Industrial Engineering Applications in Metrology: Job Scheduling, Calibration Interval and Average Outgoing Quality

A thesis submitted for the degree of Doctor of Philosophy

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Abstract

This research deals with the optimization of metrology and calibration problems. The optimization involved here is the application scientifically sound operations research techniques to help in solving the problem intended optimally or semi-optimally with a practical time frame. The research starts by exploring the subject of measurement science known as metrology. This involves defining all the constituents of metrology facilities along with their various components. The definitions include the SI units' history and structure as well as their characteristics. After that, a comprehensive description of most of the operations and parameters encountered in metrology is presented. This involves all sources of uncertainties in most of the parameters that affect the measurements. From the background presented and using all the information within it; an identification of the most important and critical general problems is attempted. In this treatment a number of potential optimization problems are identified along with their description, problem statement definition, impact on the system and possible treatment method. After that, a detailed treatment of the scheduling problem, the calibration interval determination problem and the average outgoing quality problem is presented. The scheduling problem is formulated and modelled as a mixed integer program then solved using LINGO program. A heuristic algorithm is then developed to solve the problem near optimally but in much quicker time, and solution is packaged in a computer program. The calibration interval problem treatment deals with the determination of the optimal CI. Four methods are developed to deal with different cases. The cases considered are the reliability target case, the CI with call cost and failure cost of both first failure and all failures and the case of large number of similar TMDEs. The average out going quality (AOQ) treatment involves the development two methods to assess the AOQ of a calibration facility that uses a certain multistage inspection policy. The two methods are mathematically derived and verified using a simulation model that compares them with an actual failure rate of a virtual calibration facility.

Acknowledgment

I would like to thank all those who have helped me to accomplish this research. My highest gratitude goes to the Royal Saudi Air Force (RSAF) from which resources I have greatly benefited and learned. I am also greatly indebted to my advisor, Dr. QingPing Yang who had extended me all valuable directions, guidance and encouragement. Special thank goes to my family, colleagues and friends for their support and cooperation.

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6. The work is sufficiently and properly referenced throughout the document.
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Table of Content

List of Tables

List of Figures

Acronyms

AOQ: average outgoing quality

BFL: best fit line

CI: calibration interval

CP: calibration procedure

EPL: end point line

IMC: Institute of Measurement and Control

IPI: In Process Inventory

LSL: least square line

MRA: mutual recognition arrangement

MACJSP: multiple attributes calibration jobs scheduling problem

MIP: mixed integer program

QA: quality assurance

SI: standard international

TL: terminal line

TMDE: test measurement diagnostic equipment

TO: technical order

UUT: unit under test

CHAPTER 1

GENERAL

1.1 Introduction

Metrology is the science of measurement and its applications. It is composed of two main branches, namely, measurement systems and calibration. Measurement systems are consisted of everything required to obtain an acceptable value of a particular measurand. This includes equipment, standards, procedures and many other tools. Calibration is the process by which measurement systems and their outcomes are assured correctness, precision and accuracy. Calibration is performed by metrologists, using calibration standards, according to the method indicated by calibration procedures, and carried out usually within a calibration facility.

This research deals with the optimization of all the problems involved in a fairly large calibration facilities (calibrate more 10000 device per year). The optimization will be performed by applying sound scientific methods and on top of it are the techniques of operations research and systems analysis. The methodology of the research will follow a number of stages. First analyze the system and define all of its components. Second, identify and define all the complex problems associated with any part of the calibration system for which the techniques of operations research can potentially be used to solve them. Finally, three of those identified problems are solved completely.

1.2 Research Objectives

The ultimate objective of the research is to apply optimization to metrology and calibration.

The thesis objectives are:

A. To find and address critical problems in metrology.

B. To solve the problems identified in details.

C. To search the literature for a previous identification of similar problems and solutions.

D. To explore the techniques of Operations Research that lend themselves to the problems.

E. To develop an innovative solution to solve the problems identified (optimally or semi optimally).

1.3 Scheme of the Research

The solution scheme follows three main parts. These are describing the system, identifying its problems and solving them optimally if possible. Following is a brief explanation of how each part will be accomplished (see Figure 1):

- Part I: Describing the system

  This part involves the following:

    - Define the metrology realm and its boundaries. This is covered in chapter two.
    - Describe metrology basics. This is covered in chapter three.

- Part II: Identifying the system problems

  Relying on part I, this part involves the following:

    - Identify the sections within which there are potentially an optimization problem
    - Identify the problems explicitly

- Part III: Solving the problems.

  Based on Part II, this part involves the following:

    - Identify the suitable operations research technique that will be used to tackle the problem
    - Develop the solution method
        - Develop the model or the algorithm that will solve the problem optimally
        - Develop the form with which the solution will be implemented

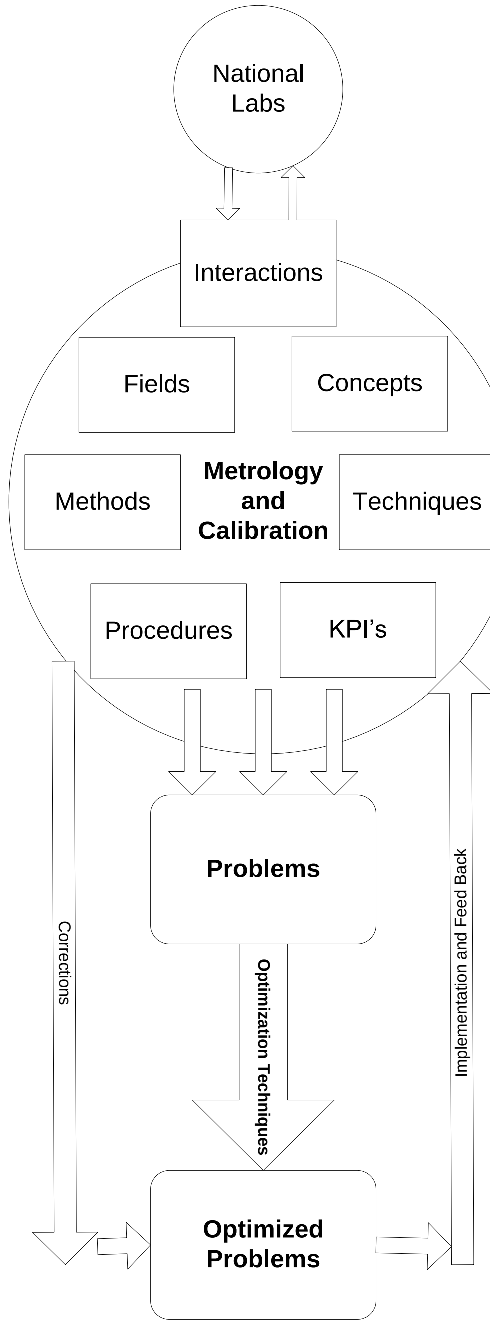


Figure 1: Research Methodology

CHAPTER 2

LITERATURE REVIEW

2 Literature Review

The literature review (uses Harvard System for citing) covers all the research chapters and topics. Each chapter review is listed together. The references are amongst the most important ones. Enough information is given in each citation about the paper content and in most cases it is enough for the reader that does not require him to check back the full paper. Some topics on the other hand are not treated in the literature because hardly anything is found about them.

2.1 Metrology Realm

Evans and Macdonald (2011) provided a summary of previous studies using metrological methods. Taymanov and Sapozhnikova (2010) argued there are growing indications of a crisis in conventional methods of metrological assurance. Ashworth (2004), described the arguments by which the modern metrology was inspired. Elisa (2005) explained the evolution of the measuring of time, current state-of-the-art measures and future challenges. Stone (1998) has postulated that the science of metrology has moved from man as the measure to man as the measurer. Giacomo (1996) draws attention on metrology, the science that gives the meaning of measurements. The founding principles for a good system were set by the decimal metric system, the forefather of SI. Placek (1993) discussed how today's needs for measurement instruments are determined. Schultz and Warren (2003) discussed the complexities of Islamic metrology in the Arab and Muslems countries. He remarks that metrology standards are not the same everywhere and quoted some Muslims authors. Berry (2002) explores the intimate and complex relationships which exist between physics, metrology and development. He indicated that metrology, the science and application of measurement, has since the 19th century been a vital part of the infrastructure of developed countries.

2.2 Metrology Operations

The manual Calibration: Philosophy in Practice (1994) is a comprehensive book compiled by Fluke Corporation. It is devoted entirely to electrical metrology in general. John (1995) in his book Principles of Measurement covers all aspects of measurement and measuring instrument in details. It is an introductory course to the subject but in rather more detailed explanation. Barry and Taylor (1995) put together an excellent reference about the SI system of units.

2.3 Operation Research

Operation research techniques and methods are too many to be described or run through in this context. My intention is to define the technique when I am going to use it in this research. There is a massive literature on various disciplines in operations research, and this will also be referenced whenever there is a need to that. The main references, however, are the general introductory text books that are used to cover most of the techniques of OR and their applications in industry. Taha (1987) is a comprehensive in-depth introductory course in operations research in general, with main focus on mathematical programming. Winston (1994) is another introductory course to the operations research techniques in general. It provides a plethora of examples and problems especially in algorithms and optimization problems solution techniques. Williams (1978) covers in detail the steps required for building a good linear, integer or mixed integer programs. French (1986) provided an introductory course in the subject of job shop and flow shop scheduling of both single and multiple machines. Michael (1995) covers the subject of scheduling in more detail than an ordinary introductory course like French's. It includes models of deterministic and stochastic scheduling problems and provides advanced techniques for solving them.

2.4 Problems in Metrology

Steve (2006) discussed the impact of backlogs and turnaround time. He states that the impact of these two performance measures degradations can be far more damaging than in prior days when products had advantageous and unique features. Bronnikov et al. (2010) discussed some trends in research on the physics underlying metrology as the science of measurement. Bucher and Jay (2007) discussed three sets of characteristics a calibration facility could fall under any one of them. They called them the good, the bad and the ugly (after a famous movie of the same name!). These characteristics cover all the aspects of the calibration system at all levels. Kononogov (2006) considered fundamental problems of modern metrology. Mandyam and Viswanathan (2010) considered a manufacturing system that operates in a high-variety, low-volume environment, with significant setup times. Simpson and Kenneth (1958) considered a manufacturing or servicing facility operations as chains of operations separated by inventories. Jin and Ydstie (2007) studied developments of the inventory control strategy. Elhafsi and Elsevier (2002) studied a two-level inventory system that is subject to failures and repairs. His objective is to minimize the expected total cost so as to determine the production plan for a single quantity demand. Chung-Ho and Chao-Yu (2002) investigated the problem of minimizing the average fraction inspected (AFI) of a continuous sampling plan. A solution procedure is developed to find the sampling plan parameters that meet the average outgoing quality limits (AOQL) requirement, while minimizing the AFI.

2.5 Multiple Attributes Calibration Jobs Scheduling

Cheng-Hsiung, Ching-Jong and Chien-Wen (2012) addressed a scheduling problem with multi-attribute setup times originated from the manufacturing plant of a company producing PVC-sheets. Shiqing, et al. (2011) proposed a multi-objective dynamic scheduling approach that combines three attributes based on a hybrid multiple attribute decision making (MADM) technique. Suresh and Mohanasundaram (2006) studied a job shop scheduling problem with the two objectives of minimizing the makespan and the mean flow time of the jobs. Feng, et al. (2008) solved the multiple objectives job shop scheduling problem. They proposed a solution that is based on a multi-objective orthogonal genetic algorithm. Numerical results are used to verify effectiveness and efficiency of the algorithm. Baykasoğlu, özbakir and Sönmez (2004) studied the flexible job shop scheduling problem. Ping-Teng and Yu-Ting (2001) proposed an integrated approach to modeling the job shop scheduling problems, along with a genetic algorithm/tabu search mixture solution approach. Udomsakdigool and Kachitvichyanukul (2008) proposed an ant colony optimization meta-heuristic to solve the job shop scheduling problem (the algorithm takes inspiration from the foraging behavior of a real ant colony to solve the optimization problem). Sha and Hsing-Hung (2010) constructed a particle swarm optimization (PSO) for an elaborate multi-objective job-shop scheduling problem. Sheldon, Yonah and Bernard (1992) prove that for unit time problems, an appropriate objective function can be formulated, which, when optimized, satisfies both the primary and secondary objectives. Low, Tai-Hsi and Chih-Ming (2005) investigated the job shop scheduling problems with re-entrant operations where the setup times is sequence dependent and cannot be combined with the job processing time. The objectives are three practical performance measures; the minimum total job flow time, the minimum total job tardiness and the minimum machine idle time. Rong-Hwa and Chang-Lin (2009) presented an ant colony optimization (ACO) heuristic for establishing a simple and effective mechanism to solve the overlap manufacturing scheduling problem with various ready times and a sequentially dependent setup time. Richard, John and Winkofsky (1982) presented a programming model for job shop scheduling which can consider a multiple-performance system of evaluations and incorporate multiple organizational goals. Zeng, et al. (2007) presented a solution method to the NP-hard scheduling problem. Wang et al. (2012) proposed an enhanced Pareto-based artificial bee colony (EPABC) algorithm to solve the multi-objective flexible job-shop scheduling problem. Franke, Lepping and Schwiegelshohn (2007) presented a methodology for automatically generating an online scheduling process for an arbitrary objective with the help of Evolution Strategies. Tavakkoli, Azarkish and Sadeghnejad (2011) presents a new mathematical model for a bi-objective job shop scheduling problem. Deming (2008) presented a particle swarm optimization for multi-objective job shop scheduling problem. Nhu and Joc (2008) presented an efficient approach for solving the multiple-objective flexible job shop. Ghasem and Mehdi (2011) present a new approach based on a hybridization of the particle swarm and local search algorithm to solve the multi-objective flexible job-shop scheduling problem. Framinan and Leisten (2008) tackle the problem of total flow time and make-span minimization in a permutation flow shop. Ling-Feng, Lin and Nagi (1999) presents a hierarchical approach to scheduling flexible manufacturing systems (FMSs) that pursues multiple performance objectives. Ramesh and Cary (1989) viewing job shop scheduling as a multi objective decision problem, they developed a framework for arriving at an effective schedules.

2.6 Calibration Interval Treatments

Ng and Pooi (2008), suggested a method of two stages based on the simple linear regression. Their method differs from classical uses of regression method which rely on the inversion of prediction limits. Schechtman and Spiegelman (2002) suggested a nonlinear approach to the determination of the calibration interval. Panfilo et al. (2006) considered two different techniques in order to determine the optimal calibration interval. Carlos and Mukaihata (1990) treated the problem of determining the optimum adjustment to a calibration renewal interval of a device under test within the context of a Markovian decision process. Kuo-Huang and Bin-Da (2005) discussed a class of data-preprocessed statistical models for evaluating the optimal calibration interval of a measuring instrument. Macii et al. (2004) presented two different techniques for the establishment of the optimal calibration intervals of cesium atomic clocks. Carbone (2004), adopted a technique to manage the calibration intervals of instruments. It is based on the simple response method. According to this technique, the interval between successive calibrations is adjusted adaptively on the basis of the outcome of the last calibration process. De, Grillo and Romeo (2006) presented a procedure for the determination of the optimal calibration intervals of a measurement instrument according to the reference Standard. Balakireva and Ekimov (1992) discussed methods of analytic determination of calibration intervals for off-line measuring facilities and means of determining the calibration intervals by simulation for redundant measuring systems. Hill (2005) discussed the need for establishing a correct calibration interval between the calibrated-before-use case and the no calibration after the first one. He discussed that similar equipment calibration interval may be used to defined the CI of the equipment on hand. Martin (1998) discussed the issues associated with the establishment of calibration intervals. The discussion focuses on considering the calibration interval as a tradeoff between a given tolerance probability and cost.

2.7 Average Outgoing Quality (of an uninspected items)

Jamkhaneh and Gildeh (2010) introduced the average outgoing quality (AOQ) and average total inspected (ATI) for double sampling plan when that proportion nonconforming items is a fuzzy number. Farnum (2006) derive upper and lower bounds at the point at which the average outgoing quality limit (AOQL) of an attributes acceptance sampling plan is achieved. He develop an accurate closed–form approximation to the AOQL using a simple average of these bounds to approximate the ordinate of the AOQL. Balamurali and Chi-Hyuck (2006) used the renewal theory approach to compute AOQ and AFI for both long run and short run production processes. Hong-Fwu and Wen-Ching (2007) dealt with the problem of determining the optimal mixed policy of inspection and burn-in, where the average outgoing quality (AOQ) is used as a measure of inspection and burn-in success. Sniedovich (1989) developed a computer program for the mathematical expression constructed by Nelson and Jaraiedi for the AOQ in the situation where a product is subjected to multiple 100% inspection. Yang and Grace (1983) formulated a class of continuous sampling plans (CSP's) that switch between full and partial inspection of items in a production line in terms of discrete renewal processes. The renewal-theory framework facilitates studying both the long-run average outgoing quality (AOQ) and the average outgoing quality in a short production run of length t, AOQ(t). Yang and Grace (1990) used a sampling system; MIL-STD-105D, used in quality control consists of three sampling plans with different acceptance probabilities in turn for lot inspection. They derive the performance measure, average outgoing quality (AOQ), of this sampling system from a renewal process in which AOQ is expressed in terms of the moments of the stopping times. Hui-Chung, Hsien-Tang and Min-Chun (2006) examined a multi-characteristic screening procedure using multiple screening variables. An extended OMS procedure using a heuristic algorithm is employed to reach the required average outgoing quality (AOQ) or conforming rate. Then two optimal models, namely the individual cut and linear cut approaches, are proposed to determine the optimal cutoff points of screening variables by maximizing the selected rate under a pre-specified AOQ or conforming rate. Moskowitz and Hsien-Tang (1988) developed a double-screening procedure (DSP), which controls for individual unit misclassification error and average outgoing quality (AOQ) for QC applications. Assuming conditions of normality, formulas for calculating the selection ratio and AOQ are derived for a DSP. Fard and Kim (1993) presented the impact of imperfect inspection on average outgoing quality (AOQ), sample size, and operating characteristic (OC) curves for a 2-stage sampling plan.

CHAPTER 3

METROLOGY AND CALIBRATION REALM

3 Metrology and Calibration

Metrology is the science of measurement, and measurement in the broader sense has existed in some form or another throughout the long known history of mankind. At the very beginning communities used primitive standards like some stones for weights or some items from nature that have a fixed length for the purpose of measurements. As time goes, measurement science has developed to more complex standards and more related methods. Following is a brief history of that.

3.1 Development

The development of metrology evolved gradually over the centuries as well as in various locations in the worlds. Early civilizations, have developed their own standards which were used heavily within their territory. But the concept of standardization has not yet (at that time) been adopted worldwide for many reasons. This continues until very recently when the need arises for a unified system of standard units that can be used all over the world (Berry, 2002).

3.1.1 History

The history of metrology can be looked at in many different ways. One way is to trace back the evolution of measurement science in one location over the entire known history of that location. The other way is to look at it in the entire world and concentrate only in the region where it flourished and had a rapid development. The first way has many disadvantages, and the biggest of all is the fact that this will leave gabs of knowledge about how a certain level in metrology has been reached in certain area and when. The development of metrology stages in history are briefly shown in figure 2 below.

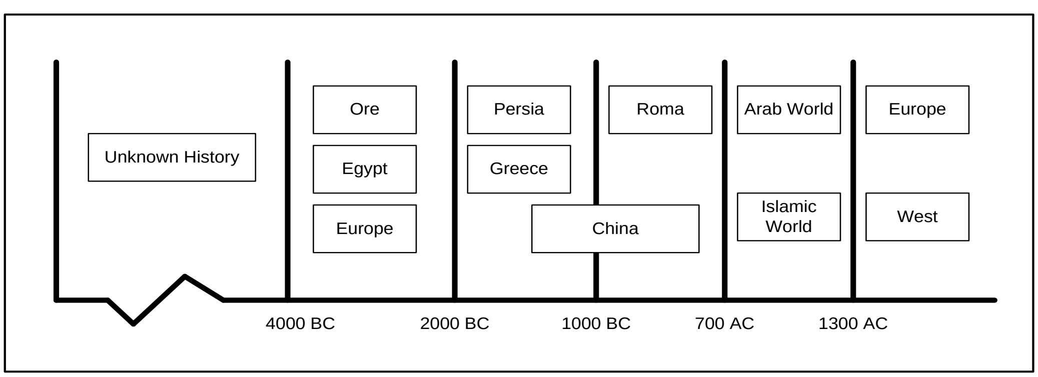


Figure 2.Metrology development around the world throughout history

3.1.2 Organization

Metrology organization in the world embarks on the Metre Convention and on the scientific entities established after that and following is a brief description of those.

3.1.2.1 Conventions

In 1790 the French National Assembly obtained Lowis XVI assent to commission the country's leading scientists to recommend a consistent system for weight and measures. As a result of that a report presented to the Academy of Science in 1791 by Lagrange, La Lande, Laplace, Borda, Mange and Concordet, recommended a system based on a unit of length. This unit of length is named the meter which is defined as the length that is equal to (one ten-millionth part of the distance from the Earth's North Pole to the equator at sea level). Legislation, authorizing construction of this new system of units was passed on 26 March 1791 and the metric system of units was born (IMC, 1998).

In 1799, it was agreed that the unit of mass would be one cubic decimeter of water at temperature of 4° C which would be the Kilogram (One cubic centimeter = one gram). A platinum weight was made and adjusted to the value of the unit and was known as the Kilogram des Archives.

3.1.2.2 Treaty (the convention du metre)

Convened by the French government, the treaty of the metre, also known as the Metric Convention was signed in Paris of May 20 1970. Attended by 17 countries, the treaty provided the machinery needed for the refinement, diffusion and use of the new metric system (Barry, 1995).

In 1875, the French government called for a meeting and in it eighteen countries subscribed to a treaty called "the convention du metre"

3.1.2.3 Structure

The structure of metrology is shown in the following table:

The Metre Convention
International convention established in 1875 with 51 member states in 2003.

CGPM Conférence Générale des Poids et Mesures
Committee with representatives from the Metre Convention member states.
First conference held in 1889 and meets every 4th year. Approves and updates the SI-system with results from fundamental metrological research.

CIPM Comité Internationale des Poids et Mesures
Committee with 18 representatives.
Supervises BIPM and supplies chairmen for the Consultative Committees.
Co-operates with other international metrological organisations.

CEN
IEC
ISO
Others

BIPM
Bureau International des Poids et Mesures

International research in physical units and standards.

Administration of inter-laboratory comparisons of the national metrology institutes and designated laboratories.

Consultative Committees:
- **CCAUV** CC for Acoustics, Ultrasound and Vibrations
- **CCEM** CC for Electricity and Magnetism
- **CCL** CC for Length
- **CCM** CC for Mass and related Quantities
- **CCPR** CC for Photometry and Radiometry
- **CCQM** CC for Amount of Substance
- **CCRI** CC for Ionising Radiation
- **CCT** CC for Thermometry
- **CCTF** CC for Time and Frequency
- **CCU** CC for Units

Table 1: International Metrology Organization Structure.

3.1.2.4 Responsibilities

The meter convention states the rules and guidelines by which the metrology system is established and organized. The CGPM is the meeting at which all major decisions regarding policies entire metrology organization and updates the SI system with results from fundamental metrological research. The CIPM supervises BIPM and supplies chairman for the consultative committees (Barry, 1995).

3.1.3 Metrology Basics

Metrology basics are the concepts, principles, methods and means by which all relevant parts of metrology structure are established. These include the concept of standardization, the definition of basic and derived measurement units, realization of those units and their traceability.

3.1.3.1 Standardization

Standardization is the process of developing and implementing standards (that could be standard specification, standard test method, standard procedure ...etc). The objective of standardization is to help with independence of single suppliers (commoditization), compatibility, interoperability, safety, repeatability or quality (Fluke, 1994).

