With the exception of the HACCP Step one (Assemble HACCP team), Step 12 (Establishing documentation and record-keeping), which are addressed outside clause 8 (in clauses 5.3 and 7.5, respectively), Clause eight of ISO 22000: 2018 is more focused on the HACCP principles and steps. Internal audit—a verification procedure (Step 11), is covered in clause 9.2.

Clause 8.1—Operational planning and control

In clause 8.1, an organization's responsibility regarding processes required to meet requirements (plan, implement, control, maintain, and update) is highlighted in more detail. Examples of establishing criteria, implementing processes control, and demonstrating that processes have been carried out as planned are also provided, and a necessity to implement risk and opportunities assessment actions is introduced.

Clause 8.2—Prerequisite programs

For the effective implementation of any food safety system, prerequisite programs are crucial. The following differences were observed between the ISO 22000: 2018 and the ISO 2005 versions: (1) The word establish was replaced with the word "*update*" in the statement "establish, implement, maintain and update PRP(s)"; (2) Since the ISO/TS 22002 series prerequisites are not compulsory, the standard includes the terms "shall" which indicates a mandatory requirement and "should" which indicates a recommendation. This change denotes that the only prerequisites organizations must implement (mandatory) are presented in the standard (clause 8.2.4). (3). Hence, the prerequisites list in the ISO 22000:2018 is similar to those specified in the ISO 2005 version. The significant differences are the additional terms such as product information/consumer awareness and supplier approval (although it is apparent that most organizations may have some related procedure in place to address the purchased materials management presented in the ISO 2005 version).

Clause 8.3—Traceability system

The ISO 22000:2018 standard presents a list of topics to be considered when organizations establish a traceability system. For example, the reworking of materials/products and the connection between received materials, ingredients, and intermediate products to the end products were not mentioned in the IS0 2005 version. The mandatory verification and testing of the traceability system's effectiveness exist in the ISO 22000:2018 version. Although this was not detailed in the ISO 2005 version, the guide for its application (ISO 22004:2014) encompassed making tests.

However, reference to quantities reconciliation (end products vs. ingredients) is a new requirement presented in the ISO 22000: 2018.

Clause 8.4—Emergency preparedness and response

Compared with clause 5.7 of ISO 22000:2005, the term "accident" was substituted with "incident." Clause 8.4 of ISO 22000: 2018 is more extensive than the one in the 2005 version. In the standard, it is currently compulsory to lessen the food safety emergencies, review, and update documentation. Additional examples of emergencies such as some new examples of emergencies were workplace accidents, public health emergencies, and interruptions of services like water, electricity, and refrigeration supply were added.

Clause 8.5.1, covers the preliminary steps to enable hazard analysis. In this clause, identifying raw materials, ingredients, product contact materials, end products (and

their intended use), preparing flow diagrams, and describing processes are considered as the first step of hazard control.

Also, the information to be collected to conduct hazard analysis is more detailed in the IS022000:2018. It is well explained that, at a minimum, the information collected by the food safety team should include statutory, regulatory, and customer requirements, food safety hazards, and products processes and equipment. A new point requiring organizations to declare the source (e.g., animal, mineral, or vegetable) of their raw materials, ingredients, and product contact materials were also added. Therefore, the new word "place of origin (provenance)" replaced the wording "origin," which demands organizations to identify their product origin.

The IS0 22,000:2018 also specifies that the organization must include the introduction of processing aids, packaging materials, and utilities in the flow diagram. When describing hazards analysis, The IS0 22,000:2018 stipulates that the food safety team address the following expanded issues:

Clause 8.5.2—Hazard analysis

The implicit understanding is that the food safety team must conduct a hazard analysis based on the preliminary information covered in the ISO 22000:2005. However, it is explicitly stated at the beginning of the ISO 22000:2018 to highlight its importance.

Changes were also observed in the type of information used to identify food safety hazards. The ISO 2018 food safety standard requires organizations to use internal information such as epidemiological, scientific, and historical data, statutory, regulatory, and customer requirements to identify food safety hazards. Therefore, instead of only focusing on the steps preceding and following the specified operation, organizations must consider all steps in the flow diagram, including the people involved.

In conducting a hazard assessment, organizations must determine the likelihood of occurrence prior to applying control measures and evaluate the severity concerning the intended use.

After identifying the hazards, determining acceptable levels, and hazard assessment, the step that follows is to select and categorize control measures. The following aspects to consider when selecting and categorizing control measures are available in the ISO. However, most of them are similar to the ISO 2005 version. Notably, three issues are more critical: (1) assessing the practicability of creating assessable critical limits and measurable/observable action criteria. This is similar to what was also previously stated in the ISO 22004:2014: (2) To assess the viability of applying well-timed improvements in case of failure (3) and using the external requirements to select control measures.