3.1.3.2 Basic Units & Derived Units

The international system of units (SI) is the basis of modern metrology. The abbreviation SI comes from the French name "Systeme International d'unites". The system was established in 1960 by the General Conference of Weights and Measures. The system in its current form is composed of seven base units, nineteen derived units and two supplementary units (see Tables 2,3 and 4). The system is to be coherent, uniform and unified. Coherent because the base units are independent of each other and the derived units are made up entirely from a combination of the base units. Uniform because the base units are defined in terms of the invariant constants of nature like the speed of light and Plank constant (except the Kilogram which is based on a physical artefact). The SI units are unified because they are compared with each other in such a way as to observe the conservation of mass-energy (Fluke, 1994).

3.1.3.3 Defintion

The SI units definitions are shown in the following tables:

sn	Parameter	Unit	Symbol	Value
1	Length	meter	m	the distance traveled by light in a vacuum during a time intrval of 1/299792458 second
2	Mass	kilogram	kg	the mass of the artifact cylinder of platinum iridium alloy kept by BIPM at Paris, France
3	Time	second	s	the duration of 9192631770 cycles of radiation corresponding to the transition between the two hyperfine levels of the ground state
4	Electric Current	ampere	A	the electric current producing a force of $2X10^{-7}$ newton per meter of length between two long wires, one meter apart in free space
5	Thrmdnmc Temperature	Kelvin	K	defined as 1/273.16 of the thermodynamic temperature of the triple point of water
6	Luminous Intensiy	candela	cd	the luminous intensity in a given direction of a source that emits monochromatic radiation at a frequency of $540X10^{12}$ hertz, with a radiant intensity in that direction of
7	Amount of Substance	mole	m	the amount of substance of a system that contains as many elementary items as there are atoms in 0.012 kilogram of carbon 12

Table 2: SI Basics Units.

sn	Parameter	Unit	Symbol	Value
1	Plain Angle	radian	rad	the plain angle between two radii that is subtended by an arc equal to the radius
2	Solid Angle	steradian	sr	the solid angle with vertex at the center of a sphere that is subtended by an area of the spherical circle

Table 3: SI Supplementary Units

3.1.3.4 Realization

The realization of the an SI unit is the method, concept, artifact and equipment by which the definition of the unit is transformed into a unique value that could be disseminated to national labs by means of reference standards.

sn	**Parameter**	**Unit**	**Symbol**	**Value**
1	Frequency	herts	Hz	1/s
2	Force	newton	N	kg·m/s²
3	Pressure	pascal	Pa	N/m²
4	Work of Energy	joule	J	N·m
5	Power	watt	W	J/s
6	Electric Potential	volt	V	W/A
7	Electric Resistance	ohm	Ω	V/A
8	Quantity of Charge	coulomb	C	A·s
9	Electric Capacitance	farad	F	C/V
10	Conductance	siemens	S	A/V
11	Magnetic Flux	weber	Wb	V·s
12	Magnetic Flux Density	tesla	T	Wb/m²
13	Inductance	henry	H	Wb/A
14	Celsius Temperature	degree	°C	K
15	Luminous Flux	lumen	lm	cd·sr
16	Illuminance	lux	lx	lm/m²
17	Activity	becquerel	Bq	1/s
18	Absorbed Dose	gray	Gy	J/kg
19	Dose Equivalent	sievert	Sv	m^2s^{-2}

Table 4: Derived Units

3.1.3.5 Traceability

Traceability is defined as the property of measurement results or the value of the standard whereby it can be related to stated reference usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties.

3.2 Components

The calibration service is usually maintained through a big interrelated systems each of which support some of the others in way or another (see Figure 3). The calibration service, however, is composed of four main parts, namely, facility, documents, personnel and equipment.

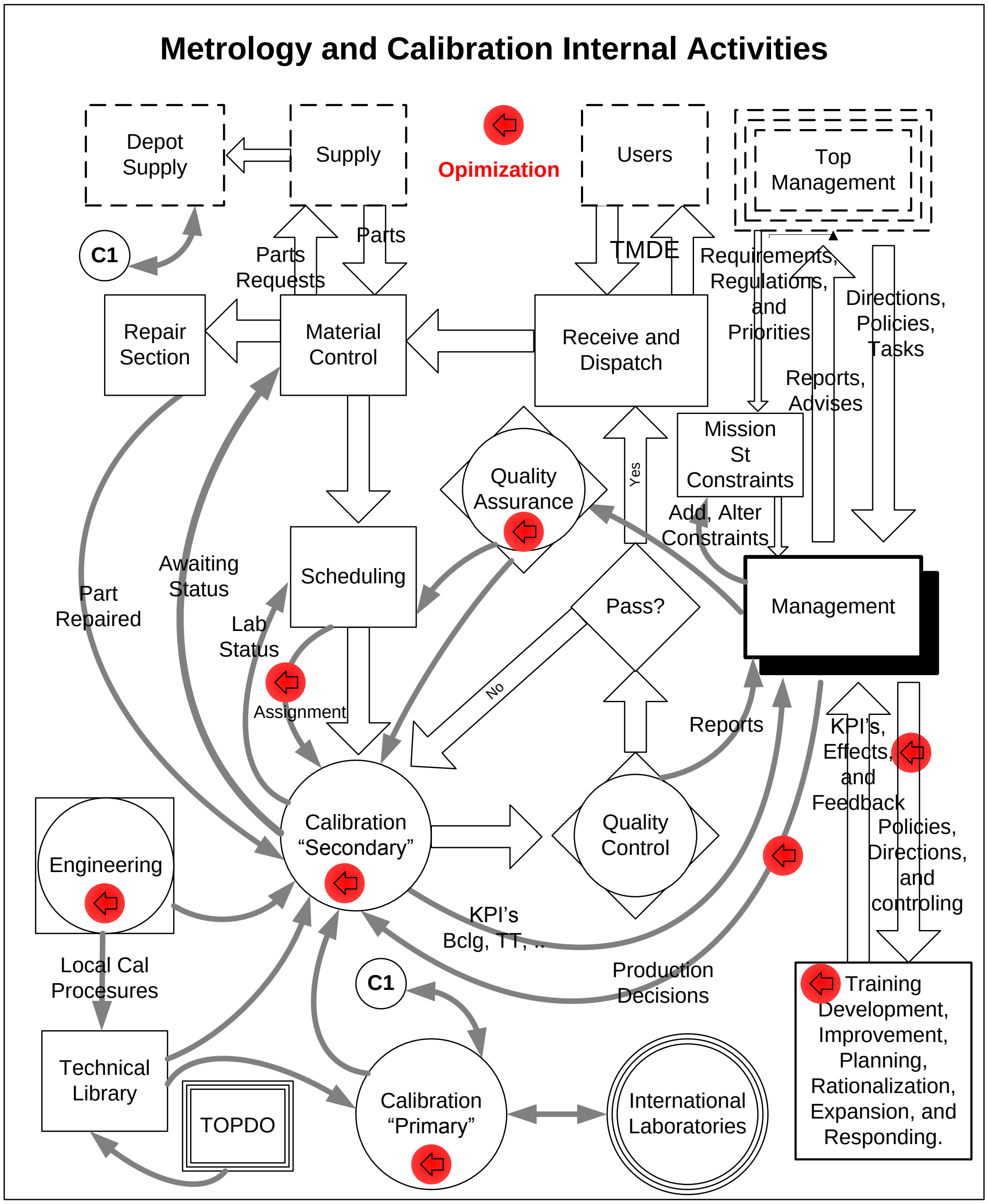


Figure 3: The General Calibration Service Organization

3.2.1 Facility

The facility is composed of the laboratories, mobile labs and the general support tools and equipment.

3.2.1.1 Laboratory

A laboratory is the core part of a calibration facility. It is a specially designated area dedicated to performing the calibration and repair of test, measurement and diagnostic equipment (TMDE). The laboratory is fitted with the necessary tools and equipment needed for calibration. It contains all types of calibration aids like workbenches, calibration standards, simple and complex measurement equipment, hand tools, connecters, leads, adapters, carts, jigs, fixtures environmental control and monitoring devices, cabinets, shelves and computers. In addition to that, it must be environmentally controlled and a constant monitor of temperature, barometric pressure, humidity must be maintained at all time. Moreover, it has some other subtle parameters that must be controlled and monitored periodically, such as, dust count, luminance intensity, vibration level, noise level and electrical interference. Specification of a calibration lab is shown in Table 5.

Acoustic Noise	Type I and Type II : Maximum noise level is 45 db
Dust Particle Count	Type I and Type II : Less than 7X10^6 pcm for Particles < 1 um and Less than 4X10^6 pcm for Particles < 0.5 um and No Particles larger that 50
Electrical and Magnetic Shielding	Type I and Type II : 100 uv/m max radiation field strength. DC ground bus to ground, less than 2 ohm. AC ground to ground, les than 5 ohm.
Lab Air Pressure	Type I and Type II : Maintain Positive Pressure of 10 Pascals.
Lighting	Type I and Type II : for Calibration 800 F, Offices 500 F, Library/Training 700 F, Bresk Room 300 F, Receiving/Storage 500 F, Corridors/Airlocks 200 F, Clean Room 500 F, Rest Rooms 100 F or I, F = Fluorescent , I = Incandescent
Relative Humidity	Type I : 35-55% rh around a regulated tem of 23^o C Type II : 20-55% rh around a regulated tem of 23^o C
Temperature	Type I : 23 C^o ± 1^o C , Type II : 23 C^o ± 1.5^o C
Vibration	No Specific Requirements
Voltage Regulation	Type I and Type II : Maximum change from avg voltage less than 10%, with consideration of holding transients to a minimum. Total RMS value of all harmonics should not exceed 5% of the RMS value of the fundamental from no load to full load of regulator.
Electrical Power Requirements	[115/230 V ac, 1 phase, 60 Hz], [220/440 ac, 3 phase, 60 Hz +1 Hz], [115/230 V ac, 1 and 3 phase delta, 400 Hz], [115/208 V ac, 3 phase wye, 400 Hz + 1 Hz], [28 V dc], [Provisions for emergency backup power

Table 5: The laboratory environment specifications

3.2.1.2 Mobile Labs

Mobile Laboratories are a very important part of large calibration facilities. These are basically big cars fitted with loaders at the back door to assist in carrying heavy equipment in and out of the car, shelves with shock absorber and straps to stack and hold equipment during movement and air conditioning unit to control the temperature of equipment cabinet so that calibration standards do not lose traceability. Their primary use is to calibrate devices in situ.

3.2.1.3 General Support

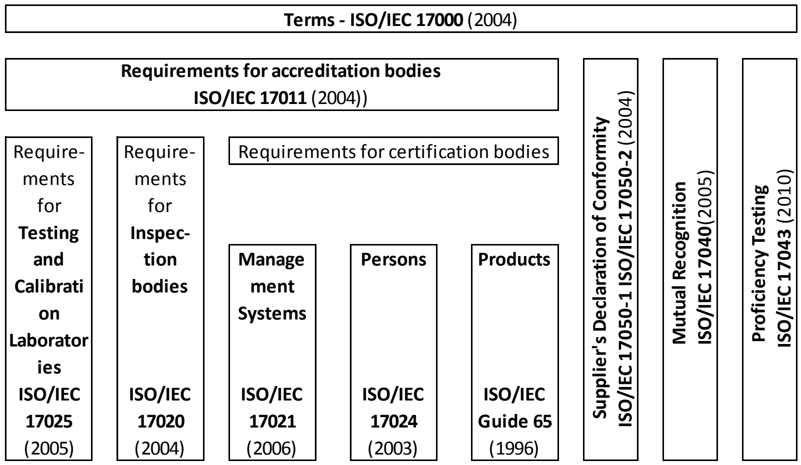
General Support is basically of two types: support areas and support equipment. Support areas are those areas that support all the activities within the lab. These include receive & dispatch area in which incoming and calibrated TMDE's are handled; scheduling and TMDE's control area, in which TMDE's are stored before entering the lab or after being checked and found they need parts; offices, conference room, storage rooms, plant rooms, kitchen and breaks room.

3.2.2 Documentation

Documents within a calibration facility refer to all technical documents that are either controlled or not controlled. Generally, these are divided in to four types of documents: standards, manuals and technical orders, calibration procedures, and general reports.

3.2.2.1 Standards

Standards are a special type of documents prepared and provided by the International Standard Organization (ISO). They are basically an extensive guideline on how to accomplish a certain set of activities. An example of this is ISO/IEC 17025 which is the standard used by accreditation body to check the competency of calibration laboratories. There are a large number of standards for various purposes (see Figure 4 for a detailed list of standards).



ISO/IEC 17000:2004	Terms, Reference document
ISO/IEC 17011:2004	Accreditation bodies
ISO/IEC 17020:2004	Inspection bodies
ISO/IEC 17021:2006	Certification bodies for management systems
ISO/IEC 17024:2003	Certification bodies for persons
ISO/IEC 17025:2005	Laboratories
ISO/IEC 17065:2011	Certification bodies for products, processes and services
ISO/IEC 17040:2005	Peer assessment
ISO/IEC 17050-1:2004 ISO/IEC 17050-2:2004	Supplier's declaration of conformity

Figure 4: Standards Document

3.2.2.2 Manuals and Technical Orders (TO)

These are the documents that are provided by the equipment manufactures for the purpose of operating and maintaining the item. They contain all the schematics, block diagrams, part lists and function of every part of the device. Usually, these documents are used by technicians to operate and maintain the item. A calibration facility must hold a library of those manuals and TO’s in order to perform their calibration duties.

3.2.2.3 Calibration Procedures

CP’s are controlled documents kept in the calibration facility library to be used by technicians to calibrate TMDE’s. They are basically, a step-by-step guideline on how to use the laboratory calibration standards to calibrate TMDE’s.

3.2.2.4 Letters Memos and Reports

These are exactly what the name implies a number of various documents that cover a wide range of subjects and used for many purposes. These includes communication between managers and their employees that deals with various aspects of the production and work requirement.

3.2.3 Personnel

Personnel within a calibration facility are divided into four distinct groups namely: metrologists, calibration technicians, engineers and support group.

3.2.3.1 Metrologists

Metrologists are those who apply measurement science, mathematics and physics to utilize, calibrate and maintain primary calibration systems, develop and devise method of calibrating electrical, mechanical, physical, optical, dimensional and chemical TMDE's.

3.2.3.2 Engineers

Engineers, are those who apply measurement science, mathematics, physics, and engineering principles to design, develop and maintain, systems, equipment and methods for calibrating electrical, mechanical, physical, optical, dimensional and chemical TMDE's. They use advance mathematics and scientific knowledge to analyze, identify and solve calibration problems that faces metrologists and technicians and lie outside the realm of metrology.

3.2.3.3 Technicians

Calibration Technicians are those who apply measurement science, mathematics and physics to use and maintain secondary calibration systems and use them in calibrating electrical, mechanical, physical, optical, dimensional and chemical TMDE's. They identify and use appropriate calibration procedures and address measurement problems.

3.2.3.4 Managers and Support

This category of personnel includes all managers from those at board level to those who run small sections within the facility. Their qualification depends on their positions and their assigned responsibilities.

3.2.4 Equipment

Equipment covers all instruments, devices and tools that are used in the calibration. It is mainly divided into three types of equipment: standards, test stations and tools.

3.2.4.1 Lab Standards

Standards are those instruments that store a certain physical quantity which is used as the basis for measurement of that quantity. In general all units of measurements have definitions, realizations and representations. The definition of a unit is an exact value and it is the ideal form of the unit. The realization is the value obtained from an experiment whose outcome matches the definition with the least possible deviation. The value obtained from the realization is embodied into a representation of the unit which is then used as a standard for transferring that value to other lower accuracy working standards and consequently shop level measurement devices (Fluke, 1994). Standards come in one of the following form: national standards, intrinsic standards, ratio standards, consensus standards and indirectly-derived quantities.

3.2.4.2 Test Stations

Test and calibration stations are those working areas that are dedicated to do a specific calibration job. The station is not to be used for anything else other than the job it is designed for.

3.2.4.3 Automated Systems

Automated systems are a collection of devices connected together to do a certain calibration job. The devices are controlled by a specially developed computer program that includes within it the calibration procedures required to be carried by the system.

CHAPTER 4

METROLOGY AND CALIBRATION OPERATIONS

4 Metrology and Calibration Operations

Metrology and calibration operations are all the activities that are defined over the calibration domain (Fluke, 1994), (Kononogov, 2006), (Pool, 2008).

4.1 Domain

The domain of metrology is centered on all the attributes that has an effect on measurement and the relevant calibration fields.

4.1.1 Calibration Concept

Calibration conceptually is the process by which a TMDE's performance is related to the invariant constants of nature.

4.1.1.1 Purpose

The purpose of Calibration is to assure acceptable performance of TMDE's.

4.1.1.2 Measurement Attributes

Measurement attributes are the characteristics associated with measurement. Each of which refers to a certain issue that needs to be considered, and if not, it will have a certain impact on the measurement validity. The attributes are measurement, superiority, repeatability, reproduce-ability, tolerance, range, sensitivity, stability, drift, precision and accuracy.

4.1.1.2.1 Linearity

Linearity (which is known as drift in some context) is the amount of error change throughout an instrument's measurement range. Linearity is also the amount of deviation from an instrument's ideal straight lines performance. Linearity is usually measured by one of the following method:

- Terminal Line (TL): TL is the straight line connecting the origin and the end point (see Figure 5).

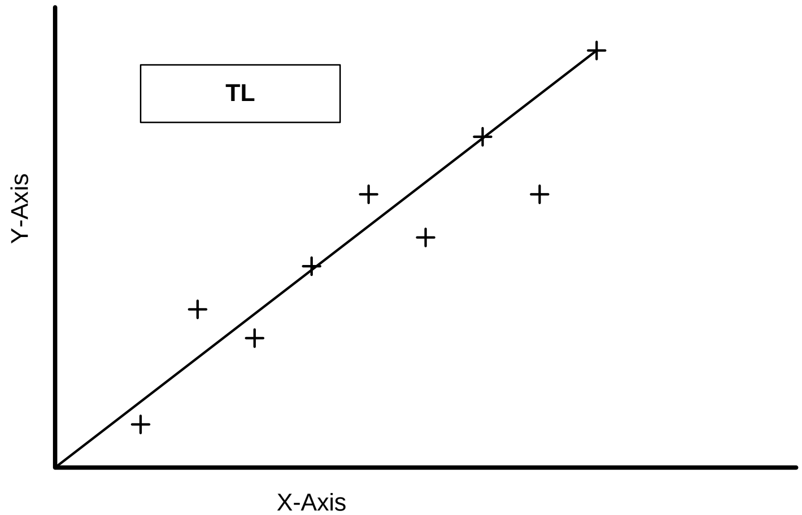


Figure 5: Terminal Line

- End Points Line (EPL): EPL is the straight line connecting the two end points (Figure 6).

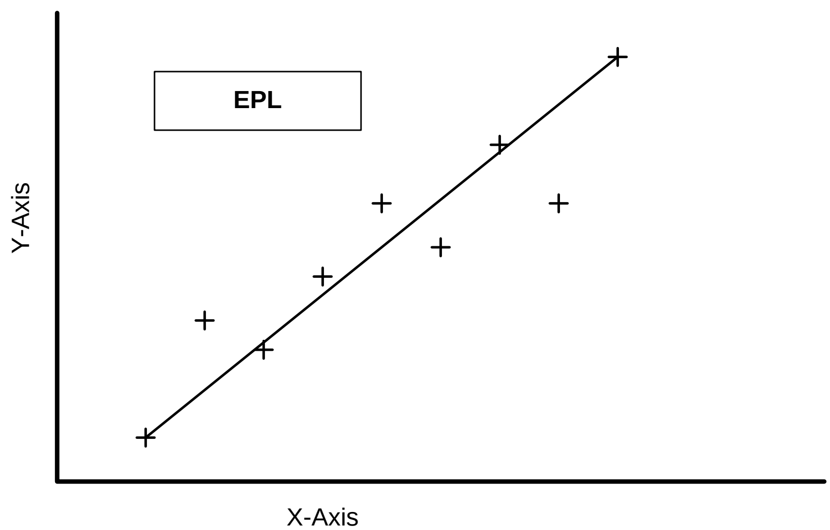


Figure 6: End Points Line

- Best Fit Line (BFL): which is a line drawn at the midpoint and parallel to the two parallel straight lines that encompasses the points (Figure 7).

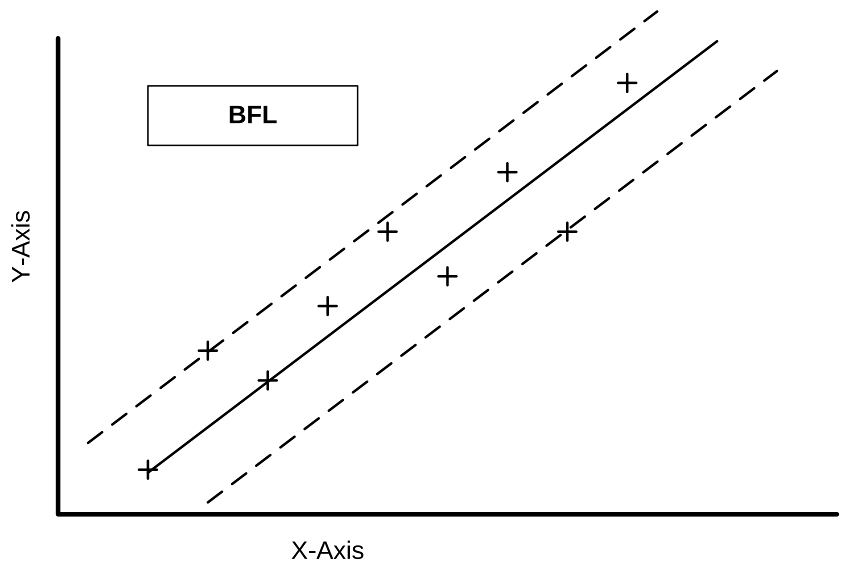


Figure 7: Best Fit Line

- Least Square Line (LSL): LSL is the linear regression line that is fitted through the points (Figure 8).

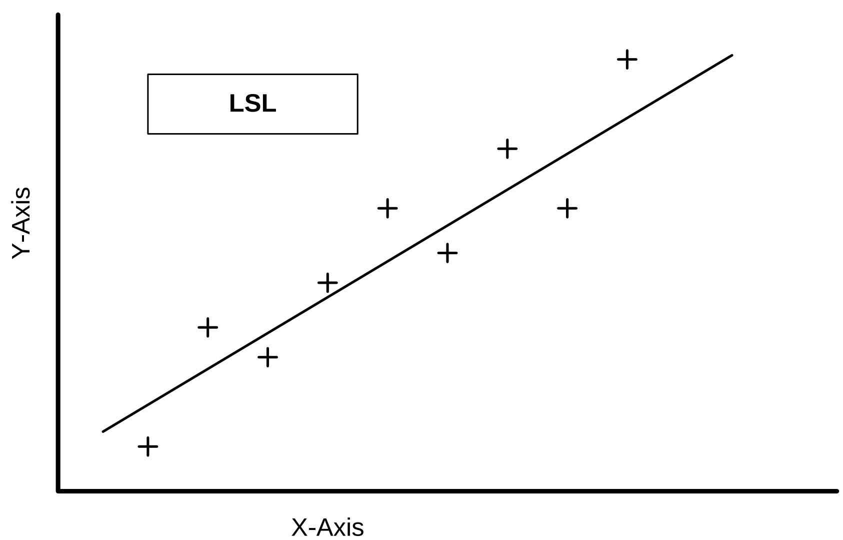


Figure 8: Least Square Line

4.1.2 Calibration Fields

Calibration fields are a generic term meant to describe scientific areas over which a group of devices are deigned. That group of devices is set to measure certain parameters for which the calibration process is traceable to a unique sub-set of basic units. The fields can be looked at from many perspectives which will in this case lead to many definitions. In a generic term, the calibration fields are mainly divided into five main fields, namely: electrical, mechanical, physical, chemical and hybrid systems.