Clause 8.5.4—Hazard control plan (HACCP/OPRP plan)

In the ISO 22000:2018 standard, information that was previously separated into two clauses: *Establishing the operational prerequisite programs* and *Establishing the HACCP plan is combined*. This assists in recognizing that the Hazard Control Plan must include a critical limit(s) at CCP and action criteria for Operational Prerequisite Programs (OPRP).

This standard presents the need to document the monitoring methods used in monitoring systems. The standard also augments the probability of utilizing *comparable methods* for calibration *to verify reliable measurements or observations for* OPRPs.

Clause 8.6—Updating information specifying the PRPs and the hazard control plan

The clause in the ISO 22000:2018 standard remains similar to clause 7.7 in the 2005 version. Above and beyond using a hazard control plan to substitute what was

previously considered operational PRP(s) and HACCP plan, it announces that after establishing the hazard control plan, organizations need to update raw materials, ingredients, and product-contact materials characteristics.

Clause 8.7—Control of monitoring and measuring

The ISO 22000:2018 standard's clause 8.7 was adjusted to make it more explicit. it has been declared that for monitoring and measuring PRP's hazard control plan, organizations must provide evidence that specified monitoring and measuring methods and equipment are adequate to ensure the monitoring and measuring procedures. The clause is more demanding for monitoring and measuring software as it requires organizations to validate its adequacy prior to use and when it is changed/updated.

Clause 8.8—PRPs and the hazard control plan verification

There are three differences identified in this clause: (1) The list of the constituents of the verification activities in ISO 22000:2018 corresponds to clause 7.8 of the ISO 2005 except that implementation, and the PRP's effectiveness (s) must be confirmed. Hence, the rewording of operational OPRP(s) and HACCP plan to hazard control plan is also to be noted. (2) It is mandatory in the ISO 22000:2018 standard that organizations must warrant the objectivity of the person who does the verification activities (3) Every time nonconformity is found in testing final manufactured goods or natural process samples, the ISO 2018 version postulates the necessity to take corrective actions.

Clause 8.9—Product control and process nonconformities

It is well explained in the clause that organizations must ensure that process nonconformities are addressed. Clause 8.9.2.4. of this standard clearly explains the information reserved to describe corrections made.

In the ISO 2005, the clause indicated that only designated persons (with competence and authority) might evaluate nonconformities and initiate corrections and corrective actions, which was dispersed throughout the clause. However, in the ISO 22000:2018 version, the clause is placed at the beginning of the title. Organizations must also review nonconformities identified by consumers or in regulatory inspection reports. In contrast, only customer complaints were given as examples in the 2005 version.

Clause 8.9.4.3—dispositions of non-conforming products, it is required that any product that fails to remain within critical limits at CCPs not be released.

Clause 9—Performance evaluation

Clause 9 covers the evaluation of how the system performs. The clause covers the monitoring, measurement, and analysis; including valuation—a new item, which forces organizations to indicate what and when monitoring and measurement should take place, and how, when, and by whom will the results be analyzed and evaluated. Also, when conducting internal audits, and after introducing the audits program (which must be used to verify the FSMS against the food safety objectives and policy), the clause expects organizations to recognize the importance of integrating the changes in the FSMS and the results of monitoring and measurement. The clause also highlights the importance of reporting the audit results to the food safety team and pertinent management. Items such as nonconformities and corrective actions, the performance of external providers, adequacy of resources, and opportunities for continual improvement were added to the management review section of clause nine. The internal and external issues are covered as inputs for addressing any applicable change essential for the FSMS mainly, changes including decisions and actions related to output continual improvement opportunities.

Clause 10—Continuous improvement

The is a new sub-clause that was added to clause ten of ISO 22000:2018 which gives clear guidance on addressing nonconformity and corrective action. The sub-clause is similar to the one in ISO 2005 standard however, the need for an organization to continuously improve the effectiveness of the FSMS and its suitability and adequacy was added in the 2018 version. No relevant changes were found in the last clause of the system (*updating the FSMS*).

The standard considers these changes essential to help organizations reduce food safety hazards and beneficial in alignment with the organization's strategic direction for the food safety management system.

For effective implementation, ISO 22000:2018 is developed on a high-level structure and enables an organization to use a process approach (PDCA) cycle along with risk-based thinking. This high-level structure is beneficial in the integration of other management standards. This standard enables an organization to control food safety hazards along the food chain. This "Norm" also applies to all types and sizes of organizations in the food industry.