4.1.2.1 Electrical

Electrical field is a vast area under which come a tremendous number of calibrate-able devices. These devices -although they may have some mechanical parts- do share one thing in common; they all do measure electrical quantities and their measurements are traceable to the electrical base units (Ampere).

4.1.2.2 Mechanical

Mechanical field is similar to the electrical field in size and probably much more in variety of devices types that come under it. In general, any TMDE that measures mechanical quantity like length, force and pressure, comes under the mechanical field.

4.1.2.3 Chemical

The chemical field clearly involves all devices that deal with chemicals. TMDE's within this field are usually classified according to the parameter they measure. Examples of these are alcohols content measuring meters, a certain chemical agent identifying device and many others.

4.1.2.4 Physical

The Physical field is a big field that encompasses many totally different areas. It is defined over all those areas which cannot be any of electrical, mechanical or chemical and yet involves the measurement of some natural phenomenon like time or temperature [51].

4.1.2.5 Hybrid Systems

Hybrid systems as the name implies is the field of all disciplines. Devices within this field are composed of parts that belong to a combination of at least two of the mechanical, electrical, physical and chemical areas.

4.2 Activities

There are various activities involved in the calibration facility, each of which has its role and partially contribute to the correct performance of the facility in general. These activities are the services, the production, the quality function, the engineering function and the training and following is a description of each.

4.2.1 Product and Services

In general the product and services of a calibration facility is centered on calibrating TMDE's and to do that the lab standards must be maintained at all time and made traceable to higher echelon reference standard.

4.2.1.1 Calibration of TMDE

Calibration is the process by which test, measurement, and diagnostic equipment is assured correctness, precision and accuracy. It is accomplished by comparing TMDE or unit under test (UUT) to a measurement standard that is traceable to the relative basic units realized in international laboratories. Calibration is performed in calibration laboratories and according to certain calibration procedures that are written by a metrologist, the manufacturer of the item or by an engineering authority. The calibration is performed in specific laboratory conditions and under the TMDE normal operation configuration. The outcome of calibration determines the performance quality of the TMDE with respect to its required specification.

The calibration results are presented in a calibration certificate in the case of calibrating a primary standard and in the form of guard band tag labeled with the calibration date and probably with the next calibration due date (Fluke 1994).

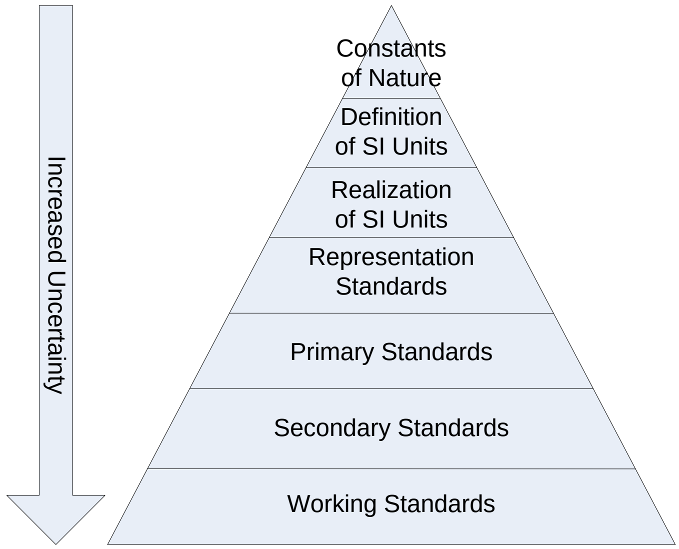


Figure 9: Calibration Levels based on uncertainty and number of TMDE's

4.2.1.2 Maintain Laboratory Standards

Maintaining lab standards involves performing periodical calibration on the lab standards as well as performing quality checks on the validity of the calibration performed on them. In addition to that the process involves determining the right number of similar standards that increases availability of standards within the lab.

4.2.2 Production

Production in a calibration facility involves calibration and repair of TMDE's. The calibration task requires calibrated lab standards, and the repair task requires tools and spare parts. These two requirements have added a great deal of complexity to calibration facility over a conventional repair shop. In addition to that the calibration based production system has many characteristics that make it unique and different from any conventional production system. These are the number of levels, the nature of the system, the dynamics and inter-actions between its activities.

4.2.3 Quality Assurance

The function of calibration labs is to provide calibration services. These services are mainly in the form of calibrated TMDE's. The quality level is mainly determined by the TMDE's technical specification and/or by customers' requirements. The employed quality system is to monitor, control and improve the quality of personnel, equipment and production.

4.2.4 Engineering

The engineering section in general performs all technical tasks other than calibrations (for those are performed by metrologists and technicians). These technical tasks are divided into three main types: technical queries, technical consultancy and writing local calibration procedures.

4.2.5 Training

Training is concerned with providing all personnel involved in the calibration facility with the required skill to perform their job. Within the context of metrology training is divided into three types of training, namely, strategic training, tactical training and on-the-job training (OJT).

CHAPTER 5

METROLOGY AND CALIBRATION OPTIMIZATION PROBLEMS

5 Metrology and Calibration Optimization Problems

As it has been evident from the previous chapters that talked about various aspects of metrology and its related issues, there are also many problems that will face the operators and decision makers involved in the field. The problems are quite diverse and touch upon every discipline in metrology. Generally, these problems are an integrated part of all levels of metrology starting from the strategic level of establishing the facilities and identifying the required capabilities and passing through the tactical level of the production planning and batching of work, to the operational level of scheduling and detailed planning.

5.1 Production Cycle Problem

Production within a calibration facility follows a cycle that starts from the receive-and-dispatch (R&D) section passing by almost every other section and goes back to where it started (see Figure 10). The cycle goes as follows: the TMDE's is received by the R&D then it is passed to scheduling, from there it goes to the lab and once calibrated it is passed to the quality control section (QC). In the QC the item is inspected for correctness if it fails it will go back to the lab and to the same technician to recalibrate it again. If the item passes the inspection it goes to the R&D from which the customer can collect it.

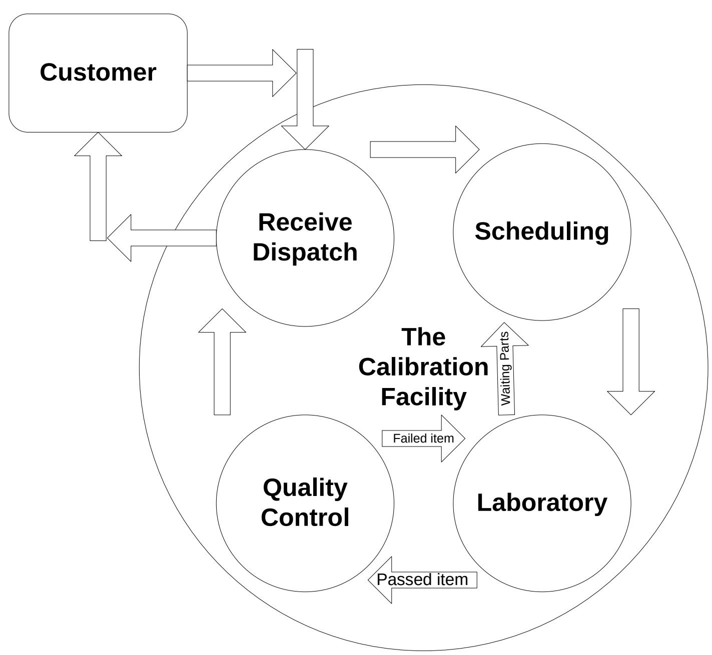


Figure 10: The Production Cycle.

5.1.1 Description

Each section performs a certain function and during that operators may be required to go back and forth between various sections within the facility. An example of that is the need for an inspector to go back and forth between the QC and the lab. Another example is the trips made by the technician between the lab and the scheduling section. There are usually other trips between the primary lab and the secondary lab which involves the transportation of heavy equipment. The production cycles is actually composed of many cycles. Some of these are very small cycles that involve only few people and is restricted to a small area. These cycles have in general a layout problem associated with it that needs to be optimized so that all the cycles are performed correctly and in harmony with each other. The need for that is not always obvious, because effect of any disruption to any one of the production cycles cannot always be assessed before the disruption happens.

5.1.2 Potential Optimization Problems

The problem involves the optimization of all or part of the problems embodied in the following problem statement.

[Problem Statement]

Given a particular calibration facility perform the following optimizations to improve the operations and the general performance of it:

- A facility layout planning based on the production cycle that considers the following:
    - Operational requirement
    - Number of expected trips from/to other sections
    - The material handling equipment available
    - The contingency requirement such as:
        - Environmental system breakdown
        - Catastrophic accidents
            - Electrical stoppage
            - Contamination

            - Chemical
            - Radiation
        - Accidental explosion
    - Disasters
        - natural
            - Fire
            - Flood
            - Earthquake
        - Deliberate
            - Bombardment
            - Sabotage
- A facility layout planning at the section levels.
    - Entrances
    - Space utilization
- A tool management policy
    - Locations
    - Order
    - distribution
- Redundancy in
    - Alternative locations
    - Equipment storages

5.1.3 Impact on the System

The impact of identifying and solving these problems will be outstanding. The effect will cover every aspect of the facility. Following is a list of most of the aspects that will be positively affected:

- Cost of damage equipment
- Cost of lost potential
- Cost of bad reputation or loss of customer confidence
- Planning time and cost

- Cost of implementation time of new changes
- Ability to explore different production scenarios
- Ability to integrate new capabilities into the existing ones
- Ability to control and mitigate the effect of catastrophic accidents
- Ability to control and mitigate the effect of natural or deliberate disasters
- Ability to spot sources of small production problems
- Ability to correctly identify hidden optimization problems

5.1.4 Suggested Treatment

The most important part of this generic problem is the identification and definition of the specific problem. Although these problems are encountered in any calibration facility, each facility has its own unique problem that is different in its structure as well as in its solution. Therefore, unless you are dealing with an already established facility you cannot clearly define the associated problems as it have been identified above.

5.2 Calibration-Jobs Scheduling Problem

Calibration –jobs scheduling is one of the most difficult problems faced in any production facility. The problem can take many forms such as job shop, flow shop, multiple parallel machines and many others. Following is a description of the scheduling problems encountered in any medium to large sized calibration facility.

5.2.1 Description

A fairly large sized calibration facility receives quite a high number of jobs per week (usually in the order of 100 jobs per week). All these jobs need to be calibrated and/or repaired. Each job has its own attributes and among these are the duration time of the calibration, the type of the job being electrical, mechanical or any other type, the complexity of the job, the time the job has been waiting in the facility and many others. On the other hand the technicians who are going do the jobs has also their own attributes like the specialty, the skill level, the time available for production and many others. The lab also has its own attributes such as the number of work benches, the number of calibration standards, the number of supporting tools and many others. All of these attributes must be considered when the supervisor starts scheduling the jobs to the technicians (see Figure 11).

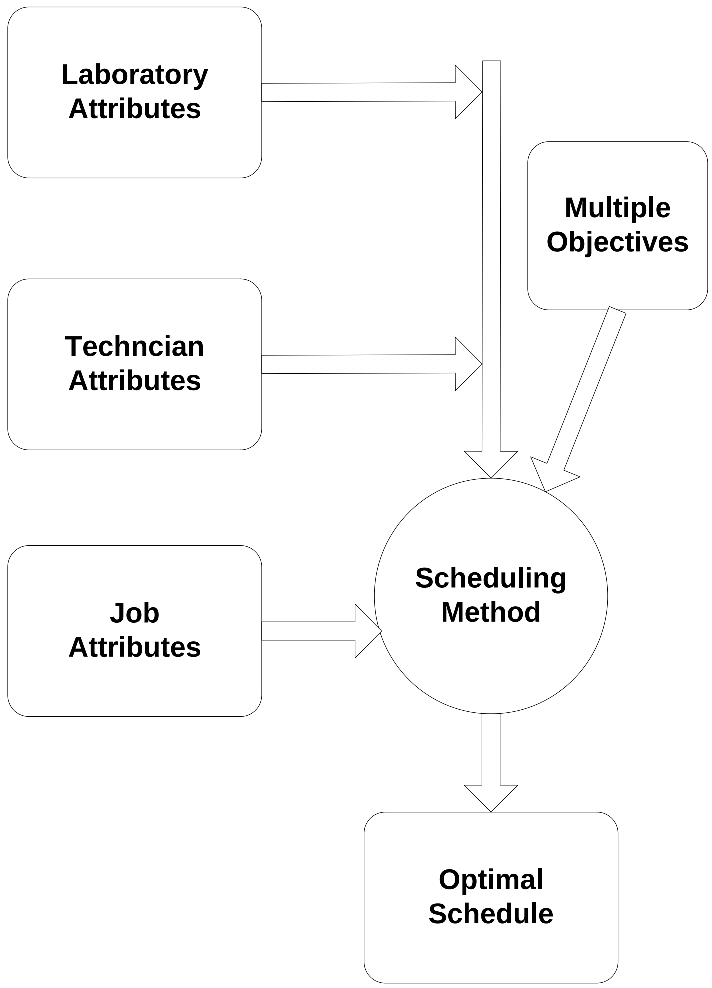


Figure 11: Scheduling Problem Constituents.

For the number of attributes of either the job, the lab of the operators check chapter 6.

5.2.2 Potential Optimization Problems

The potential optimization problems within the context described above can be many. The following problem statement comprises the generic one for which there might be many variations. Changes in this case will be limited to the objective function. Changes to the value of the scheduling parameters are permitted and will have no impact on the structure of the solution method that will be pursued.

[Problem Statement]

The MACJSP is defined completely in chapter six.

5.2.3 Impact on the System

The impact on the system when solving the scheduling problem as it is described above will be shown in many aspects. Following is a brief list of those:

- Increased efficiency of the lab production through
  - Proper assignment of jobs
  - Elimination of conflicts in assignments
  - Produce a schedule almost instantaneously
  - Eliminate the need for experienced scheduler
- Increased utilization of the lab resources
- Allow for multiple objectives optimization such as
  - Balanced backlog
  - Reduced turnaround time
  - Increased operators satisfaction because of the fair tasks distribution and the elimination of favoritism
- Provide a means of exploring different production scenarios such as:
  - The impact of running two or more working shifts.
  - The impact on some KPI's after increasing the work force by some value.
- Increased customer confidence in the calibration facility
- Increased management confidence in the technicians

5.2.4 Suggested Treatment

Scheduling in general is a well developed operation research technique. There are many problem statements already treated and has concise constructive algorithms developed to solve them optimally. These algorithms unfortunately cannot be used here. The reason for that is that the problem on hand cannot be reduced to be a special case of any one of the problems reported in the literature. Generally speaking, most of the practical scheduling problems encountered in complex production systems are really hard problems, and therefore we need a good way of solving them optimally or semi optimally.

5.3 Backlog and Turnaround Time

Backlog and turnaround time are two basic production performance measures related to the item being produced or serviced. The two measures are closely related in terms of their presence and magnitude. The backlog is the number of accumulated items or TMDE's entered the calibration facility and stored next to the production lab waiting for processing. In case of high back log more than one item could processed simultaneously leading to better utilization of operators and standards. The turnaround time is the amount of time the item spent in the system from the moment it entered the receive-and-dispatch area to the moment it left it again as a calibrated item. The turnaround item does not include the time waited for requested parts of the item to arrive in case a repair is needed for the item (see Figure 12).

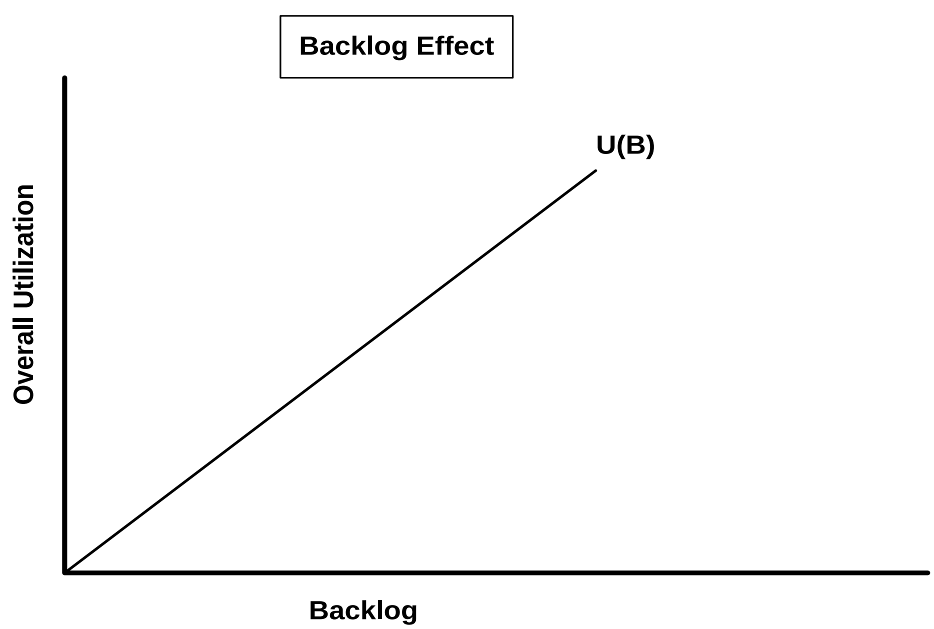


Figure 12: Backlog Effect.

5.3.1 Description

TMDE's arrive to the calibration facility at the receive-and-dispatch area. Usually, the arrival of the TMDE's is a customer decision, but most of the time it is based on a calibration call by the calibration facility to remind the customer of the time of next calibration. Either ways, will have no effect on the total amount of time the item spent in the system. Once the item is arrived, it is processed and the operators complete its paperwork and then move it from section to section until it is finally completed. Since the item is repeatedly calibrated; a history of the item is recorded. Among the many useful statistics provided by the history file of the item; is the turnaround times recorded of the item. Both the backlog and the turnaround time are used as a performance measure of the calibration facility. The backlog is used by both the facility management and engineers to monitor in-process inventory and equipment, tools, standards and technicians utilization. The turnaround time is used by the customer to monitor his own TMDE's utilization manifested in the availability of the calibrated item (see Figure 13). The two measures are usually correlated in such a way that an increase in one will lead to an increase in the other (see Figure 14).

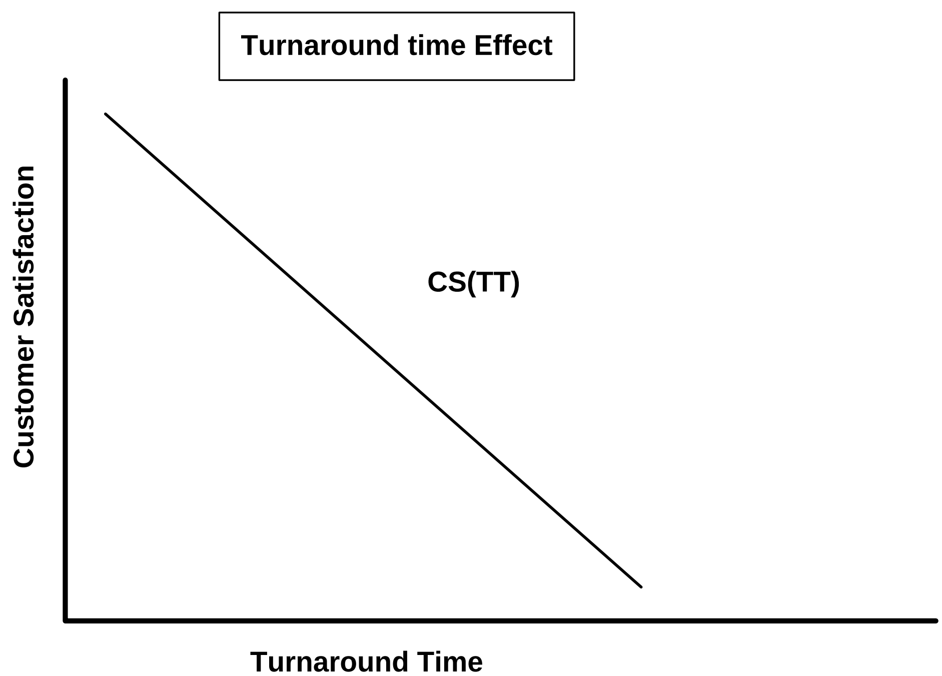


Figure 13: Turnaround Time Effect.

5.3.2 Potential Optimization Problems

The backlog referred to in this problem is the number of TMDE's ready for processing. It does not include those items that are awaiting parts or those that has repair problem. If those items are to be included then another variation of the problem will be considered. The turnaround time referred to here is the total time in the system.

[Problem Statement]

Given a number of technicians **n**, a number of trainees **m**, a preset trainer to trainee ratio, a turnaround maximum acceptable level, a relationship function **F(Backlog) = Turnaround** between backlog level and turnaround time of TMDE's, an in process inventory capacity **II**, a utilization factor **U** and a planning cycle **Z**. Find the optimum backlog level that satisfies all the production constraints and customer requirement without sacrificing the limitations imposed on utilization of technicians and equipment and also the efficiency of work. The problem has many variations depending on the following cases:

- There will be a penalty only, for exceeding the Turnaround time maximum level
  - The penalty is fixed
  - The penalty is a function of Turnaround time
- The will be a reward for reducing the Turnaround time.
  - The reward is fixed
  - The reward is a function of Turnaround time
- There will be either a penalty or a reward for either case.

5.3.3 Impact on the System

The optimization of the backlog value will have a drastic impact on the daily production of the calibration facility. The impact can be positive or negative depending on the magnitude of the backlog value. Following, is a classification of the impact based on the magnitude of the backlog:

- High backlog
  - Pros
    - Increase equipment utilization
    - Increase technicians utilization
    - Increase training efficiency (due to the availability of TMDE's)
    - Reduce the average processing time of some TMDE's (for example, the calibration time of one thermocouple is half an hour, also the calibration of five thermocouples is half an hour, because they can be done all together)

- Cons
    - Fill up all in-process inventories and at the extreme case it may cause the rejection of incoming TMDE's due to lack of space.
    - Cause a system overload in all aspects such as receive and dispatch, scheduling, management, handling tools and many others.
    - Increase the turnaround time and consequently, suffer all the drawbacks of that.

- Low backlog
    - Pros
        - Cause production starvation
        - Cause equipment idleness
        - Cause technicians idleness
        - Reduce production efficiency
    - Cons
        - Increase the amount of time available for supporting tasks
        - Increase options of calibrations to the technicians
        - Increase the level of cleanness and tidiness

Following, is a classification of the impact base on the magnitude of the turnaround time value:

- High Turnaround Time

High turnaround time is not welcomed by both the facility management and operators and the customers. For the calibration facility, it means a fill up of the in-process inventory, and for the customer it means reduced item availability and a shorter calibration life.

- Low Turnaround Time

Low turnaround time is the main objective of both the lab management and the customers for many obvious reasons. In most of the cases, there will be no immediate reward for very short turnaround time, but there is a hidden reward observed by customer satisfaction and good reputation for the facility. These last two attributes, well act as an advertisement to the facility which leads to further business opportunity (the hidden reward).

5.3.4 Suggested Treatment

This problem can be approached and solved optimally by using a solution scheme consisted of two stages. In the first stage, a number of related key performance indicators must be defined. After the definitions, a set of functions and relationships must be developed to tie KPI's together and to tie each of which to the production parameters specially the backlog and turnaround time. In the second stage, a simulation model must be developed by using either established suitable simulation software, or a built from scratch program using any sequential logic computer language. Spread sheets like Excel may also be used to do the simulation. The result of the simulation runs could then be used to find out the optimal value of the backlog and the turnaround time (see Figure 14). In the diagram α and β are the two angles between the line and the two axises.