2.2 Process approach and risk-based thinking

In addition to making ISO 22000 and the resulting FSMS easier to integrate with other ISO management systems, the IS0 22000:2018 introduces the Plan-Do-Check-Act (PDCA) cycle and risk-based thinking. ISO 22000 can help organizations reduce risk exposure and improve safety by combining organizational and operational risk management into one management system. For example, combining PDCA and risk-based thinking to manage business risk with HACCP to identify, prevent and control food safety hazards. Organizationally, this approach provides the opportunity to consider all the different things (both good and bad) that might impact the company [15]. The approach allows for prioritization of the FSMS objectives that it is implemented to accommodate the effects of these risks. On the operational side, risk-based thinking and implementation are based on HACCP principles associated with food safety management. **Figure 2** below shows how they can be seen in the diagram below.

The PDCA Cycle in the food industry.

The PDCA cycle is comprised of the Plan, Do, Check and Act concepts [16], and the cycle is suggested for beginning a new improvement project, implementing changes, continuous process improvements, and planning data collection and analysis (ASQ) [17]. There are four main stages for the PDCA cycle: Plan, Do, Check and Act [18]:

The "Plan Stage": The problem is identified during the planning stage, and data on the intended root causes are collected. Lastly, the intended outcomes are selected, as well as developing a plan to meet the outcomes. The planning stage is performed to assist in evaluating and forecasting problems that might occur during the execution stage and provide alternative modification strategies to prevent possible problems.

The Implementation stage: In this stage, the solution to the problem is developed and implemented, and the results are measured.

The "Check Stage": During this stage, the status and effectiveness of the plan are implemented. For example, checking whether the intended outcome was met and the reasons for not meeting the intended outcome if the outcome was not met.

Act Stage: This is the final stage of the PDCA cycle process and the first stage for the next cycle. In this stage, solutions are reviewed against standards, and actions are taken; information and results about the process and recommended changes are documented.

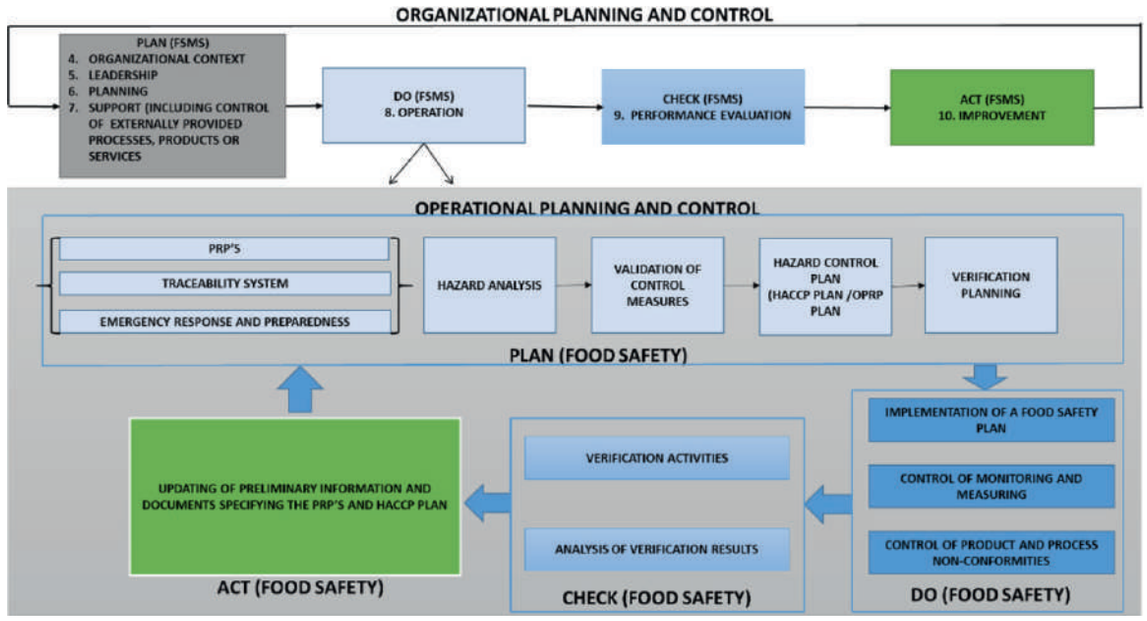

Figure 2.
The food safety PDCA cycle.

2.3 Uses of the PDCA cycle in the food industry

The PDCA cycle is a managerial decision-making strategy that guarantees that process, product, or service goals are accomplished [19]. The plan involves establishing goals and procedures to achieve the set goals. All employees are expected to meet performance standards and behave appropriately hence, contributing to the effective achievement of the goals set by the organizational management.