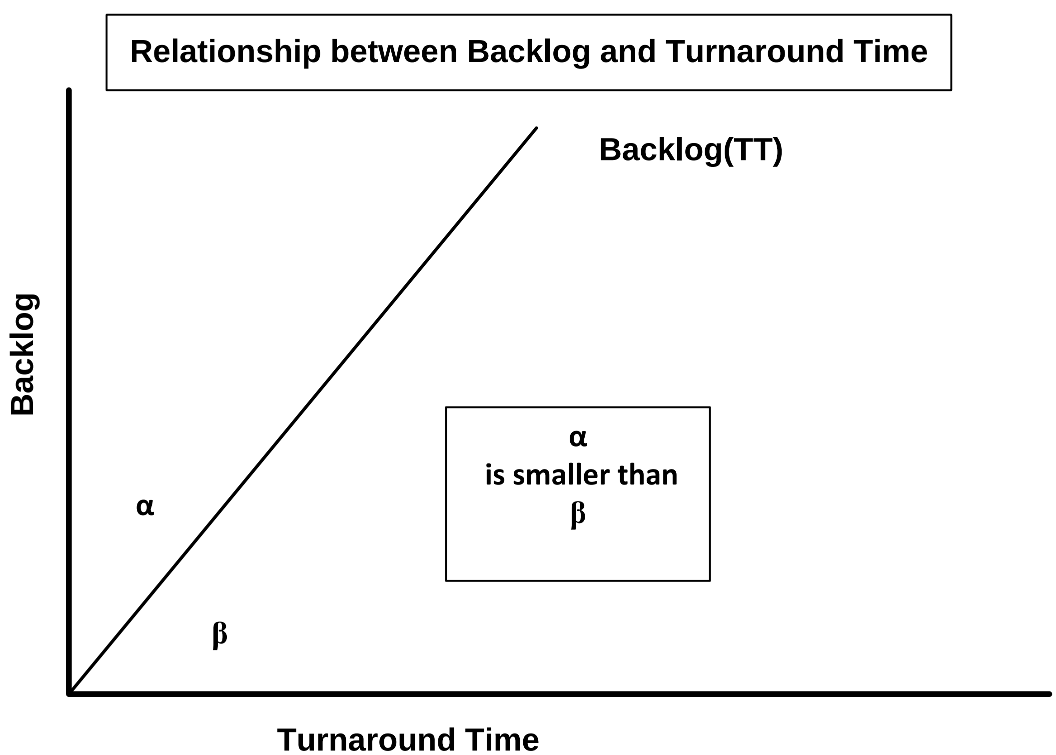


Figure 14: Relationship of Backlog to Turnaround Time.

5.4 Average Outgoing Quality Problem

Quality control or quality assurance is an integrated part of the calibration facility operations. The main objective of any production facility is to offer the customer defect-free- products if they can, or more practically, produced items with few defects. This can be done when the calibration facility has a means by which they can assess their average outgoing quality (AOQ). The correct assessment of AOQ is not an easy matter and sometimes it can be extremely difficult in case of many operators (see Figure 15). In the context of this research the calibration facility is assumed to have an inspection policy that monitors the performance of every technician without having to inspect every task he performed. The reason for that is quite obvious; it is easy to assess the AOQ if you perform a 100% inspection (because in this case you would know exactly the percentage of defectives items).

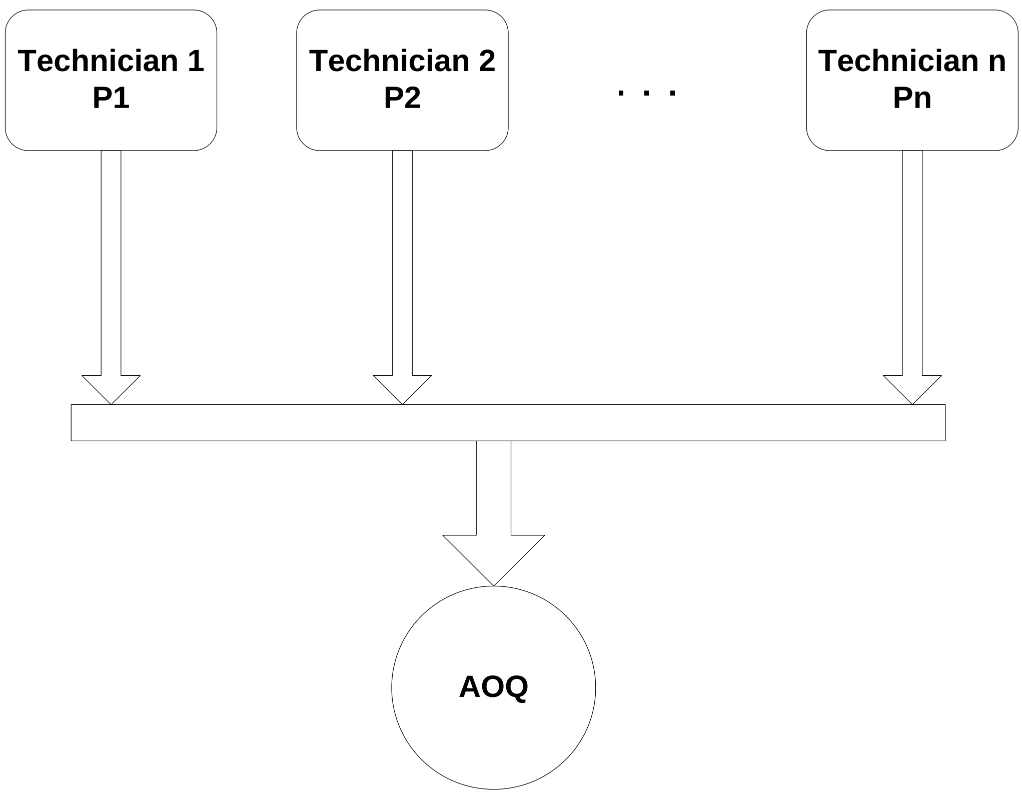


Figure 15: Average Outgoing Quality

5.4.1 Description

For a short term, the assessed AOQ will become a characteristic of the lab and it will remain as such until a real change on the process or the methods of the calibration is performed. The AOQ will also be the monitor for the facility performance as a whole as well as the first warning to the management of any newly developed bad production streak that may pop up suddenly for various reasons.

5.4.2 Potential Optimization Problems

Given a specific inspection plan and given a number of technicians **n**, each of which has associated with him a certain success rate **Pi** and a number of items **mi** produced by him in the time interval chosen by the inspection policy. Find the average outgoing quality of the calibration facility with 95% confidence.

5.4.3 Impact on the System

The impact of knowing the calibration facility average outgoing quality on the system performance is considered to be an efficiency driver. Knowing the value is not so much the goal, what is more important is the method by which this value is arrived at. The method of assessing the average outgoing quality of the system is the primary objective and for that matter the development of this method depends entirely on the inspection policy used in the system. The impact on the system may be seen in the following:

- Complete the feedback cycle to establish a fully production controlled loop which allows for the addition of some corrective measure continuously.
- Knowing the size of the defective items that leave the system
- May allow for the establishment of quality control chart that alerts the facility when the quality is drastically harmed.
- Depending on the method it may allow for tracing back to the source of generating more than normal defective items.
- Help the engineers and top management to develop quality improvement policy and monitor their progress.
- Stop any developed defective items streak that may happen due to various reasons (for instance a newly assigned operator or a newly bought instrument).

5.4.4 Suggested Treatment

The suggest method consists of two parts:

- Part one is to identify the inspection policy used by the system to monitor the operator's performance. This should involve the following:
  - A clear definition of the inspection policy
  - An analysis of the policy to formulate the mathematical relationship that governs it.
- An algorithmic way of utilizing the operators' records generated by the policy to assess the AOQ solely from that.
- A later confirmation method to validate the algorithm would be to assign some operators to complete the inspection to a 100% inspection to compare the AOQ resulted from both methods (the developed one and the 100% inspection).

5.5 Inventory Components Problem

Inventory is an integrated part of any calibration facility. It is - in most cases- considered the bottle neck of the production system within the organization. There are many types of inventories in any one calibration facility (see Figure 16). In general, two of the many types of inventories are of particular interest to calibration facilities; these are storage inventory and work-in-process inventory (IPI).

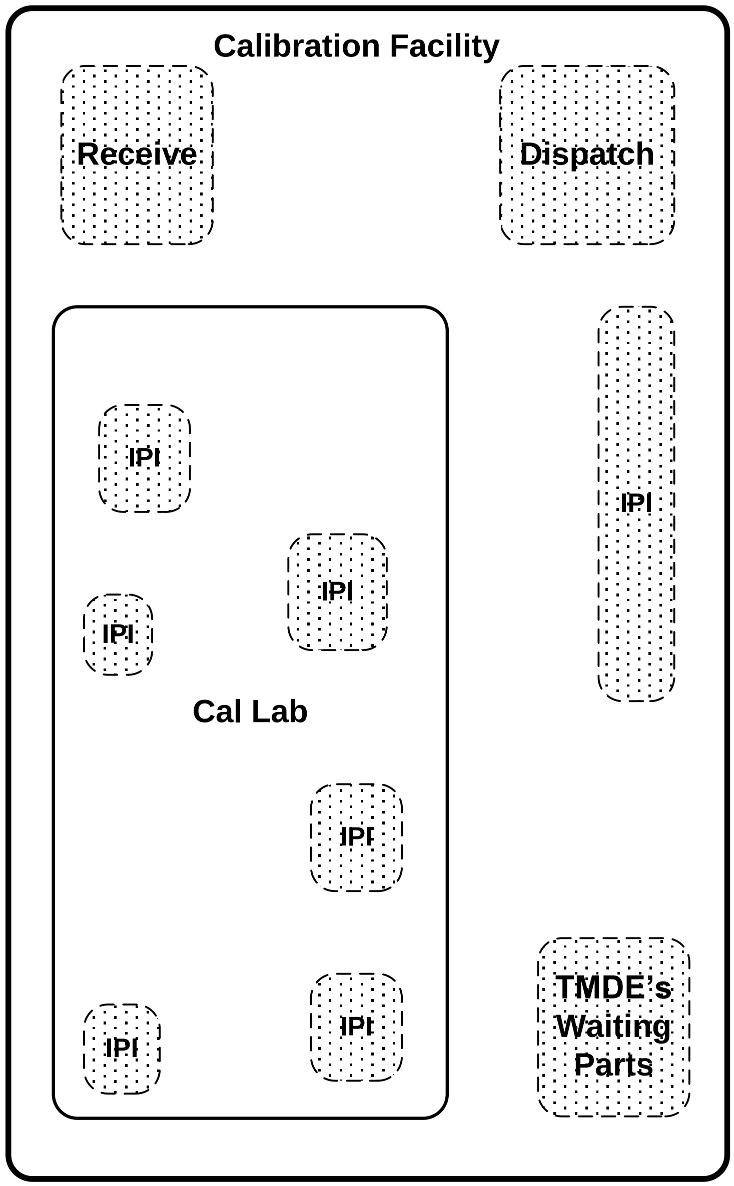


Figure 16: Inventories within a Calibration Facility.

Storage inventory are those empty rooms used to store incoming/outgoing TMDE's as they are received and dispatched respectively. Another storage inventory is the place reserved for TMDE's that need repair and are deferred by the technician to the storage awaiting the ordered part. The other type is the work-in-process inventory which is the empty spaces between works stations used to hold the unfinished work.

5.5.1 Description

As it was described before a TMDE enters the production cycle as soon as they arrive and continues its journey from section to section until it finally reaches the dispatch area where it can be collected by the customer. During that time the TMDE need to stay for a while in some area which could be from an hour or so to many days and even months (for extreme cases the item may stay for years waiting for a spare part to arrive). Whether the waiting time of the items is long or short, as long as the production line is moving items will accumulate. At any workstation if the production rate is higher than the arrival rate then there will be no problem. The problem arises when the arrival rate of incoming items is higher than the servicing rate at that station [89].

5.5.2 Potential Optimization Problems

Sometimes part of the solution for a certain problem is defining the problem concisely. This is the case here:

[Problem Statement]

The problem of the inventory can be divided into two main parts:

- Part one: identifying all the inventory components within the boundary of the facility and this should include:
  - The types of inventories
  - The sizes (dimensions) of each inventory based on its usages
  - The access-ability of the area
- Part two: Devising a solution method to optimize the problem identified in part one. The solution is more specific to the lab under consideration. The devised method should do the following:
  - Specify the maximum capacity of any particular inventory component.
  - Specify the number of each inventory types.

- Specify along with their sizes which ones of each type are permanent and which ones are temporary.
- Optimizes the capacities over the items profits, the cost of the inventory and the production constraints.
- If possible the method should take the form of a model that can be used again and again for different instances.

5.5.3 Impact on the System

Having the problem been successfully identified and successfully solved the facility will enjoy many benefits. These benefits could be summarized in the following:

- Inventories will be more organized which will increase their space utilization leading to an increase capacity
- Increased capacity leads to fewer TMDE being turned away for lacking space which will be translated eventually to more profit.
- Gives more insight on the potential of the lab for expansion because the inventory might be the bottle neck in the production system in a particular facility.
- Organizing in-process inventory within the lab increases the following:
    - Work flexibility
    - Smoothness of work flow
    - Utilization of lab resources
    - Ability of the lab to handle large TMDEs

5.5.4 Suggested Treatment

The proposed solution should be according to the following steps:

- Step 1: Develop the detailed facility layout which includes:
    - The location and size of each workstation.
    - The location and size of each inventory component
    - The location and size of each support equipment and/or auxiliary equipment
    - Marking of all entrances, isles, inlets, power stations and any other similar utility.

    - Marking of whether the object is fixed or movable.
- Step 2: Identify all the characteristics of each inventory components
- Step 3: Devise a method for each problem a lone and then ties them together toward the end.

5.6 Capacity-based Determination Problems

In any calibration facility there are many activities or resources that are of limited number and it is usually considered a limiting factor in the organization. As an example of these are the training capacity, the acquisition of calibration capabilities and many others. The training capacity depends on the number of technicians and the workload of the facility. This set of problems involves any decision problem regarding any capacity based problems. The first step in the treatment here is exclusively identifying most of these problems and then subjecting them to the suitable solution scheme.

5.6.1 Description

Capacity-based problems are so many in a calibration facilities but some of them are more important than others. Here, the two chosen ones are the establishment of new capability and the capacity for internal training. Although the two problems are totally different from each other, they share the common theme of having some limited bounds around them caused by some scarce resources that cannot be easily increased in a short period of time or with limited incurred cost.

5.6.2 Potential Optimization Problems

Amongst the many important problems, there are two capacity based problems that are of great importance to the calibration facility as a production organization, to its employees and to the main customers of it. The solution of those not only solves the underlining problems, but it solves many other hidden problems in the production system that has a certain relationships with them. These are as follows:

First Problem: Establishment of new capability.

[Problem Statement]

Given a number of TMDE's **n** and the cost of calibration of one unit internally **Ci**, the cost of calibration of one unit externally **Co**, the availability requirement of the TMDE **m**, the establishment cost of the calibration capability **Ce**, the running cost of the capability **Cr** and the planning horizon **Z** find the best course of action between either calibrating internally or externally from the point of view of the calibration facility.

Second Problem: Determining the optimum number of trainees within the facility.

[Problem Statement]

Given a number of areas within the lab **a**, a number of technicians in each area **ni**, a training ratio **R** of trainees to trainer, a training time per period per one trainee **t**, a production time per period per trainer d and a training period **P**, find the optimum number of trainees the facility could handle.

5.6.3 Impact on the System

The impact of solving those two problems on the system will be so drastic and very deep and at the same time exceptionally stimulating for further improvement (see Figure 17). The success in solving these two problems will encourage the management and the technician to identify the other similar problems and subject them to analysis and consequently solution.

The establishment of the new facility optimization will provide many advantages for the calibration facility. These could be some or all of the following:

- Increase the service spectrum of the calibration facility in terms of TMDE's variety.
- Increase the breadth of knowledge of the technicians involved.
- Increase the organization profit.
- Increase the ceiling of services for the non profitable organizations.
- Increase the utilization rate of both equipment and personnel.

The training capacity problem will have both short term benefits and long term ones. These are as follows:

- Increase the competent work force.
- Increase technician's utilization.
- Taking the advantage of the presence of customer TMDE's to train the trainees instead of paying for that in some other training institutions.
- Increase production flexibility in the near future through increasing the number of qualified technicians.
- Increase the organization profit through training.

- Sharpening the old technicians' knowledge by allowing them to extend training to the others for that is known to be one of the advanced training methods.

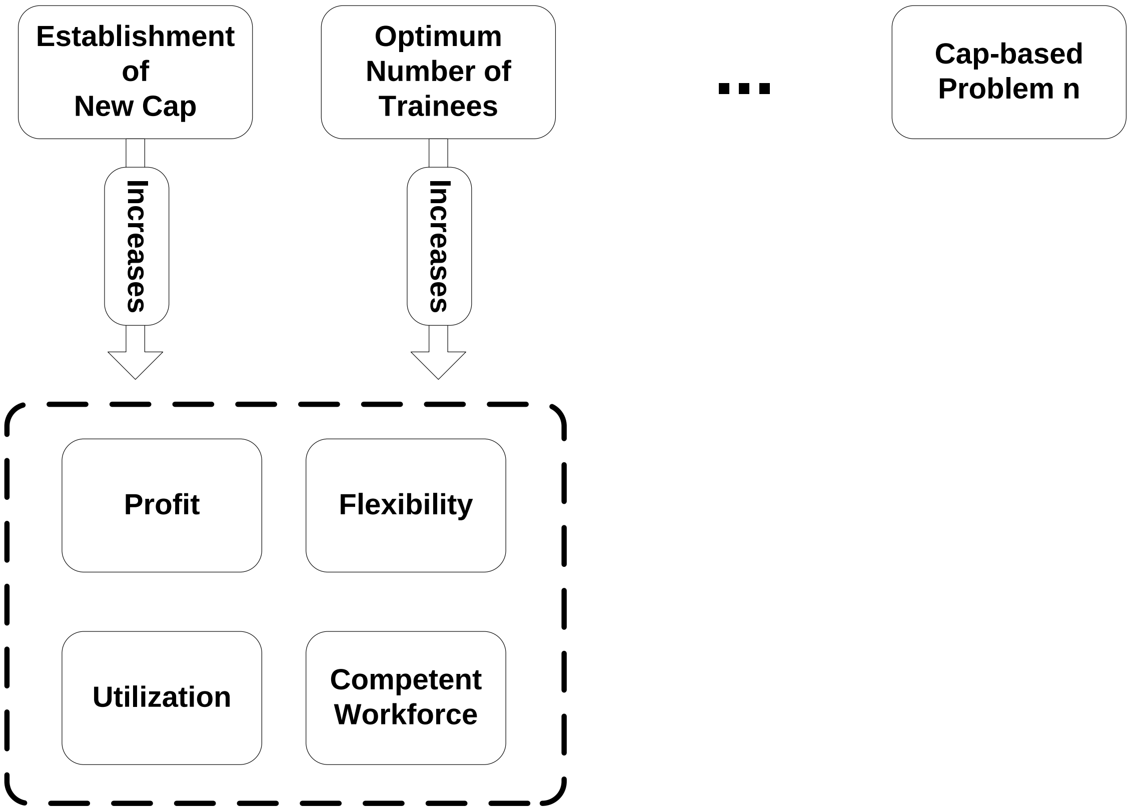


Figure 17: Effect of Optimizing Capacity-based Problems.

In general, there are many advantages –and hardly any disadvantages- for solving capacity-based problems at all levels. The solution of those problems –sometimes- may give rise to some new problems (capacity-based problems or others) that have not existed before. This later case may happen in one facility but not in some others, although they may have addressed and solved the same problem and that is due to the nature of the production system in each one of them.

5.6.4 Suggested Treatment

The solution to these types of problems in general and these two in particular is not very demanding. The most important part of the solution though is the clear and concise definition of the problem along with the identification of all related parameters. The reason for that can be summarized in the following points:

- A clear definition of the problem will assist in identifying all of the possible problem variations.
    - The variations may then be prioritized and solved one after the other. This could lead to solving some of the low priority variations automatically by the mere solution of the higher ones.
- A concise definition will assist in the following:
- Isolating the problem from mixing with other problems that may be in conflict with the underlined problem.
- Allowing the management and technicians to have a good grip over the dynamics of the production system under optimization.
- Identifying all the parameters of the problem to assist in bounding the solution or in other words make the problem solvable and allow an optimum solution to exist.
    - An example of that maybe clearly shown when you formulate the problem as a linear program and due to missing one or more parameters you fail to capture all the constraints of the problem. This may lead to an open solution space that prohibits the simplex algorithm from reaching an optimal solution.

The solution for the capacity-based problem can follow many approaches depending on a multitude of factors.

5.7 Calibration Interval (CI) Determination Problem

TMDE's are calibrated by standards that are traceable to international references held at international labs like NPL and NIST. The calibration of the TMDE's is repeated periodically to make sure of the continuity of a reliable measurement. During the calibration life of the item, its performance drifts from the correct one. Most of the time the drift is linear and the slope of it is always negative (see Figure 18).

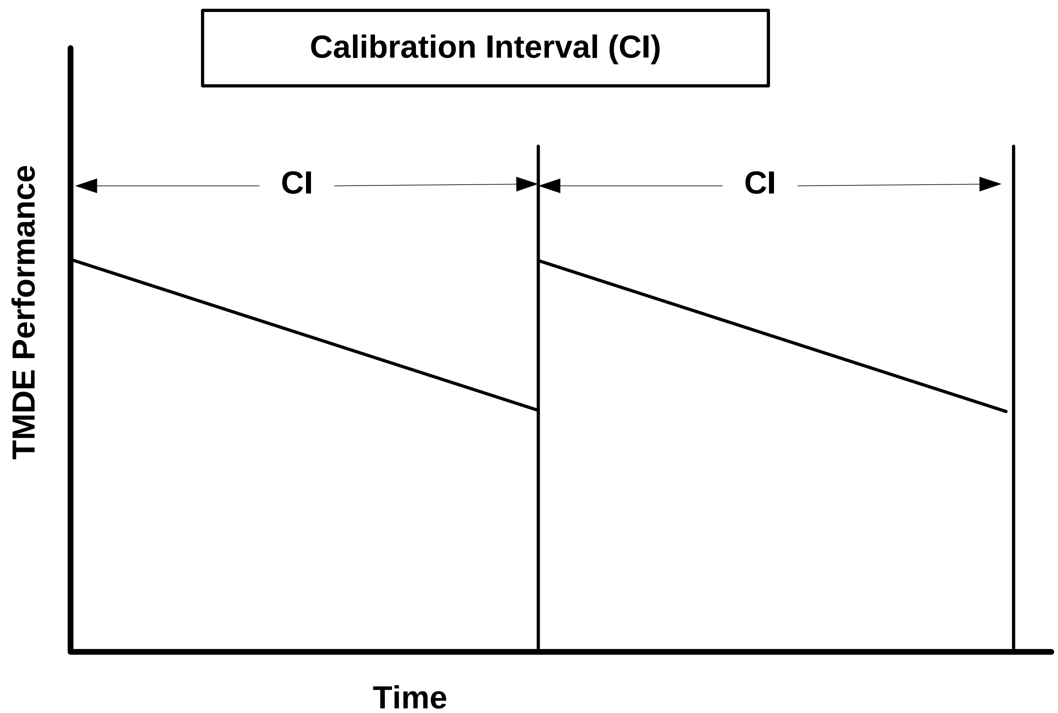


Figure 18: Calibration Interval of a TMDE.

5.7.1 Description

During the calibration life of any TMDE's, the measurement performance of it is subject to drift over time and this drift causes error in the measurement performed by the device. The drift cannot be eliminated in the design phase and the only way to eliminate it is to bring back the TMDE precision and accuracy to its previous level through calibration. The calibration must be performed as soon as the performance of the device deteriorated to an unacceptable level.

The calibration interval is assigned in such a way that the TMDE performance is reliable during the entire period and the measurement error does not exceed a certain level. The estimation of the length of the calibration interval –in general- is a very difficult problem. Usually the device is given the calibration interval suggested by the manufacturer. But then the CI is either shortened or made longer. A longer CI allows for more drift to take place at the end of the device call life (see Figure 19), but the device calibration frequency is reduced and consequently the calibration cost.

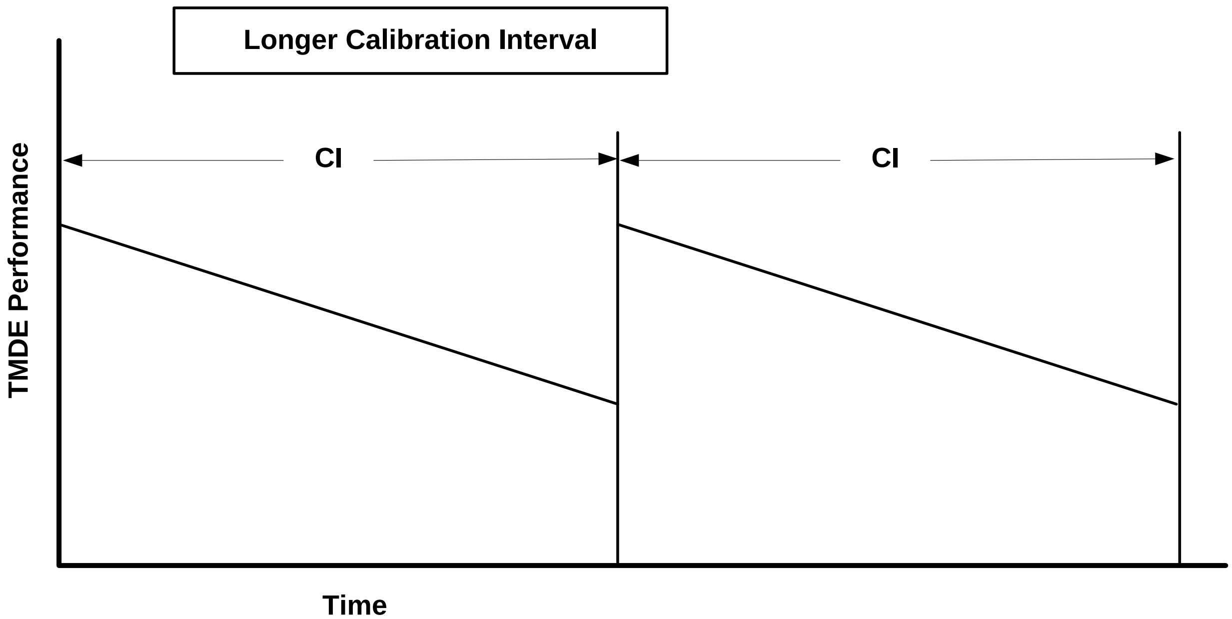


Figure 19: Longer Calibration Interval of a TMDE.

A shorter CI does not allow too much drift and the device performance will stay close to normal at the end of the calibration life (see Figure 20), but the cost of calibration is highly increased. There are many ways reported in the literature that deals with this problem. Most of these ways -if not all- concentrate on the period that guarantees a high reliability in the measurement and this is done through some statistical means. At the same time most of the methods of estimating calibration intervals ignore the cost involved in the process and if they do they include only the cost of the calibration.

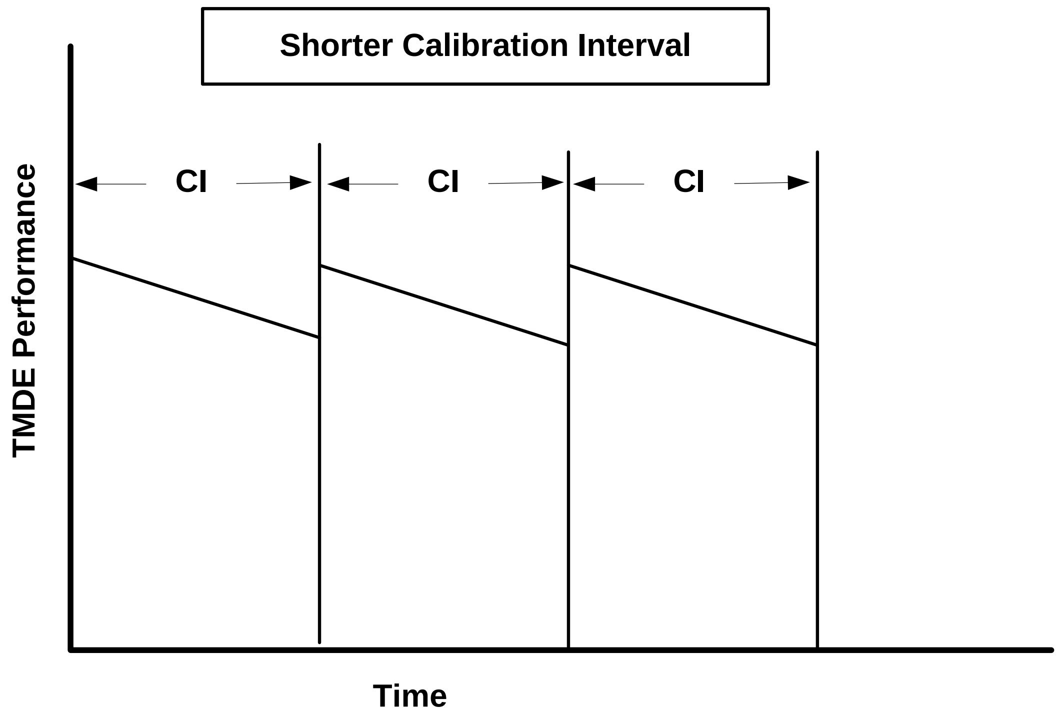


Figure 20: Shorter Calibration Interval of a TMDE.

5.7.2 Potential Problems Associated with it

The problem of identifying the calibration interval of a certain type of TMDE can be formulated in many ways. The formulation here will be restricted to the one that involves cost.

[Problem Statement]

Given a calibration cost of device i Ci, the cost of using a drifted device i Di and a reliability function of the device Ri, find the optimum calibration interval that provides the lowest cost and preserves the operational performance required.

5.7.3 Impact on the System

The major impact will be on the customer make use of optimum CI achieved. His measurement will always be correct and his confidence in his device will be high. He may incur a little bit more of the calibration cost but that will be paid off by the drastic increase in the device reliability.

5.7.4 Suggested Treatment

The solution scheme for this problem should be dependent on the type of the organization and the size of the workload. The size of the organization is important in determining its ability to expand, replenish resources or quickly increase the size of the workforce. The size of the workload would be important because it would define the impact on the system and consequently directing the CI analysis towards the option that mitigates the difficulties that may be encountered.

There are basically three methods that may be used to assess the optimum CI (see Figure 21). The first one is to perform an analytical assessment with the objective of constructing a formula that is used directly to find the optimum CI.

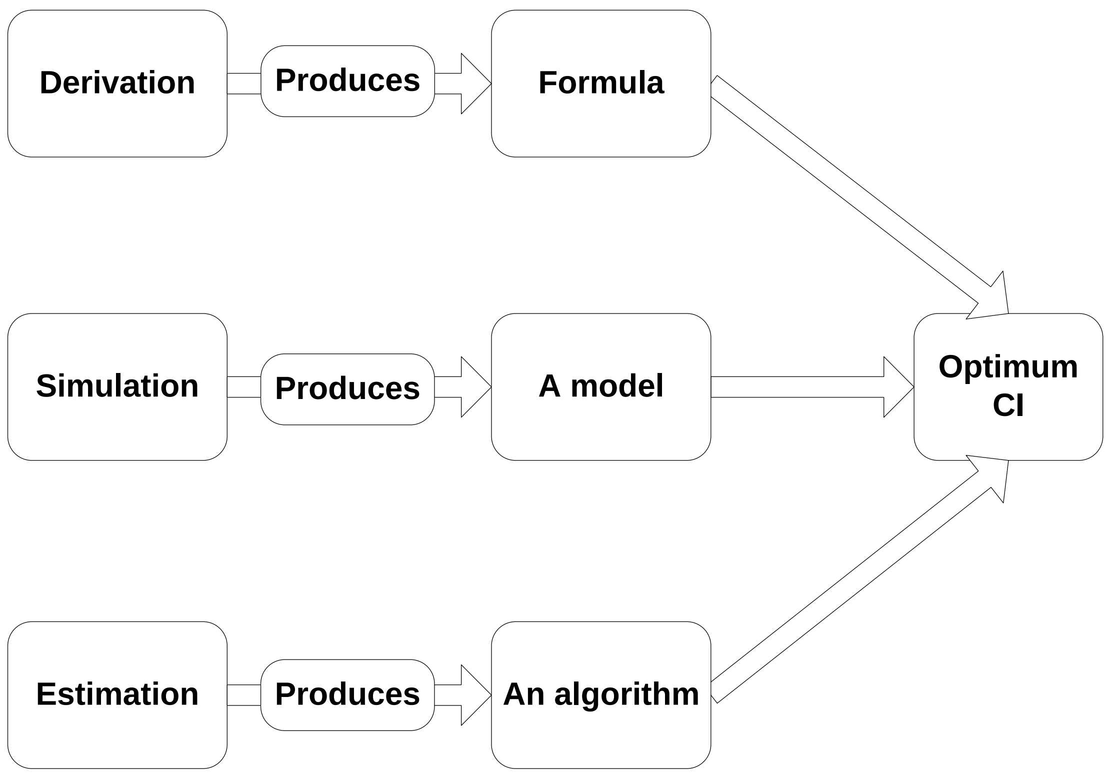


Figure 21: Suggested Methods for Determining Optimum CI.

If there are enough data of recording out of tolerance TMDE's then another approach may be followed to assess the optimum CI. The approach goes as follows:

- Use the data to define a relationship between the CI and the reliability.
- Construct a simulation model that allows exploring different CI values.

- Augment the cost in the model so that at each CI the two cost components are calculated.
- Use cost values generated as dependent variable with the CI associated with them as the independent variable and plot them. Find the CI that corresponds to the minimum cost and label it CI1.
- Repeat the whole processes again to get CI2,
- Repeat until you get CIm where m is a sufficiently large number.
- Compute the average of the CI's produced and report it as the optimum.

A third method may be used in case there are well-preserved-records of out of tolerance events and their magnitudes. The method is to device an algorithm to statistically compute the optimum CI from the data.

The method that will be used here is the first one (the derivation method).

5.8 Uncertainty Calculation Problem

Uncertainty is a value associated with the measurement of a parameter that sets the boundaries for the validity of the measured value. Accreditation bodies require calibration labs to include a statement of uncertainty in all of their measurements in order to be accredited. The specific guideline on how to calculate and report uncertainty is fully described in the document labeled ("Guide to the Expression of Uncertainty in Measurements"). The uncertainty of measurements is affected by almost every factor involved in the measurements (see Figure 22.). The source of effect of each factor in the measurement uncertainty is different from factor to factor. For example the personnel effect comes from the technician experience, his fitness (e.g ill or tired) conditions during the measurement and many other reasons, whereas the effect of the environment comes from variations in temperature, humidity or barometric pressure or from the presence or absence of vibration or some electromagnetic *i*nterference. All of these effects need first to be quantified and then accounted for when building the uncertainty budget to compute the final uncertainty value.

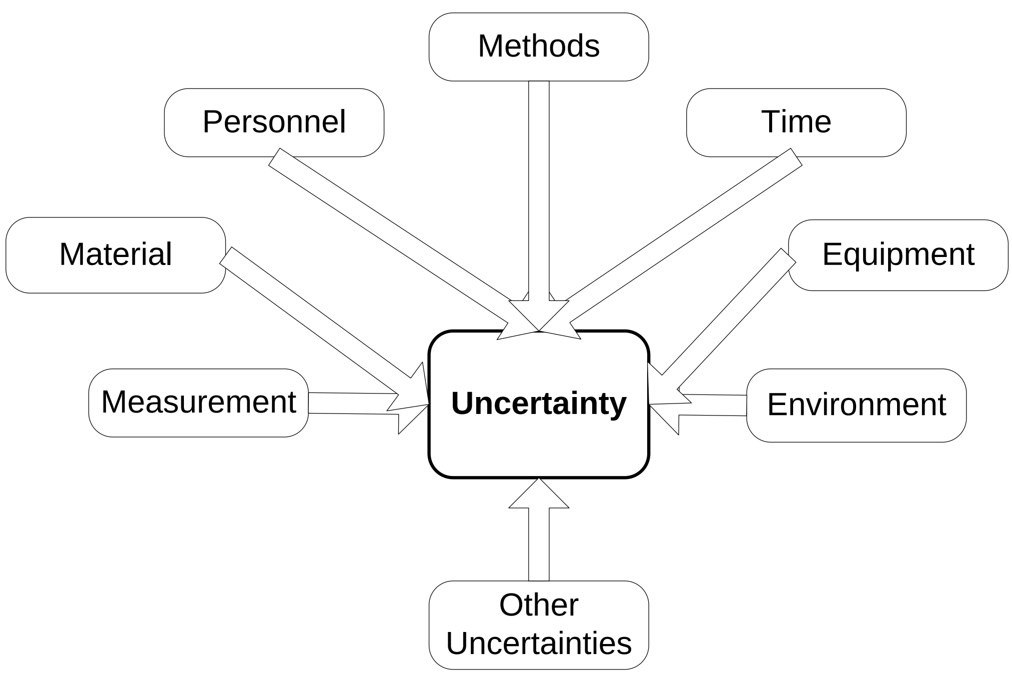


Figure 22: Factors Affecting Measurement Uncertainty.

Description

The determination of the value of the uncertainty of measurement is the most important part of the calibration process performed on any TMDE. The uncertainty value along with the uncertainty budget the value comes from is reported in the calibration certificated. If there is a mistake in the value then the whole calibration is wrong. Mistakes that occurred in the uncertainty value usually comes from mistakes committed in the uncertainty budget. The steps of constructing the uncertainty budgets are defined in the GUM and many of its document derivatives. These steps can be summarized as follows:

- Identify the uncertainty sources.
- Identify type A and type B evaluations
- Identify the underline probability distribution of each source.
- Determine the sensitivity coefficient for each source.
- Determine the interaction between sources.
- Compute the standard uncertainty of each source.
- Determine the degree of freedom associated with each source.
- Compute the combined standard uncertainty.
- Compute the combined degree of freedom of the final figure.
- Compute the extended standard uncertainty.
- Round off the uncertainty value.
- Report the measured value with the calculated uncertainty.

The above steps are too demanding in terms of performing the calculation. Any mistake in any one value of those will have a relatively significant effect on the final uncertainty. For example, a wrongly set sensitivity coefficient may change a certain value from a millimeters to a centimeters (a ten times change). There are in general many values during the process of building up the uncertainty budget that are susceptible to making mistakes. The main source of this susceptibility is really ambiguity associated with calculating some parameters or the misunderstanding of it (NAMAS, 1997).

5.8.1 Potential Optimization Problems

The problem here is a problem with the people rather than with system or with the procedure. A straight forward solution is to teach the people the proper way to build the uncertainty budget. But this solution is already implemented and yet people still commit the same mistakes. The solution suggested here is meant to work even with those who have some difficulty in understanding some parts of building the uncertainty budget.

[Problem Statement]

Remove all the ambiguity and misinterpretation associated with all related terms that are required to construct an uncertainty budget of measurements. The main objective of this is to make sure that the uncertainty budget is constructed correctly right from the beginning and the steps involved are carried out according to the guideline set forth by the GUM.

5.8.2 Impact on the System

The impact will be from two sides:

One is from the customers which appears in the increased confidence of the measurement performed in the facility.

The other side is in the facility which appears also in the technician's confidence that they will correctly perform the uncertainty budget.

The main effect is really the ability to correctly assessing the uncertainty of measurements "the ultimate objective of the calibration process".

5.8.3 Suggested Treatment

Develop comprehensive intelligent software that performs all the required computation of the uncertainty associated with measurements. The software should be intelligent enough to overcome all of the misinterpretation of ambiguous terms and quantities needed for the computations.

5.9 Grouping of Reference Standards

Since calibration is basically a comparison between the unit under test (UUT) and a reference standard, the standard must be precise and accurate. Most of the time standards are maintained individually (the standard gets calibrated in national labs and once returned it is used directly to calibrate other lower level standards or customer TMDEs). But some other standards cannot be trusted to hold their values once returned for various reasons. Therefore, a particular standard of those must be joined with similar standards in a group so that their pooled average value will then become the value of the unit intended to be obtained by the standard (see Figure 23). In this case if the value of one member of the group got changed for some reasons the average value will not be changed much and that individual member may then be subjected to corrections or to further investigation.

5.9.1 Description

There are many standards that are used in groups rather than individually. Usually these standards are at the higher echelon like at the primary level or higher. These standards are usually those that provide a basic unit value or one of its equivalents (for example, the voltage instead of the basic electrical unit which is the Ampere). The grouping of standards is currently applied with the time standard, the voltage standard, the resistance standard and the mass standard. Although these units are spread and used through groups; the method by which they are dealt with is different from one to another.

The voltage value for example is used differently than the time value. In case of the voltage, a number of voltage cells are connected to a high precision digital voltmeter, a computer and a controller. The value of each cell is monitored around the clock for all the cells. At each pass a reading is taken from each cell then the average is computed and differences of each individual and the average is computed and all the values are stored in the computer to maintain the cells values history. In the case where there is a UUT cell needs to be calibrated; one of the cell members is disconnected and UUT is put in its place. The group then continues the same way and the average value of the group is then assigned to the UUT.

it.

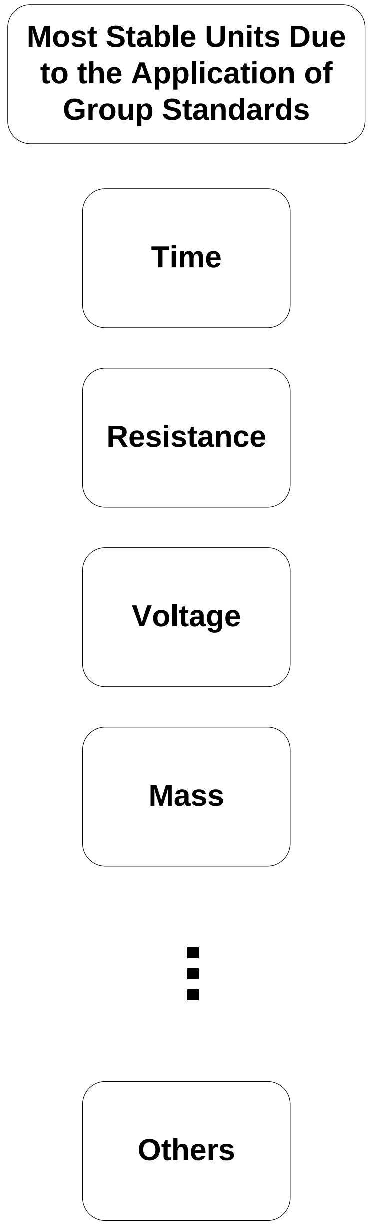


Figure 23: Group Standards

On the other hand the mass value is used in a different way. Usually one artifact –let say a one kilogram mass piece- is sent to a national lab to get calibrated. Once this piece is returned; its value is disseminated to the other mass pieces in the primary lab so that each one piece is then compared to customer piece of similar nominal value to calibrate it.

5.9.2 Potential Optimization Problems

There are many problems associated with the grouping of standards. The one that will be dealt with here is the construction of mass equations. The ultimate objective here is to develop a formula, a relationship or a formal guideline that relates the number of equations and the uncertainty of each member of the mass set calibrated. The objective is to be optimized over the cost of weightings and the gain of the increased uncertainty.

[Problem Statement]

Given a one kilogram artifact value, a set of mass weight and a precise balance with known characteristics (uncertainty, repeatability, linearity … etc.). Optimize the weighing scheme for both the number of weighings and the lowest obtainable uncertainty of each one objective alone. The objectives must be weighed by the cost of weightings and the gain obtained from the improved uncertainty.

5.9.3 Impact on the System

The impact will of two effects:

The first one is internal, and is shown in the time saved in the weighting scheme.

The second one is external, and is shown in the best uncertainty claimed by the lab which may attract more business.

5.9.4 Suggested Treatment

The suggested method should be as follows:

1. Develop a set of equations that covers the mass set to be calibrated.
2. Perform all the weightings and record the results.
3. Compute the uncertainty associated with each mass piece.
4. Redo steps 1 to 3 with a different set of equations.
5. Repeat step 4 until a sufficiently large number of runs has been generated.
6. Analyze the results and develop a relationship between the number of equations and the best uncertainty achieved.

CHAPTER 6

SCHEDULING PROBLEM

6 Multiple-Attribute Calibration Job Scheduling Problem (MACJSP)

6.1 Introduction

Calibration jobs scheduling problem is one of the most complicated, demanding and challenging problems. The complexity of the problem arises from the multiple attributes nature of each of the calibration facility constituent (laboratory, operators, calibration jobs …etc.). In addition to that, most of the calibration jobs can be done in a relatively short period of time (job processing time) counted in hours. This characteristic implies that there will be many alternatives to consider in the scheduling process as opposed to the case in which jobs have a large processing time, leaving the scheduler with limited scheduling alternatives.

This paper will present a new method to solve the MACJSP. First, we will discuss the reasons and logic behind the need for solving this problem. Second, the methodology of the solution is presented. Third, problem definition is presented. This will be followed by a mixed integer program (MIP) model development. After that, the development of the Heuristic algorithm is provided. Finally, an analysis and comparison of the two methods are provided in light of some test problems along with some preset criteria.

6.2 Discussion

Normally, calibration jobs are scheduled by highly experienced supervisors or senior technicians. Those supervisors and technicians employ their knowledge of the laboratory attributes and of the jobs and operators to produce a schedule intuitively. Usually, only feasible schedules are sought by the scheduler in this case, with less attention paid to other objectives like operator utilization, work spread and reduction of jobs waiting time. The problem gets even more difficult as the number of jobs increases and –in this case- even a feasible schedule may not be found. Moreover, an added difficulty is the number of calibration standards and laboratory resources that are required by different jobs. These cannot be precisely considered by the scheduler when assigning jobs to operators at certain times due to various operational requirements by various calibration jobs. This may cause some operational problems such as the need –at a particular hour- for an extra number of standards (or/and resources) more than what are already available in the laboratory. As a result of that, a poor schedule may be produced.

The effect of poor scheduling can sometimes be devastating. This is manifested in outcomes such as excessive delays of calibration jobs which in turn reduce the utilization of calibrated assets by the user and leads to unfair distribution of work amongst operators which negatively impacts operator morale and may lead to increased complaints from some workers. The increased frequency of these shortfalls may create a bad working environment that will have unpredicted consequences. The poor consideration of the availability of calibration standards and resources may also lead to work stoppages and unacceptable job delays.

In order to eliminate all of the problems associated with poor scheduling, the calibration jobs scheduling problem needs to be solved optimally based on preset criteria. The set of criteria must include some objectives that guarantee -once attained- smooth and efficient operations within the laboratory and a fair and comfortable work load and jobs distribution. The objectives that will be used in this model are the concurrent fulfillment of the following: the reduction of the maximum waiting time of jobs (a user objective), the fulfillment of jobs priorities (a user objective), the maximization of operator utilization (a laboratory management objective), and the fair distribution of workload among operators (an operator objective).

There are few methods that may provide an optimal solution and the most commonly used one is mathematical programming (a technique used in operations research). In this paper the scheduling problem is formulated as a mixed integer programming model (MIP model). The MIP model is then solved using LINGO (a specialized program used to solve linear and integer programs). The solution is applied to a large instance created in an Excel worksheet where it is imported to LINGO, solved and the solution is exported back to Excel. The solution is then analyzed along with an analysis of the method used in creating and solving the model. A statement on the performance of the model and on the time complexity of the solution method is presented. The statement is used as the base for justifying the development of an alternative method.

Although the MIP model provides a means by which the scheduling problem can be solved optimally, it has some drawbacks and limitations. The drawbacks include the difficulty to construct the model which requires a profound knowledge of operations research in general and of mathematical programming in particular. This is a skill that is hardly found in a calibration laboratory. In addition to that the solution of the model requires a specialized and relatively costly program (such as LINGO) and an operator capable of coding the model into the program script. The biggest limitation is concerned with the time the software takes to solve the MIP which can get to an impractical length depending on the size of the instance being solved. This is largely due to the method the program uses to solve the MIP model which can get sometimes similar to complete enumeration or even worse.