2.3.1 Corrective actions

Corrective action is a practice whereby management communicates with organizational employees to improve their behavior after other methods such as coaching and performance appraisal failed. Corrective action is also considered an aspect of quality management that aims to remedy a task, process, product/service, or a person's behavior when any deviation from an intended plan is identified. Once the deliverables deviate from the required output, corrective actions can be applied to the entire project whether tangible or service. For example, in Human resources for higher education institutions, corrective action also applies to individual employees and functions to communicate aspects of attendance, unacceptable behavior, or performance that require improvement.

For corrective actions, [20] suggest not using the PDCA cycle as a whole however, it must be broken down into the following seven food safety management system steps for corrective action procedures: **Planning Stage -Step one and two: Understanding the system requirements and planning the process**.

In the course of the planning stage, the managers must understand the FSMS, the nature of the deviations, and a root cause analysis must be conducted to determine the cause of the problem. The risk and consequences of the deviations must be frequently evaluated.

Do Stage-Steps 3, 4, and 5: Develop and Document, Conduct Training, and Implementation.

After the root cause analysis of the problem is determined, planning to correct the deviations can be performed. When developing corrective action, [21] is recommending the following actions by organizations:

- Determining the actual cause for the deviations.
- Developing action plans to ensure the effectiveness of corrective actions and preventative actions.
- Determining the need for training and ways to ensure and evaluate the effectiveness of the training.
- Determine whether there is a need to update the procedures.

Corrective actions may be implemented as soon as the right ones have been determined, procedures updated, and training performed. Implementation of the corrective actions could take account of retesting the food products, confirming and observing procedures, and revising food safety records to make certain employees follow the procedures.

Check Stage-Step 6: Test/check the system.

After a few cycles of corrective actions implementation, ensuring that the corrective actions become a permanent solution is essential. The check stage can be done by gathering employee feedback, employee interviews, reviewing the documentation, and monitoring employee activities.

Act Stage-Step 7: Adjust and improve.

In the last stage, the effectiveness of the corrective actions and preventative actions are reviewed, and the efficiency and effectiveness of the corrective actions are determined. Based on data obtained from the users, the corrective actions may be improved.

2.3.2 Internal audit

Internal audit is a fundamental process in any food safety management system because it helps evaluate its functioning as intended. It enables checking for the process systems and validates processes against their intended result—furthermore, internal audit assists in preparation for third-party audits [22]. This section will review the internal audit process from the PDCA cycle perspective.

The Internal Audit comes into play during the "Check" stage and allows checking of the process put in place during the "Plan" and "Do" Stages. During internal audits data is collected using document reviews, observations, and employee interviews, and used as evidence of the effectiveness of the implementation of the FSMS hence, the process allows for a full systemic review of the FSMS.

The envisioned internal audit purpose is to assure that one finds and resolves the deviations or gaps in the food safety management system before the third-party audit identifies them. The deviations found during the internal audits are documented and further reviewed for immediate corrections and follow the Corrective Actions and Preventative Action procedures. The Internal Audit and Corrective Actions procedures are inter-connected. That is the "Act" stage, where information gathered can be used to improve the organization's food safety management system [23].

2.4 Advantages and disadvantages of PDCA cycle

The PDCA cycle has its advantages and disadvantages. One of its advantages is that it is intended to be repeatable and reused as necessary, thus permitting continuous improvements. It allows for mistake documentation, assessment, and rectifications that can be frequent as needed. Any changes can be tested on a small scale before being implemented on a large scale [24].

According to [25], one of the disadvantages to the PDCA Cycles is that including the actual work only comes in the action plan; it can take very long and even get stuck at the "Plan" stages while being analyzed and not proceeding to the next step.

3. Conclusions

The literature discussed above evidence indicates the importance of implementing a food safety management system. Developing and implementing a food safety management system can assist any type of food production and manufacturing organization to ensure that they provide services or safe food products to their customers. As such, it is apparent that each organization can develop a FSMS relevant and suitable to address the needs of the interested parties. For effective implementation of the FSMS, ISO 22000:2018 was developed on a high-level structure where organizations use a process approach (PDCA) cycle along with risk-based thinking. The high-level structure assists organizations in integrating the FSMS with other management standards. The ISO 22000:2018 standard applies to all types and sizes of organizations in the food industry and supports organizations to control food safety hazards along the food chain. This standard also applies. Therefore, it is critical for food safety and quality management in the food industry.

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