The need, therefore, arises to develop a method by which the calibration-jobs scheduling problem is solved in an appreciable time, with less effort, with high efficiency and with barely any cost. The MIP model may still be used for moderately sized instances and in the case where the laboratory has the right expertise that may modify and recode the model when there is a need for that.

This paper –beside what has already been discussed- is mainly concerned with the development and construction of a heuristic algorithm that solves the mentioned calibration-jobs scheduling problem efficiently and in an appreciable time. The heuristic algorithm is then automated and the produced software is made available for immediate use.

6.3 Methodology of the Solution

This paper discusses the development of a method for solving the multi-attribute calibration-jobs scheduling problem (MACJSP). The development of this method will be accomplished through eight sequential phases namely: Scheduling problem definition, mixed integer programming model, LINGO model, analysis of integer program model, heuristic algorithm development, heuristic algorithm automation, analysis of heuristic algorithm and conclusion (see figure 24).

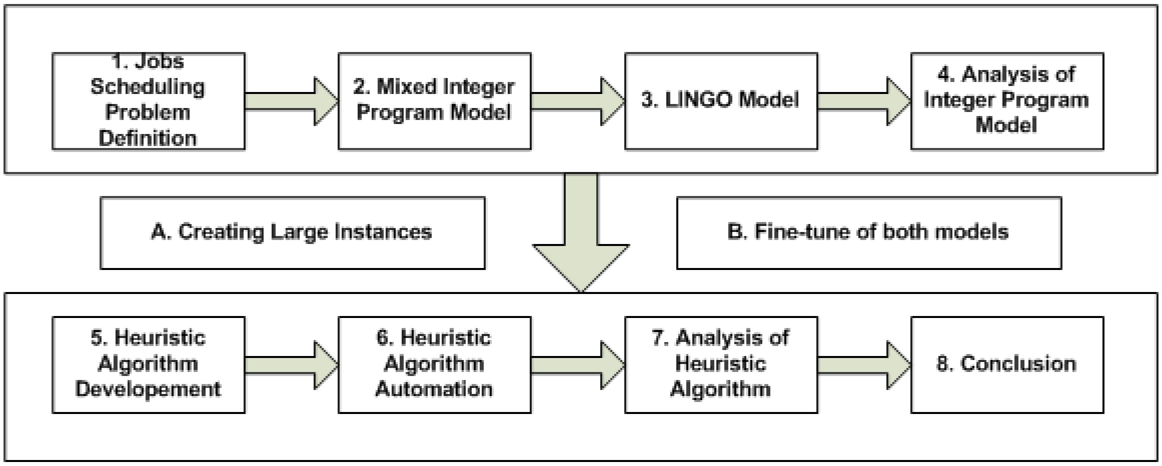


Figure 24: Phases of Development

6.4 Problem Definition

The problem definition is broken down to two parts, namely the problem statement and the problem attributes. Following is a description of both.

6.4.1 Problem Statement

The MACJSP is defined as the following: Given a number of jobs (instruments to be calibrated) at a calibration laboratory that has a number of operators (each of which has a certain skill level and a predetermined set of job types that he is capable of performing), a set of calibration standards (each of which may have more than one copy), and a number of resources (each of which have a number of copies). It is required to schedule the jobs to the operators in a way that optimizes some preset objectives. The schedule must satisfy the given values of all the attributes of either of jobs, operators, standards and resources. The schedule has to be done in a reasonable time and performed by an operator with fairly limited scheduling and calibration experience.

6.4.2 Problem Attributes

The laboratory has the following attributes: number of jobs, number of standards, number of resources, number of operators, number of calibration areas, number of job complexity levels, number of priority designations, number of operator areas of expertise, number of hours per shift, number of shifts per day, and the number of working days per week (see Table 6).

Typical Laboratory Attributes Values		
Nom	**Symbol**	**Attributes Values**
Standards	L_S	Standards Attributes
Resources	L_R	Resource Attributes
Operators	L_O	Operators Attributes
Areas	L_K	Areas Attributes
Complexity	L_C	1= Simple 2= Difficult
Days	L_D	Day
Shifts	L_F	8 hours
Hours	L_H	Hour
Priority	L_P	1= Normal 2=Urgent 3=Immediate
Skills	L_A	Skills Attributes

Table 6: Lab Attributes

The operator has the following attributes: the time available per week, the skill of the operator, the experience level (capability of complex jobs), the utilization factor and the shift for which the operator is assigned see Table 7.

Typical Operators Attributes Values						
SN	**Name**	**TO**	**LO**	**AO**	**SO**	**FO**

Table 7: Operator Attributes.

Standards and Resources have the attribute of number of copies (see Table 8 and 9).

Standards number of copies (S_C)		
SN	**Nom**	S_C_m

Table 8: Standards Attributes.

Resources number of copies (R_C)		
SN	**Nom**	R_C_n

Table 9: Resources Attributes.

The K area or the calibration area to which jobs belong, is shown in Table 10.

K Area	**Definition**
1	Volt
2	Res
3	Impedance
4	Micro Wave
5	Electro-Mechanical
6	Mechanical
7	Radiac
8	Electrical Lab Standards
9	Automatic Calibration

Table 10: Areas Attributes.

The calibration job has the following attributes: job type, priority, waiting time, job complexity, job processing time, standards and resources requirement (Table 11).

Job	YJ	PJ	WJ (day)	CJ	TJ	Job-Standard Requirement SJ	Job-Resource Requirement RJ

Table 11: Job Attributes.

Job standards and resources requirement are shown in Table 12 the body of the table contains the value of either zero or one (zero indicates that job does not require that standard or resource and one that it does).

Job-Standard Requirement				
job	S1	.	.	Sm
1	S_{11}			
.				
L_J				S_{jm}

Job-Resource Requirement				
job	R1	.	.	Rm
1	R_{11}			
.				
L_J				R_{jm}

Table 12: Job-Standard and Job-Resource Requirements.

Operator's expertise is shown in Table 13.

L_A	
1	K1
2	K2
3	K3
4	K4
5	K5
6	K6
7	K7
8	K8
9	K9
10	All Electrical Areas
11	K1,K2,K3 and K4
12	K1,K2 and K3
13	All Mechanical Areas
14	All Areas

Table 13: Operator Specialty.

The final schedule is produced in the form of either a five-day schedule (see Table 14) or a one-day schedule (see Table 15)

L/H				operator														
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
days	1	hours	1															
			2															
			3															
			4															
			5															
			6															
			7															
			8															
	2	hours	1															
			2															
			3															
			4															
			5															
			6															
			7															
			8															
	3	hours	1															
			2															
			3															
			4															
			5															
			6															
			7															
			8															
	4	hours	1															
			2															
			3															
			4															
			5															
			6															
			7															
			8															
	5	hours	1															
			2															
			3															
			4															
			5															
			6															
			7															
			8															

Table 14: Schedule Output Form One Week.

L/H				operator														
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	One Day	hours	1															
			2															
			3															
			4															
			5															
			6															
			7															
			8															

Table 15: Schedule Output Form One Day.

6.5 Model Development

6.5.1 Assumptions

6.5.1.1 A standard is tied up to the job for the entire processing time.

6.5.1.2 Processing times of jobs are integer values with the units of hours.

6.5.1.3 Jobs arrive at the beginning of the day.

6.5.1.4 Scheduling is done at the beginning of day one of the week.

6.5.2 Objectives

6.5.2.1 Produce a feasible schedule that assigns each job to a technician. The required standards are also assigned to the job during the processing time.

6.5.2.2 Satisfy the priorities of all jobs.

6.5.2.3 Maintain even distribution of work amongst technicians.

6.5.2.4 Maximize the utilization of operators.

6.5.2.5 Minimize the maximum time taken by the job in the system.

6.5.3 Notations

6.5.3.1 Indexes

$i = 1 \ldots \infty$ general

$l = 1 \ldots \infty$ general

$h = 1 \ldots \infty$ general

$j = 1 \ldots L\_J$ jobs

$d = 1 \ldots L\_D$ day

$f = 1 \ldots L\_F$ *shifts*

$m = 1 \ldots L\_S$ *standards*

$n = 1 \ldots L\_R$ *resources*

$o = 1 \ldots L\_O$ *operator*s

6.5.3.2 Laboratory Attributes

$L\_J : is\ the\ number\ of\ Jobs$

$L\_S : is\ the\ total\ number\ of\ Standards$

$L\_R : is\ the\ total\ number\ of\ Resource\ Types$

$L\_O : is\ the\ number\ of\ Operators$

$L\_K : is\ the\ number\ of\ Calibration\ Areas\ (K\ areas)$

L_C : *is the number of Job Complexity Levels*

L_D : *is the number of days per week*

L_F : *is the number of shifts per day*

L_H : *is the number of hours per shift*

L_P : *is the number of priority designations*

L_A : *is the number of Operator areas of expertise*

6.5.3.3 Standard Attributes

S_C_m : *is the number of copies of standard* **m** , $m = 1$ *to* L_S

6.5.3.4 Resource Attributes

R_C_n : *is the number of copies of Resource* **n** , $n = 1$ *to* L_R

6.5.3.5 Operator Attributes

V_o : *is the time (in hours) available per week for operator* **o**

A_o : *is the skill of operator* **o**

E_o : *is the experience level (capability of complex jobs) of operator* **o**

U_o : *is the utilization factor (0 to 1) of operator* **o**

6.5.3.6 Job Attributes

K_j : *is the type of job* **j** , values are from 1 to L_K

P_j : *is the priority of job* **j** , values are from 1 to L_P

W_j : *is the waiting time (in days) of job* **j**

C_j : *is the complexity of job* **j** , values are from 1 to L_C

T_j : *is the processing time (in integer hours) of job* **j**

S_{jm} : *is the standards requirement of job* **j** , values are:

$$S_{jm} = \begin{Bmatrix} 1 \text{ if standard } \mathbf{m} \text{ is required by job } \mathbf{j} \\ 0 \text{ otherwise} \end{Bmatrix}$$

R_{jn} : *is the resources requirement of job* **j** , values are:

$$R_{jn} = \begin{Bmatrix} 1 \text{ if resource } \mathbf{n} \text{ is required by job } \mathbf{j} \\ 0 \text{ otherwise} \end{Bmatrix}$$

δ_w *and* δ_p Are weights used to normalize the values of W_j *and* P_j *respectively*. The choice of the weights values should be selected to increase or decrease the contribution of each variable in the objective function.

6.5.4 Decision

6.5.4.1 Variables Definition

6.5.4.2 $X_{jodh} = \begin{Bmatrix} 1\ if\ job\ j\ is\ assigned\ to \\ operator\ o\ in\ day\ d \\ in\ hour\ h\ \ and \\ 0\ otherwise \end{Bmatrix}$

6.5.4.3 $Z_{jodi} = \begin{Bmatrix} 1\ if\ the\ ith\ T_j\ hours\ is \\ assigned\ for\ job\ j\ in\ day\ d \\ by\ operator\ o\ and \\ 0\ otherwise \end{Bmatrix}$

6.5.4.4 $Q_{jo} = \begin{Bmatrix} 1\ if\ job\ j\ is\ assigned \\ to\ operator\ o \\ and \\ 0\ otherwise \end{Bmatrix}$

6.5.4.5 $U_o = a\ value\ between\ 0\ and\ 1,\ the\ utilization\ of\ operator\ o$

6.5.5 Objective Function Development

The waiting time of job j W_j is minimized by scheduling first the jobs that has stayed longer in system. This is done by maximizing $\delta_w W_j Q_{jo}$

Similarly, the priorities are satisfied by increasing their relative contribution to the Objective Function as their priority gets higher. Therefore, $\delta_p P_j Q_{jo}$ is maximized.

Summing all over their values the 2 segments of the objective function become:

$$max\ \{\sum_{o=1}^{L_O} \delta_w \sum_{j=1}^{L_J} W_j Q_{jo} + \sum_{o=1}^{L_O} \delta_p \sum_{j=1}^{L_J} P_j Q_{jo}\}$$

$$max \sum_{o=1}^{L\_O} (\delta_w \sum_{j=1}^{L_J} W_j Q_{jo} + \delta_p \sum_{j=1}^{L_J} P_j Q_{jo})$$

$$max \sum_{o=1}^{L\_O} \sum_{j=1}^{L\_J} (\delta_w W_j Q_{jo} + \delta_p P_j Q_{jo})$$

And in a more tight form:

$$max \sum_{o=1}^{L\_O} \sum_{j=1}^{L\_J} (\delta_w W_j + \delta_p P_j)\, Q_{jo}$$

6.5.6 Constraints Development

The operator must be able to handle the complexity of the job, that is:

1. $\boldsymbol{C_j Q_{jo} \le E_o} \quad for\ all\ j, o, d\ and\ h$

The job type must be within the specialty of the operator, that is:

2. $(\boldsymbol{K_j - A_o})\boldsymbol{Q_{jo} = 0} \quad for\ all\ j\ and\ o$

A job is done only once or none, that is:

3. $$\sum_{o=1}^{L\_O} \boldsymbol{Q_{jo} \le 1} \qquad for\ all\ j$$

The sum of all jobs processing times assigned to an operator will not exceed his available time per week, that is:

4. $$\sum_{j=1}^{L\_J} \boldsymbol{T_j Q_{jo} \le V_o} \quad \forall\ o$$

The assigned number of any standard at any hour must not exceed the number of copies of that standard. That is:

5. $$\sum_{o=1}^{L\_O} \sum_{j=1}^{L\_J} \boldsymbol{S_{jm} X_{jodh} \le S\_C_m} \quad for\ all\ m, d\ and\ h$$

The assigned number of any resource at any hour must not exceed the number of copies of that resource. That is:

6. $$\sum_{o=1}^{L\_O} \sum_{j=1}^{L\_J} \boldsymbol{R_{jn} X_{jodh} \le R\_C_n} \quad for\ all\ n, d\ and\ h$$

The hours assigned for the processing of any job must be consecutive, that is:

7. $$\sum_{h=i}^{i+T_j-1} \boldsymbol{X_{jodh} \ge T_j Z_{jodi}} \quad for\ \ i = 1 \dots 9 - T_j\ , all\ j, o\ and\ d$$

A period of T_j hours -at any given day- is used for processing a job j only if that job is assigned to an operator o at that day.

8. $$\sum_{d=1}^{5} \sum_{i=1}^{9-T_j} \boldsymbol{Z_{jodi} = Q_{jo}} \quad \forall\ j, o$$

The sum of assigned hours to process a job is equal to its processing time, that is:

$$\mathbf{9}.\quad \sum_{j=1}^{L\_J}\sum_{d=1}^{5}\sum_{h=1}^{8} X_{jodh} = G_o \qquad \forall\ o$$

The total time an operator is occupied in any given day does not exceed 8 hours, that is:

$$\mathbf{10}.\quad \sum_{j=1}^{L\_J}\sum_{h=1}^{8} X_{jodh} < 8 \qquad \forall\ o, d$$

A job is assigned to an operator only when he is not occupied with another job, that is:

$$\mathbf{11}.\quad \sum_{j=1}^{L\_J} X_{jodh} \le 1 \qquad \forall\ o, d, h$$

This constraint defines the total time an operator is occupied G_o :

$$\mathbf{12}.\quad \sum_{j=1}^{L\_J} T_j Q_{jo} = G_o \qquad \forall\ o$$

The none-negativity constraints:

$$\mathbf{13}.\quad X_{jodh}\ ,\ Q_{jo}, Z_{jodi}\ , S_{jm}\ , R_{jn} \ge 0 \qquad \forall\ j, o, d, h, i, m, n$$

6.5.7 Model Structure

$$\max \sum_{o=1}^{L\_O} \sum_{j=1}^{L\_J} (\delta_w W_j + \delta_p P_j)\, Q_{jo}$$

$ST.$

1. $C_j Q_{jo} \leq E_o \quad \forall\, j, o$
2. $(K_j - A_o) Q_{jo} = 0 \quad \forall\, j, o$
3. $\sum_{o=1}^{L\_O} Q_{jo} \leq 1 \quad \forall\, j$
4. $\sum_{j=1}^{L\_J} T_j Q_{jo} \leq V_o \quad \forall\, o$
5. $\sum_{o=1}^{L\_O} \sum_{j=1}^{L\_J} S_{jm} X_{jodh} \leq S\_C_m \quad \forall\, m, d, h$
6. $\sum_{o=1}^{L\_O} \sum_{j=1}^{L\_J} R_{jn} X_{jodh} \leq R\_C_n \quad \forall\, n, d, h$
7. $\sum_{h=i}^{i+T_j-1} X_{jodh} \geq T_j Z_{jodi} \quad for\ \ i = 1 \dots 9 - T_j, \forall\, j, o, d$
8. $\sum_{d=1}^{5} \sum_{i=1}^{9-T_j} Z_{jodi} = Q_{jo} \quad \forall\, j, o$
9. $\sum_{j=1}^{L\_J} \sum_{d=1}^{5} \sum_{h=1}^{8} X_{jodh} = G_o \quad \forall\, o$
10. $\sum_{j=1}^{L\_J} \sum_{h=1}^{8} X_{jodh} < 8 \quad \forall\, o, d$
11. $\sum_{j=1}^{L\_J} X_{jodh} \leq 1 \quad \forall\, o, d, h$

12. $$\sum_{j=1}^{LJ} T_j Q_{jo} = G_o \qquad \forall\ o$$

13. $$X_{jodh}\ ,\ Q_{jo}, Z_{jodi}\ , S_{jm}\ , R_{jn} \geq 0 \qquad \forall\ j, o, d, h, i, m, n$$

6.5.8 Model Complexity

Model complexity is defined as the ratio of the number of constraints to the number of variables. The ratio could be as high as one (higher than one indicates redundant constraints that could be omitted with no effect on the solution) and as low as zero. As the ratio gets closer to one, the problem approaches a simple simultaneous equations problem which will be solved quickly. On the other hand, as the ratio gets smaller the problem solution space gets larger and consequently does the time for the simplex algorithm to find the real valued solution. After the real valued solution is obtained, it will take more time for the branch and bound algorithm (which the algorithm used by LINGO) to find the integer solution.

The MIP model developed has a fixed number of variables and a variable number of constraints. The variability in the number of constraints comes from the variable "Z" which is the period number. To clarify this, suppose the processing time of a certain job is 3 hours. In this case we will have 9-3 or 6 Z variables. If the processing time is 7 we will have 9-7 of 2 Z variables (Z1 stand for the first 7 and Z2 stand for the second 7). This property of the model shows that the number of constraints is data dependent and consequently the model complexity is also data dependent.

For a particular instance, the highest number of constraints is obtained when all jobs processing times are equal to 1. The effect of the complexity level produced on the instance solution time is very drastic. It reduces the solution time from the order of many hours to the order of a few seconds. Therefore, to gain an improvement in the model solution time, this advantage must be exploited. This is done by manipulating the instance data so that it follows the best form which is the one that gives the highest of the number of constraints. Following are the various instance cases and how to deal with each one of them:

Case 1 when all processing time are equal to "one"

Do nothing (the problem is at its best form)

Case 2 when all processing times are equal to “two”

Change it to “one” and change the number of hours to 4 instead of 8.

Case 3 when all processing times are equal “four”

Change it to “one” and change the number of hours to 2 instead of 8.

Case 4 when all processing times are equal to 8

Change it to “one” and change the number of hours to 1 instead of 8.

Another advantage might be gained if we reduce the scheduling horizon from 5 days to one day. This will drastically decreases the model complexity and causes a great reduction to the solution time.

6.6 The Heuristic Algorithm

6.6.1 Logic of the Heuristic Algorithm

The algorithm is based on a fairly simple idea. The idea is to schedule first the jobs that are done by fewer people and leave those that are done by most last. The reason for this is quite obvious. Jobs that are done by say only one operators may not get the chance to be scheduled later because the only one who can do them may be occupied. On the other hand, jobs that are done by everybody can be easily scheduled because they will fit in any available time.

6.6.2 Structure of the Heuristic Algorithm

Step0 Initialize **Schedule(H,O)** to zero

Let: J=1,2,…,LJ ; C=1,2,…; H=1,2,…,8

Step1 Calculate the Weight Associated with each Job According to:

Sj=αWj+βPj

Step2 For each Worker Find the number of Jobs he can do **OCJ(O,C)**

Step3 Order Workers in a descending order of the number of jobs they can do, so that operator **OCJ(m,n)** can do less jobs than **OCJ(m,n+1)** for all m and n

Step4 For each Job Identify all workers who can do it **JBO(J,C)**

Step5 For each Job in **JBO(J,C)**, sort workers according to workers order obtained in Step3

Step6 Group Jobs according to the number of workers who can do it **G(I,K)**

I=0,1,…,LO ; K=1,2,…

G(I,K) contains all jobs that are done by I operators

Step7 Order the jobs in each group in a descending order of their **Sj**, so that

For each **G(I,m)** and **G(I,m+1)**, **Sm** > **Sm+1** for all I and m

Step8 Set I=1 ; K=1 ; L=1 ; OF=0

Step9 Take the Job J=**G(I,K)**

Step10 Take worker O= **JBO(J,L)**

If Processing time of J > Available time of O Then

L=L+1

GOTO Step10

Step11 Identify the number of available periods AP and their location **Lo** under worker O

Set D=1

Step12 Assign Job J to worker O in the **Lo**(D) sufficient (equal to the processing time) period

Step13 Check the availability of Standards and Resources

If Standards and Resources are within the number of Copies of each **Then**

Append Job J to the list of Scheduled Jobs so that **SJ=SJ+{J}**

OF=OF+1, Set K=2

GOTO Step9

Else If <= AP **Then**

Remove the assignment of Step12

D=D+1

GOTO Step12

Else If there still worker to do Job J **Then**

Remove the assignment of Step12

L=L+1

GOTO Step10

Else If there still jobs to do **Then**

Remove the assignment of Step12

K=K+1, L=l

GOTO Step9

Else If there still groups to do **Then**

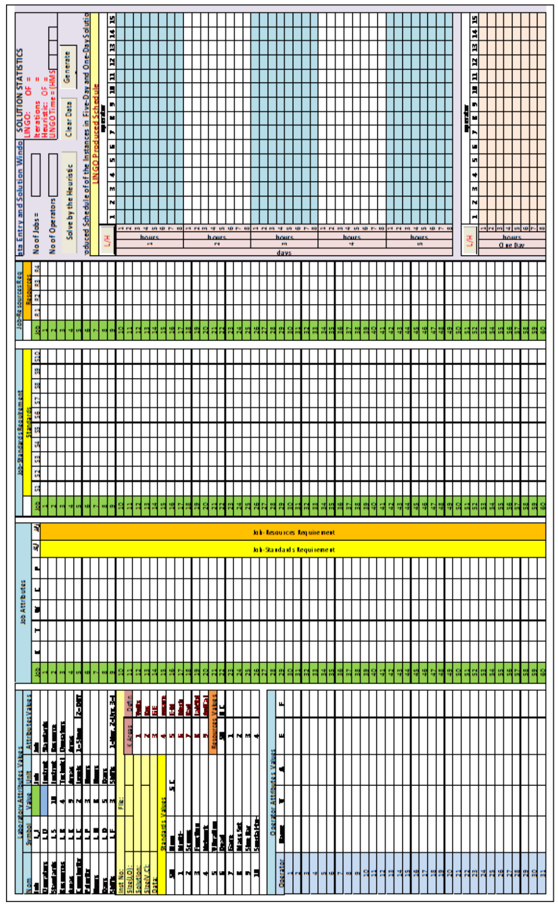
Remove the assignment of Step12

I=I+1, K=1, L=1

GOTO Step9

Step14 **Report the Schedule**

6.6.3 Automation of the Heuristic Algorithm



The Heuristic algorithm is programmed in Visual BASIC in an Excel Sheet. The Excel Sheet contains formatted field for all of the problem attributes along with the final

Table 16: The MACJSP Heuristic Algorithm Program.

schedule of both 5-day and 1-day schedule (see Table 16). Data can be entered or randomly generated and once all the fields are completed the Heuristic is activated by pressing the “solve by the heuristic” Button. This Excel Sheet is shown in Table16.

6.7 Comparison

The two methods namely the MIP Model and the Heuristic Algorithm performed well. A set of 10 randomly generated test problems (the last problem of which is of relatively large size).are utilized to show the two methods relative performance. The comparison is based on calculating the ratio of the OF obtained from the Heuristic (OF2) to the OF obtained from the MIP Model (OF1) which is OF2/OF1. The outcome of the comparison is shown in Table17 (the last column of Table 17 is rounded off for convenience). The ratios obtained are statistically analyzed and the 95% Confidence Interval is produced.

Problems		**MIP Model**			**Heuristic Algorithm**			**% Of Opt**
Sn	Size (J X O)	OF1	Jobs	time	OF2	Jobs	time	**OF2/OF1**
Problem 1	60 X 6	382	14	52	330	13	1	86
Problem 2	60 X 6	301	10	34	282	11	1	93
Problem 3	60 X 6	403	14	43	336	12	1	83
Problem 4	60 X 6	401	16	45	376	14	1	93
Problem 5	60 X 6	363	12	56	338	12	1	93
Problem 6	60 X 6	467	15	45	430	16	1	92
Problem 7	60 X 6	283	11	46	256	9	1	90
Problem 8	60 X 6	492	18	56	456	17	1	92
Problem 9	60 X 6	251	13	54	230	10	1	91
Problem 10	117X 6	2434	48	60	2182	48	1	89

Mean	**90.2**	**SD**	**3.359894**	**95% Confidence Interval**	**{83,97}**

Table 17: Comparison of MIP and HA Objective Function.

The statistical conclusion states that 95% of the time the OF value of the schedule obtained from the Heuristic Algorithm is between 83% and 97% of the OF value of the schedule that would be obtained from the MIP Model (the Optimal Schedule)

A way from the performance of both methods in terms of time, the two methods are compared according to a set of criteria that includes cost, ease of use, solution time, OF value, effort required to modify the model or the program and overall maintenance. The values of the assessment are reached as follows (see Table 18):

Total cost is high for MIP because the user needs to buy LINGO SW to solve the MIP. The MIP is difficult to use because it needs profound knowledge of operations research and specially integer programming. The solution time is the time taken by either of the methods to reach the final solution. The OF reached is 100% for the MIP model and around 90% of it by the Heuristic (as it has been shown above). The modification is difficult for the MIP because it needs knowledge of OR and only VB programming knowledge for the Heuristic. The maintenance (changing objective or constraints) could be very difficult for the MIP if at some point a drastic change in the data or in the problem structure is required.

Sn	Criterion	MIP Model	Heuristic Algorithm
1	Total cost	High	Low
2	Ease of use	Difficult	Easy
3	Solution time	Bad	Excellent
4	OF reached	Excellent	Very Good
5	Modification	Difficult	Moderate
6	Maintenance	Easy to Difficult	Easy to Moderate

Table 18: Comparison of MIP and HA Using a Set of Criteria.

The final analysis indicates that the Heuristic is an extremely better choice over the MIP Model.

6.8 Conclusion

In conclusion, the MACJSP is a very complex problem. The problem is dealt with in two methods. The first is by modeling it as an MIP model, and then solved using LINGO program. The modeling process was complex and requires a profound knowledge of Operations Research. The solution obtained by the model is optimal but takes an unacceptable time to reach for some of the problems. The second method is by designing and building a Heuristic Algorithm that solves the problem in an appreciable time. The heuristic is shown to be very efficient. A comparison is made between both methods and the result is analyzed. The analysis revealed that the Heuristic Algorithm is much better for all practical purposes. The heuristic algorithm is packaged in an Excel worksheet that allows the user to enter or randomly generates problems data, then instructs the program to solve the problem and produce a schedule.

CHAPTER 7

CALIBRATION INTERVAL DETERMINATION PROBLEM

7 Optimization of Calibration Interval Determination

Test measurement and diagnostic equipment TMDEs calibration intervals are dealt with in various ways. This treatment here, deals with various aspects of this problem depending on the situation.

7.1 Introduction

The estimation of the length of the calibration interval –in general- is a very difficult problem. There are many ways reported in the literature that deals with this problem. Most of these ways -if not all- concentrate on the period that guarantees a high reliability in the measurement and this is done through some statistical means. At the same time most of the methods of estimating calibration intervals ignore the cost involved in the process and if they do they include only the cost of the calibration.

Here, a number of methods are developed to deal with the problem of CI determination problem. The methods are meant to cover most of the cases encountered in calibration which includes cost and non cost-based cases, critical equipment and large number of similar TMDEs. The methods will always optimize some criteria such as cost, performance or workload size of the TMDEs inventory.

7.2 Reliability

TMDE's reliability is a measure of how good the performance of the device is, over a certain period of time. Usually, the device reliability can be defined in two different ways. The first one is the reliability of the device over its entire life. This reliability has no impact on the calibration interval estimation and hence is of no concern to the analysis of this treatment. The second one is the reliability of the device over the calibration interval or in general the reliability over a short period of time. This later one will be the subject that will be dealt with. The assessment of this measure of TMDE’s performance will be based on statistical methods relying on data collected from the history of out-tolerance records. The assessment of reliability could be based on statements provided by the device manufacturer, obtained from the average reliability of similar devices or based on statistics gathered from the failures of the device.

7.3 Calibration Interval

TMDE’s measurement performance is subject to drift over time and this drift causes error in the measurement performed by the device. The drift cannot be totally eliminated in the design phase and the only way to eliminate it is to bring back the TMDE precision and accuracy to its previous level by means of calibration. The calibration must be performed as soon as the performance of the device deteriorated to an unacceptable level. The device is then required to be periodically calibrated and the period after which the device is recalibrated throughout its useful life is called the device calibration interval.

TMDE's are usually devices that measure a number of parameters, and the performance of the measurement may not deteriorate for all the parameters at the same time. Therefore, within the context of this analysis any deterioration of one parameter will be considered a failure in the device even if the performance of each and every other parameter is acceptable. The calibration interval is assigned in such a way that the TMDE performance is reliable during the entire period and the measurement error does not exceed a certain level.

7.4 CI Determination Methods

CI determination methods are quite rigorous and demanding in terms of symbols and formulas required defining the related functions. Therefore, a concise development is presented in the following which starts by the notations involved and followed by the functions used in the methods formulation.

7.4.1 Notations

$f(t)$ is the device failure density function.

$F(t)$ is the device failure probability function.

$R(t)$ is the device reliability function.

$h(t)$ is the hazard function.

MTBF is the mean time between failures which is the mean time between the beginnings of the failure to the beginnings of the next one.

MTTF is the mean time to failure which is the mean time between the ends of the failure to the beginning of the next one.

MTTR is the mean time to repair which is the mean time required to repair a failed item it is basically the time taken from the moment of the failure to the moment of starting the operation again.

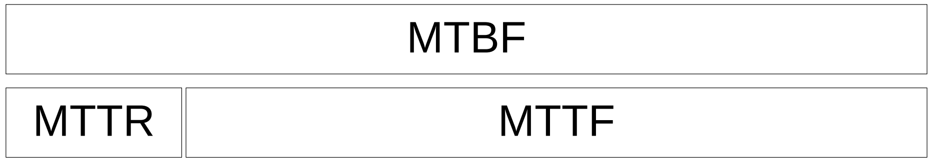


Figure 25: Mean time between failures.

Cc is the cost of calibration.

Co is the cost of using an out of tolerance device.

Cf is the cost of the first failure.

λ is the failure rate.

I is the calibration interval.

I* is the optimum calibration interval.

7.4.2 Functions Definitions

The failure density function $f(t)$ is the function of the time to failure random variable t. This failure function is the most widely used function to describe the failure pattern of a device.

The failure density function:

$$f(t) = \lambda e^{-\lambda t} \qquad \text{(a)}$$

The failure function $F(t)$ is the probability that a device will fail by time t.

The failure probability function is:

$$F(t) = 1 - e^{-\lambda t} \qquad \text{(b)}$$

The reliability function $R(t)$ is the probability that a device will perform its intended function during time t.

The device reliability function is:

$$R(t) = e^{-\lambda t} \qquad \text{(c)}$$

The hazard function $h(t)$ is the probability that a device of age t will fail in the small interval of time t to t+dt (i.e. now).

The device hazard function is:

$$h(t) = \frac{f(t)}{R(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \qquad \text{(d)}$$

The mean time to failure of the device is:

$$MTTF = \int_0^{\infty} e^{-\lambda t} dt = \frac{1}{\lambda} \qquad \text{(e)}$$

The mean time between failures of the device is:

$$MTBF = MTTF + MTTR \qquad \text{(f)}$$

For all cost figures the units that will be used is Saudi Arabian Riyals (SARs) and months for the CI.

7.4.3 Reliability-Target Solution (RTS)

This is the simplest case for calibration interval determination. The way is found in many texts. Here it is assumed that there is a device or a number of similar devices for which you have a specific reliability level required. The basic assumption actually for most of the devices reliability functions is that they have an exponential function with a constant failure rate. In cases where the failure density function is believed to be some other distribution the only change then is to change the functions in the Excel worksheet and algorithm will use it accordingly.

$R(t) = e^{-\lambda t}$

Given that R^* is the reliability target required

Find the Calibration interval I that maintain R^*

$R^* = e^{-\lambda I}$

Taking the “ln” of both sides we get:

$\ln R^* = \ln e^{-\lambda I}$

$\ln R^* = -\lambda I$

$$\boxed{I = \frac{\ln R^*}{-\lambda}} \qquad (1)$$

7.4.4 Cost-based Solution Development

This case is about determining the CI for those devices that has some cost associated with their failure. There are basically two types of cost-based cases. The first case, is the one in which the cost of all failures is considered. The second case is the one in which only the cost associated with the first failure is considered. In the treatment of both cases the calibration cost is also considered.

The total cost is mainly composed of the cost of the calibration and the cost of using an un-calibrated TMDE. The cost of the calibration is somehow the easiest part to find from the constituents of the total cost. The difficult part is the cost of using a device that gives a measurement with large error (un-calibrated devices). The cost varies according to users application and could vary drastically even for the same device. As an example, we may look at a precise balance that is used to measure gold on a daily bases. In this case a large error in the measurement could lead to a large amount of gold given to customers for free, and knowing the high price of gold the loss could easily be a number of times higher than that of the calibration cost. Another example with the same device is when the balance is used to measure a certain chemical substance in a chemistry lab to conduct a certain experiment. In this case the extra weight caused by the error in the measurement could destroy the result of the experiment and causes the need to repeat it again and incur a high cost (the cost of the experiment).

After the model is constructed and solved different variations of the problem is considered and dealt with. The sensitivity of the model is then analyzed against all the parameters of the problem and a statement on the overall sensitivity of the model is provided. Although the solution provides the user with an optimal calibration interval based on the information fed to it, it allows the user to change some or all the parameters to see their effect on the cal interval which may fine tone the solution and remove any unrealistic estimates of the problem parameters. The solution of the model is then packaged in a computer program with an interactive data entry interface that allows users to interactively enter the problem data and then get the solution.

The importance of the problem lies in three aspects. The first one is in the fact that it prevents the high cost that may be incurred in case of ignoring the cost of using an un-calibrated device. The second aspect is in the fact that the cost involved may differ greatly from device to device or between two similar devices used in two different applications (the two examples above may refer to similar balances but with two different cost figures). The third aspect is in the structure of the solution which is relating the reliability of the device over the cal interval with the total calibration cost incurred for that particular device. The bond between these factors allows the user of this model to automatically optimize many asset management decisions as well as cost and calibration priorities.

7.4.4.1 All Expected Failures Case (AFC)

Given a planning horizon equal to five years (60 months) the calibration parameters becomes:

The number of calibrations during the planning horizon is:

$$Nc = \frac{60}{I}$$

The number of failures can be calculated based on the fact that the state of the device can assume only one state of two namely failing or operating. This indicates that the distribution of the failures of the device can be modeled as a binomial probability distribution with the following parameters:

$$N = Nc$$

$$p = F(t)$$

$$q = R(t)$$

$$G(x) = \sum_{k=0}^{x} \binom{N}{k} p^k q^{N-k}$$

$$G(x) = \sum_{k=0}^{x} \binom{N}{k} F(I)^k R(I)^{N-k} = \sum_{k=0}^{x} \binom{\frac{60}{I}}{k} (1 - e^{-\lambda I})^k (e^{-\lambda I})^{N-k}$$

Based on that, the expected number of failures during the planning horizon is:

$$E(Nf) = \frac{60}{I} F(I) = \frac{60}{I} (1 - e^{-\lambda I})$$

Now:

Since the number of calibrations is $Nc = \frac{60}{I}$ then:

$$The\ Cost\ of\ Calibrations = Cc * Nc = Cc * \frac{60}{I}$$

And since the number of failures is $E(Nf) = \frac{60}{I} F(I) = \frac{60}{I}(1 - e^{-\lambda I})$ then:

$$The\ Cost\ of\ failures = Cf * E(Nf) = Cf * \frac{60}{I} (1 - e^{-\lambda I})$$

Therefore, the total cost incurred (TC) will be:

$$TC(I) = Cost\ of\ Calibrations + Cost\ of\ Failures$$

$$TC(I) = Cc * Nc + Co * E(Nf) = Cc * Nc + \frac{60}{I} F(t) = \frac{60Cc}{I} + \frac{60}{I}(1 - e^{-\lambda I})$$

$$\boxed{TC(I) = \frac{60Cc}{I} + \frac{60Cf}{I}\left(1 - e^{-\lambda I}\right)} \qquad (2)$$

7.4.5 Large Number of Similar Devices Case (LSC)

This method deals with the case where there are a large number of similar devices and for which there is an already established CI. The reason for CI modification in this case, is the huge potential of cost saving or work load reduction that could be achieved. The method is applicable only when the failure is determined at the calibration lab when the device is received. The failure is considered as the occurrence of out-of-tolerance value of one or more of the device parameters. The other assumption is that the device mean time to repair MTTR is negligible compared to the device mean time to failure MTTF. Usually a large number of similar devices will have originally a CI that produces a very high reliability, therefore, the reduction in the CI is not considered here. The reliability, in fact, is high enough to allow a decrease in its value in return of an increased CI.

The proposed method will follow a scheme of increasing or decreasing the CI (see figure 28) until the right one is reached.

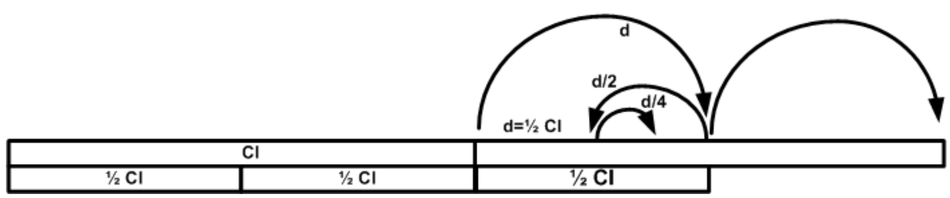
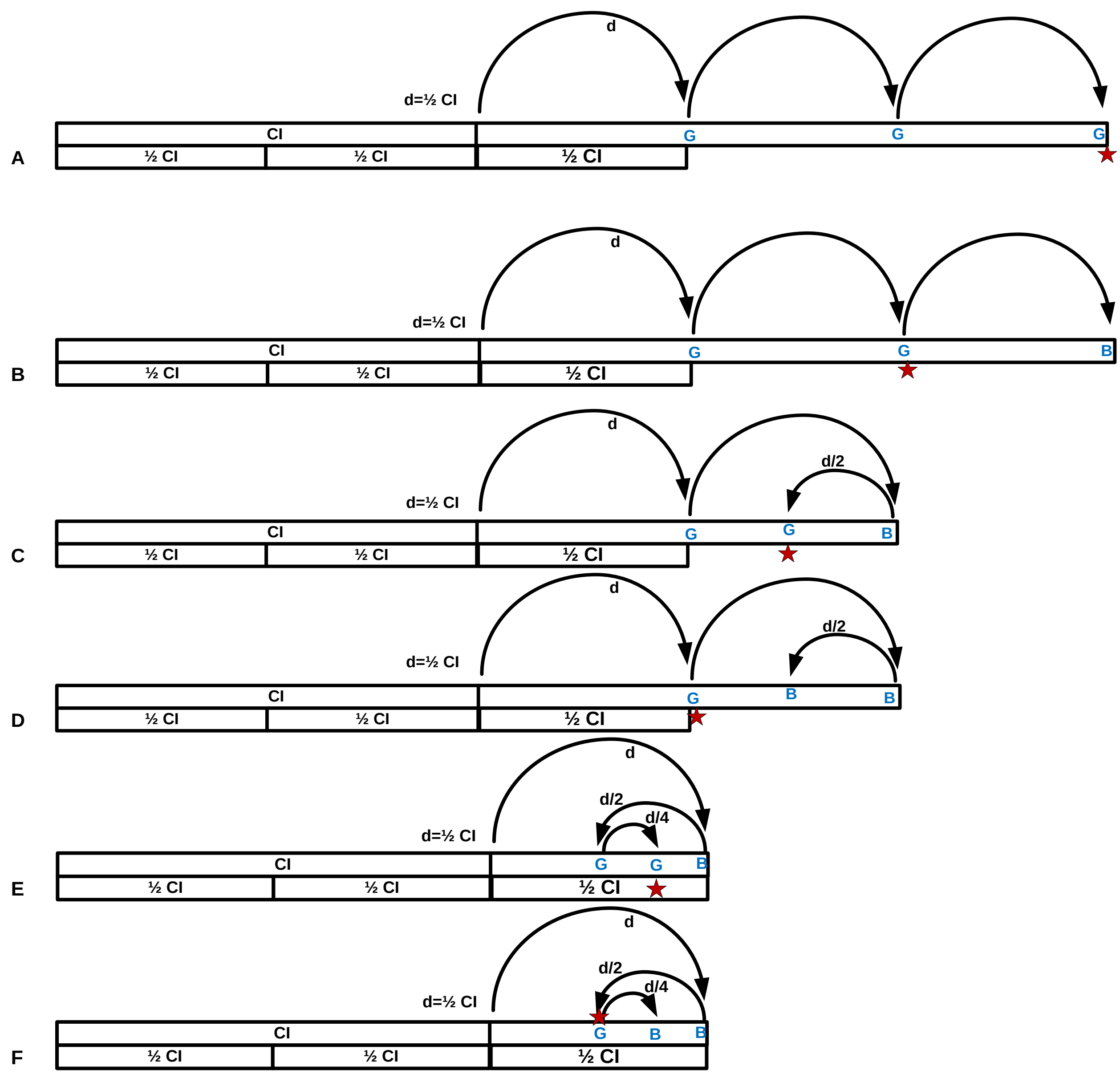


Figure 28: CI modification method.

The method of modifying the CI can be summarized in the following:

Select a sample from the group of similar TMDEs. Calibrate them and dispatch them to the users with their CI increased by a factor of “d” where d=CI/2. Once they return to calibration check their out of tolerance parameters if they fail record that and from the failures cases of all the member of the sample calculate the portion failed and compare that with the anticipated portion from the current reliability or from a preset portion of failures. If lower than a preset threshold characterize that point as "Good" with the letter "G" attached to it, otherwise, characterize it as "Bad" and attach the letter "B" to it. Select a random sample the same size as the previous, calibrate them and then increase or decrease the CI according to the proper scheme amongst those depicted in figure 29. The following schemes indicate an increase or decrease of the CI by either "d", "d/2" or "d/4". In the schemes "G" indicates "Good", "B" indicates "Bad" and the "star" symbol indicates the optimum point the CI should be change to. The method will eventually change the TMDE value to be between CI and 2.5*CI and at the same time preserve a good level of reliability.



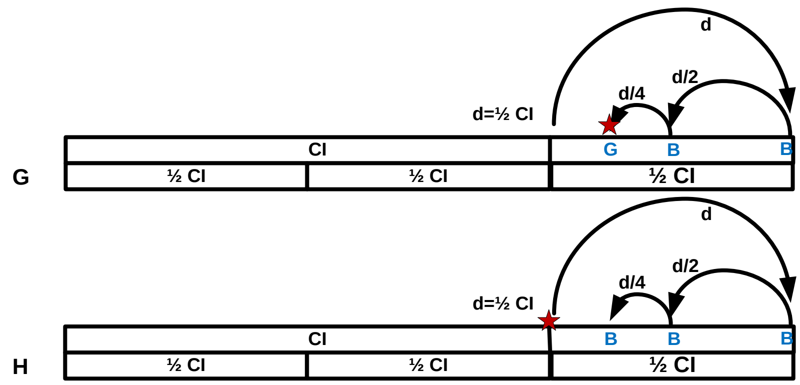


Figure 29: CI modification schemes.

The reason behind using three branches is to allow for a quick search for a good spot. If the number of branches is increased further, the method will be extremely complicated and the people who are applying it will lose track of the items status. The use of 50% of the current CI as the length of the large branch is to provide a moderate value for the minimum gain in CI value. With this value the least gain would be one eighth of the CI. Any value less than that would not justify the effort (for example, for an item of CI=3 months any increase of less than 11 days would be insignificant).

7.5 Conclusion

The estimation of the length of the calibration interval –in general- is a very difficult problem. There are many ways reported in the literature that deals with this problem. Most of these ways -if not all- concentrate on the period that guarantees a high reliability in the measurement and this is done through some statistical means. At the same time most of the methods of estimating calibration intervals ignore the cost involved in the process and if they do they include only the cost of the calibration.

In this paper the calibration interval estimation problem is modelled dealt with in a number of different methods depending on the situation. Method one deals with individual items when there is predetermined target reliability. Method two models the problem as a cost-based reliability oriented optimization problem with the objective of determining the optimal calibration interval that minimizes the total cost. Method three deals the case of having a large number of similar items.

CHAPTER 8

AVERAGE OUT GOING QUALITY

8 Average Out Going Quality Problem (AOQ)

This paper presents two methods of calculating the Average Outgoing Quality of a calibration production facility that uses a certain multistage inspection policy.

8.1 Introduction

Quality control or quality assurance is an integrated part of the calibration facility operations. The main objective of any production facility is to offer the customer defect-free- products if they can, or more practically, produced items with few defects. This can be done when the calibration facility has a means by which they can assess their average outgoing quality (AOQ). The assessment of the correct AOQ is not an easy matter and sometimes it can be extremely difficult. In the context of this research the calibration facility is assumed to have an inspection policy that monitors the performance of every technician without having to inspect every task he performed. The reason for using sampling is quite obvious; it is much cheaper and much quicker. Since it is easy to assess the AOQ if you perform a 100% inspection (because in this case you would know exactly the percentage of defective items) and since we are only inspecting samples, we need a mean by which we assess the facility AOQ.

In this chapter, a description of the problem in general is provided first. Then, the used multistage inspection policy is shown in detail. After that, the solution scheme is stated followed by the problem statement. Then, the methods of computing the Average Outgoing Quality (AOQ) are mathematically developed. The two methods are then verified by a simulation model built for this purpose. The two methods are compared in terms of their closeness to the actual measure of the facility AOQ and in terms of their usefulness and basic use.

8.2 Description

TMDE's arrive at the laboratory, booked in the system, gets calibrated by the technician and then dispatched to the user. The calibration by itself assures the quality of measurement of the device, but that is done only when the calibration is performed correctly. Therefore, the facility must have a policy by which the item is assured the right calibration. This assurance is necessary, because the user has no way of checking the correctness of the calibration performed on the item (otherwise he would have calibrated it himself). Therefore, in order to assure the quality; the items must be inspected for correct calibration and once the inspector find any problem with it the item is returned back to the technician to repeat the calibration again or otherwise the item is dispatched to the user. The inspection of the items can be performed in many ways that goes from the 100% inspection (inspecting every item coming out of the lab) to inspecting just a small sample of few items. Laboratories usually adopt one of the many inspection policies available in the literature. Usually a certain inspection policy gives the management more control over some aspects of the quality than what might be given by some other policies. The most important quality parameter, however, is the average out going quality of the lab production, or in other words the percentage of the items that leaves the system with correct calibration from amongst all the received items. If the lab has control over the number of defective items (all defective items are discovered before they leave the lab to the customer) then the inspector would return those defective items back to the lab to be recalibrated, and the result is a defect free product.

This is only attainable when the lab is performing 100% inspection which is very costly for medium to large calibration facility. The other practical alternative is to adopt an inspection policy that restricts the inspection to only a small sample of the production. The objective of the lab then focused on finding the portion of the defective items that have left the facility and already with the customers. The action would then be to correct the production directly so that the number of defective items is reduced right from the lab not through the inspection. In other words the inspection must be used as an indication of the bad quality not as a correction to it.

For a short term, the assessed AOQ will become a characteristic of the lab and it will remain as such until a real change on the process or the methods of the calibration is performed. The AOQ will also be the monitor for the facility performance as a whole as well as the first warning to the management of any newly developed bad production streak that may pop up suddenly for various reasons. .

8.3 Inspection Policy

The inspection policy under consideration is designed to inspect only a portion of the entire production. The outcome of the inspection is then used to draw some conclusions that will assess certain production decisions. The policy is designed to intelligently select the inspection based on the likelihood of the item failures. This is accomplished by increasing the inspection rate for those technicians who are more likely to make defective items than those who will not. The inspection rate is gradually increased or decreased based on the current status of the technician and his current failures. The policy is a four-stage policy that starts with the technician at level four (for new technicians who have just qualified, the starting point is at level 0). At this level, 6.25% of all the technician production is inspected. If no defect is found, he will stay at the level, otherwise he goes into various states that either brings him back to his current level or move him down one stage. At stage three, 12.5% of his production is inspected, and the same is done as the previous stage. At stage two the inspection rate is 25% and at stage 1 the inspection rate is 50%. At stage zero the inspection rate is 100% and if there is any failure found in his first 18 jobs the technician is removed from the lab and either retrained or gets subjected to a proper action. The detailed inspection policy is shown in Figure30.

Multilevel Inspection Policy		BEGIN HERE
LEVEL 4	**STATE 4***	**STATE 4R**
Inspect 6.25% of all certified production by technician.	Inspect 6.25% of all certified production by technician.	Inspect the next four items certified by technician.
If a defect is found, shift to STATE 4R.	When 14 consecutive items pass inspection, shift to LEVEL 4.	If the next four items pass inspection, shift to STATE 4*.
	If a defect is found, shift to STATE 3R.	If a defect is found before four items pass inspection, shift to STATE 3R.
LEVEL 3	**STATE 3***	**STATE 3R**
Inspect 12.5% of all certified production by technician.	Inspect 12.5% of all certified production by technician.	Inspect the next four items certified by technician.
When 18 consecutive items pass inspection, shift to LEVEL 4.	When 14 consecutive items pass inspection, shift to LEVEL 4.	If the next four items pass inspection, shift to STATE 3*.
If a defect is found, shift to STATE 3R.	If a defect is found, shift to STATE 2R.	If a defect is found before four items pass inspection, shift to STATE 2R.
LEVEL 2	**STATE 2***	**STATE 2R**
Inspect 25% of all certified production by technician.	Inspect 25% of all certified production by technician.	Inspect the next four items certified by technician.
When 18 consecutive items pass inspection, shift to LEVEL 3.	When 14 consecutive items pass inspection, shift to LEVEL 3.	If the next four items pass inspection, shift to STATE 2*.
If a defect is found, shift to STATE 2R.	If a defect is found, shift to STATE 1R.	If a defect is found before four items pass inspection, shift to STATE 1R.
LEVEL 1	**STATE 1***	**STATE 1R**
Inspect 50% of all certified production by technician.	Inspect 50% of all certified production by technician.	Inspect the next four items certified by technician.
When 18 consecutive items pass inspection, shift to LEVEL2.	When 14 consecutive items pass inspection, shift to LEVEL 2.	If the next four items pass inspection, shift to STATE 2*.
If a defect is found, shift to STATE 1R.	If a defect is found, shift to 100% LEVEL.	If a defect is found before four items pass inspection, shift to 100% LEVEL.
Inspect 100% of all certified production by the technician. When 18 consecutive items pass inspection, shift to LEVEL 1.		

Figure 30: Multistage Inspection Policy

8.4 AOQ Problem Statement

Given a specific inspection plan and given a number of technicians n, each of which has associated with him a number of items mi produced by him in the time interval chosen by the inspection policy. Find the average out going quality of the calibration facility with 95% confidence.

8.5 Solution Scheme

The solution will start by developing the analytical solution of the methods that will be used to assess the average outgoing quality of the calibration lab. The methods are going to be in the form of a formula. The formulae will then be verified by comparing them with the actual AOQ of the production facility. The comparison will be performed using a simulation model constructed in an Excel worksheet.

8.6 AOQ Determination Method

The AOQ will be determined by constructing a formula based on some production parameters. The formula will be developed in a sequential fashion

8.6.1 Notations:

L: Level of the technician which indicates the sampling rate for the technician
(Levels go from 0-4)

C: Number of Technicians.

Ri: Failure Rate of Technician i.

Pi: Production of Technician.

PLi: Production of Technician i at level L.

T: Total Production that is subject to Inspection.

XL: Average Production of technicians at level L.

X: Average Production of technicians.

Fi: Failures from technician i (actual).

S: Inspection Rate % for each level.

Sj: Inspection Rate % of each technician based on his current level.

Ej: Expected Failures.

E: Total Expected Failures.

M: Failure Rate of the Facility.

Nj: Number of Technicians at level j.

Aj: Average Failure Rate of class j where j = 0,1...4.

Vj: Quality Verification Inspection for technician j.

QL: Total QVI at level L.

Q: Total QVI.

8.6.2 Decision Variables

AOQa: the Actual Average Outgoing Quality.

AOQq: the Average Outgoing Quality computed from the QVI.

AOQL: the Actual Average Outgoing Quality computed from Levels only.

AOQ: Reported Average Outgoing Quality.

8.6.3 Method of Computing AOQ

Two methods will be developed to find the AOQ of the calibration facility that is using the above-mentioned inspection method. The first method is a corrected version of a corrupted old one used with inspection plan. The second one is totally new. The two methods will be labeled: the QVI based AOQ method and the Tech Levels AOQ method.

8.6.3.1 The QVI based AOQ Method

Based on the definitions at the notations:

The total production is:

$$T = \sum_{j=1}^{C} \sum_{i=1}^{N_j} P_{ji}$$

The inspection rate % at level j is:

$$S_j = \frac{100}{2^j} \quad for \quad j = 1 \; to \; L$$

The QVI for each technician is (the double square brackets indicate that the value enclosed is rounded up to the next integer):

$$V_i = \left[\!\left[\frac{P_i * S_i}{100} \right]\!\right]$$

Therefore, the total QVI is:

$$Q = \sum_{j=1}^{C} \sum_{i=1}^{N_j} V_{ji}$$

The expected failures in QVI of each technician are:

$$E_j = R_j * V_j$$

This is:

$$E_j = R_j \left[\!\left[\frac{P_j * S_j}{100}\right]\!\right]$$

$$E = \sum_{j=1}^{C} E_j$$

This is:

$$E = \sum_{j=1}^{C} R_j \left[\!\left[\frac{P_j * S_j}{100}\right]\!\right]$$

Therefore the failure rate of the facility is:

$$M = \frac{E}{Q}$$

The AOQq is:

$$AOQq = 0.9375 - \frac{(T - Q) * M}{T}$$

The reason for using 0.95 instead of one is that the best technician will still have 6.25 percent of his work inspected leaving him with 93.75 uninspected or 95% if we take 80% of the 6.25 which will be 5%. The 80% is just what appears to happen in practice.

$$\boxed{AOQq = 0.95 - \frac{(T - Q) * M}{T}}$$

8.6.3.2 The Technician based AOQ Method

The failure rate of all technicians is less than or equal to 20%. This is the basic requirement of a technician qualification. Any technician who has a failure rate of more than 20% , must not join the production. Based on that fact, and on the fact that there are five levels, we may assume that the failure rate of all technicians can be classified to five classes of failure rates that are equally spaced. The classes would then be:

From 20% to > 16% for those in level 0 with an average of 18%, thus A0 = 0.18

From 16% to > 12% for those in level 1 with an average of 14%, thus A1 = 0.14

From 12% to > 8% for those in level 2 with an average of 10%, thus A2 = 0.10

From 8% to > 4% for those in level 3 with an average of 6%, thus A3 = 0.06

From 4% to > 0% for those in level 4 with an average of 2%, thus A4 = 0.02

Therefore, any technician at level four would be assumed to have a failure rate of 0.02 no matter how his actual failure rate is. So do all the technicians at other levels, each one of them would be assumed to have the average failure rate of the class corresponds to his level. The logic behind that relies on the following assumptions:

It is very likely that the technician with a higher level to have a lower class, and very unlikely to have otherwise. In case the unlikely event happened, the inspection process will spot it right away and the technician level will be quickly adjusted.

Technicians' failure rates are uniformly distributed over the classes (because there is no known bias that makes it otherwise).

Technicians' failure rates within the class are also uniformly distributed for the same reason and therefore the average is a good representative of each technician failure rate.

The total production of all technicians is:

$$T = \sum_{j=1}^{C} \sum_{i=1}^{N_j} P_{ji}$$

The total production of all technicians at level L is:

$$D_L = \sum_{i=1}^{n_L} P_{Li}$$

The inspection rate % at level L is:

$$S_L = \frac{100}{2^L}$$

This leads to the QVIs (number of items subjected to inspection) at level L is:

$$Q_L = S_L * D_L$$

This is:

$$Q_L = \frac{100}{2^L} * \sum_{i=1}^{n_L} P_{Li}$$

The average production per technician at level L is:

$$X_L = \frac{\sum_{i=1}^{n_L} P_{Li}}{N_L}$$

The average production per technician at various levels, in general, can safely be assumed to equal each other (I,e X1=X2=X3=X4). This is due the fact that in most calibration labs it is a primary objective to distribute work evenly between technicians. Therefore, the following formula holds at all time:

$$X = X_1 = X_2 = X_3 = X_4$$

Therefore QL can be rewritten as:

$$Q_L = S_L * n_L * X_L$$

This gives the total QVI as:

$$Q = \sum_{L=1}^{4} Q_L$$

$$Q = \sum_{L=1}^{4} (S_L * n_L * X_L)$$

$$Q = X * \sum_{L=1}^{4} (S_L * n_L)$$

This makes the total number of failures as:

$$E = \sum_{L=1}^{4} S_L * n_L * X_L * A_L$$

This means:

$$E = X * \sum_{L=1}^{4} S_L * n_L * A_L$$

The general failure rate of the facility is:

$$M = \frac{E}{Q}$$

$$Q = X * \sum_{L=1}^{4} (S_L * n_L)$$

$$M = \frac{X * \sum_{L=1}^{4}(S_L * n_L * A_L)}{X \sum_{L=1}^{4}(S_L * n_L)}$$

$$M = \frac{\sum_{L=1}^{4}(S_L * n_L * A_L)}{\sum_{L=1}^{4}(S_L * n_L)}$$

This leads to (AOQ with levels):

$$AOQl = 0.95 - \frac{(T - Q) * M}{T}$$

The total production based on the above argument can be rewritten as:

$$T = C * X$$

$$AOQl = 0.95 - \frac{(C * X - X * \sum_{L=1}^{4}(S_L * n_L)) * M}{C * X}$$

$$AOQl = 0.95 - \frac{X(C - \sum_{L=1}^{4}(S_L * n_L)) * M}{C * X}$$

$$AOQl = 0.95 - \frac{(C - \sum_{L=1}^{4}(S_L * n_L)) * M}{C}$$

$$AOQl = 0.95 - [\frac{(C * M - M * \sum_{L=1}^{4}(S_L * n_L))}{C}]$$

$$AOQl = 0.95 - [\frac{(C * M)}{C} - \frac{(\sum_{L=1}^{4}(S_L * n_L))}{C}]$$

$$AOQl = 0.95 - [M - \frac{M * (\sum_{L=1}^{4}(S_L * n_L))}{C}]$$

$$AOQl = 0.95 - [\frac{\sum_{L=1}^{4}(S_L * n_L * A_L)}{\sum_{L=1}^{4}(S_L * n_L)} - \frac{\frac{\sum_{L=1}^{4}(S_L * n_L * A_L)}{\sum_{L=1}^{4}(S_L * n_L)} * (\sum_{L=1}^{4}(S_L * n_L))}{C}]$$

$$AOQl = 0.95 - [\frac{\sum_{L=1}^{4}(S_L * n_L * A_L)}{\sum_{L=1}^{4}(S_L * n_L)} - \frac{\sum_{L=1}^{4}(S_L * n_L * A_L)}{C}]$$

$$AOQl = 0.95 - \left(\sum_{L=1}^{4}(S_L * n_L * A_L)\right)\left(\frac{1}{\sum_{L=1}^{4}(S_L * n_L)} - \frac{1}{C}\right)$$

$$\boxed{AOQl = 0.95 - \left(\sum_{L=1}^{4}(S_L * n_L * A_L)\right)\left(\frac{1}{\sum_{L=1}^{4}(S_L * n_L)} - \frac{1}{C}\right)}$$

8.7 Method Validation

In order validate the use of the two developed methods, they must be verified against an actual production system with known technician's failure rate. The only way to get that is by simulating an actual production system and compares the two methods performance with the preset failure rates.

8.7.1 Simulation Model

The simulation is constructed in an Excel worksheet shown in Table 21. All the parameters and the intermediate steps are shown in the order of the simulation.

		Tech1	Tech2	Tech3	Tech4	Tech5	Tech6	Tech7	Tech8	Tech9	Tech10	Totals
Level (L)	Given	0	2	3	4	4	2	1	3	4	1	
Failr Rate Tecs (Ri)	Given	0.187	0.084	0.051	0.009	0.040	0.115	0.148	0.047	0.023	0.157	
Production (P)	Given	120.0	150	180	200	250	160	80.0	140	240	160	1680
Failures (Fr Not R)	R* P	22.4	12.6109	9.11867	1.88768	9.98775	18.4084	11.8	6.54202	5.61279	25.0769	123.498
Failures (F)	Rounded	23.0	13	10	2	10	19	12.0	7	6	26	128
Inspec Rate % (S)	100/(2^L)	100.0	25	12.5	6.25	6.25	25	50.0	12.5	6.25	50	
QVI (V1)	P*S/100	120.0	37.5	22.5	12.5	15.625	40	40.0	17.5	15	80	400.6
QVI (V)	Rounded	120.0	38	23	13	16	40	40.0	18	15	80	403
Expctd Failures (E fr)	R*V	22.4	3.19476	1.16516	0.1227	0.63922	4.6021	5.9	0.84112	0.3508	12.5384	51.7906
Expctd Failures (E)	Rounded	23.0	4	2	1	1	5	6.0	1	1	13	57
Failre Rate Facilty (M)	E/P											0.033929
												nL
Num of Tech Level 0	N0	1	0	0	0	0	0	0	0	0	0	1
Num of Tech Level 1	N1	0	0	0	0	0	0	1	0	0	1	2
Num of Tech Level 2	N2	0	1	0	0	0	1	0	0	0	0	2
Num of Tech Level 3	N3	0	0	1	0	0	0	0	1	0	0	2
Num of Tech Level 4	N4	0	0	0	1	1	0	0	0	1	0	3
											C	9
	Level FR	(NL*Pi)										ΣPLi
L0 FR (a0)	0.1800	120.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	120.0
L1 FR (a1)	0.1400	0.0	0.0	0.0	0.0	0.0	0.0	80.0	0.0	0.0	160.0	240.0
L2 FR (a2)	0.1000	0.0	150.0	0.0	0.0	0.0	160.0	0.0	0.0	0.0	0.0	310.0
L3 FR (a3)	0.0600	0.0	0.0	180.0	0.0	0.0	0.0	0.0	140.0	0.0	0.0	320.0
L4 FR (a4)	0.0200	0.0	0.0	0.0	200.0	250.0	0.0	0.0	0.0	240.0	0.0	690.0
												1680.0
aL*nL*(1-r)*ΣPLi			Levels	SL	NL	Sl*NL	AL	SL*NL*AL				
a0*n0*ΣP0i	0.0		0	1	1	1	0.1800	0.18				
a1*n1*ΣP1i	33.6		1	0.5	2	1	0.1400	0.14				
a2*n2*ΣP2i	46.5		2	0.25	2	0.5	0.1000	0.05				
a3*n3*ΣP3i	33.6		3	0.125	2	0.25	0.0600	0.015				
a4*n4*ΣP4i	38.8		4	0.0625	3	0.1875	0.0200	0.00375				
	152.5					1.9375		0.2088				

Table 21: The Simulation Model.

The AOQ of the actual and the two methods are shown in Table 22.

AOQ Actual	0.9265
AOQ W QVI	0.9242
AOQ W Levels Only	0.91184

Table 22: The Computed Values of the AOQ brought from the simulation.

A 30 runs is shown in Table 23 along with the average values of the actual and the two methods computed from them.

	A	Q	L
1	0.914	0.925	0.918
2	0.896	0.907	0.903
3	0.922	0.920	0.910
4	0.909	0.912	0.909
5	0.906	0.915	0.909
6	0.902	0.908	0.900
7	0.880	0.910	0.930
8	0.877	0.910	0.930
9	0.905	0.909	0.906
10	0.863	0.910	0.919
11	0.882	0.908	0.927
12	0.895	0.913	0.931
13	0.887	0.910	0.945
14	0.908	0.918	0.913
15	0.915	0.916	0.908
16	0.907	0.910	0.901
17	0.908	0.912	0.903
18	0.931	0.929	0.915
19	0.918	0.924	0.924
20	0.874	0.909	0.918
21	0.874	0.905	0.911
22	0.876	0.910	0.925
23	0.913	0.924	0.915
24	0.902	0.917	0.933
25	0.890	0.908	0.916
26	0.920	0.916	0.907
27	0.881	0.908	0.930
28	0.891	0.910	0.918
29	0.922	0.921	0.908
30	0.869	0.908	0.936

	A	Q	L
Avg	0.898	0.913	0.917

	Value	Val/A	Er%
Q-A	0.0156	0.01733	1.7
L-A	0.0194	0.02165	2.2

A simulation of 30 runs from which the average of the actual (A), the method that uses the QVI (Q) and the method that uses the technician levels only. The two methods are compared to the actual value and the error percentages are computed.

Table 23: 30 simulated runs of the AOQ.

8.7.2 Comparison

The two methods are compared in the simulation above in terms of their values compared to the actual value of the AOQ.

Both are found to be very effective and they do not differ from the actual value by more than 2.3% in most of the cases.

Method 1 is used when there is a need to utilize the outcome of the QVI's and the number of failures.

Method 2 is useful when there is a need to quickly find the AOQ without waiting for the outcome of the inspections to be complete. It can also be used to conclude that the AOQ is unchanged as long as there is no change in the number of technicians at each level (although there might be a change in the technicians' levels).

8.8 Impact of knowing the AOQ on the System

The impact of knowing the calibration facility average outgoing quality on the system performance is considered to be an efficiency driver. Knowing the value is not so much the goal, what is more important is the method by which this value is arrived at. The method of assessing the average outgoing quality of the system is the primary objective and for that matter the development of this method depends entirely on the inspection policy used in the system. The impact on the system may be seen in the following:

- Complete the feedback cycle to establish a fully production controlled loop which allow for the addition of some corrective measure continuously.
- Knowing the size of the defective items that leave the system
- May allow for the establishment of quality control chart that alert the facility when the quality is drastically harmed.
- Depending on the method, may allow for tracing back the source of generating more than normal defective items.
- Help the engineers and top management to develop quality improvement policy and monitor their progress.

Stop any developed defective items streak that may happen due to various reasons (for instance a newly assigned operator or a newly bought instrument).

8.9 Conclusion

In conclusion, method 2 is quite useful and provides the quality assurance inspectors, the lab internal management and the facility top management with an excellent assessment of the lab AOQ. It also helps the QA personnel to quickly react to any sudden decrease in service quality before a large number of bad items leave the facility. This last advantage is of a particular interest to the customers for it assures them that only smaller number of un-calibrated items may really be allowed to reach them.

CHAPTER 9

SUMMARY AND CONCLUSION

9 Summary and Conclusion

In this chapter I will present a brief synopsis of each chapter, a conclusion about the main aspects of the research and an overview of the research future directions. Although, there are many issues to consider; the information presented here will concentrate on the most important ones.

9.1 Summary

The research dealt with the problem of identifying the potential optimization problems that might be found in metrology. There are basically nine chapters that go from 1 to 9. These are the general, literature review metrology and calibration realm, metrology and calibration operations, metrology and calibration optimization problems, scheduling problem, calibration interval problem, average outgoing quality and summary & conclusion.

9.2 Conclusion

This research is highly comprehensive and deals with multiple levels of planning. The research is also quite extensive in terms of many aspects. These aspects are the subject, the size, the Importance, the diversity, the complexity and the variety in terms of the tools used to deal with it.

9.2.1 The contributions

There are four major contributions in this research. These are as follows:

1. **Metrology and Calibration Optimization Problems.** To be presented in **"CAFMET 2014, IN 31 March in Pretoria, South Africa".**

I have identified three main problematic areas within the field of metrology. The contribution to knowledge comes in two forms:

- The first is the descriptions of all the fields that constitute the source of problems to the calibration facilities in general. The description involves the impact of the presence of such problem on the performance of the facility along with the impact of solving this problem. The impact will really help in assessing the degree of improvement the facility could achieve when the problem is solved.

- The second is the clear definition of the problem statement as well as the proposed method of solution. This is of great value to researchers and engineers whose responsibility is to identify those critical problems that hinder the development of their facility.

2. **Multiple Objective Scheduling Problem.** Presented in **"NCSLI conference 2010 in USA".**

The contribution to knowledge comes in three forms:

- The first is the identification and involvement of all relative attributes that has an effect in the structure of the problem as well as in the structure of the solution. These attributes are the lab attributes, the technicians' attributes and the job attributes. The consideration of all of those attributes in the problem leads to the satisfaction of the management, the operators and the customers through the simultaneous fulfillment of many conflicting objectives.
- The second is the formulation of the multiple attributes scheduling problem as a mixed integer program. The formulation is very complex and it really paves the way for similar formulation in various MIP's especially in the construction of constraints which can be sometimes greatly challenging (see constrains 7 and 8 in page 92).
- The third is the heuristic algorithm that is developed to solve the problem almost instantaneously. This algorithm is new and can be used in similar scheduling problem with multiple and changing objective. The contribution of this algorithm in the area of solving multiple objective scheduling problem is highly significant and with little modification it could be used to solve a wide range of problems optimally or semi optimally.

3. **Optimization of Calibration Interval Determination Problem**. To be submitted in **"NCSLI Conference August 3-7, 2014, Walt Disney World Swan & Dolphin, Orlando, Florida."**

- The main contribution to science in this paper the variety of methods developed to determine the calibration interval optimally. The methods covered almost all the cases that could be encountered in practice regarding TMDE's. The methods are developed in a way that does not interrupt the daily operations of the calibration facility. For extra convenience, the methods are programmed in a computer program to promote automatic application of them whenever possible. The importance of the solution to the CI problems is coming from the fact that a huge reduction (in the order of around 30%) in the workload of the facility could be attained if the correct CI is determined. This is of great priority to cal facility especially the governmental ones.

4. **Average outgoing quality (AOQ)**. Presented in **"Measurement Systems and Process Improvement (MSPI) 2013 Workshop, NPL, 8th May 13".** The contribution to science in this paper comes into three forms.
   - The first is the first formula which will use the daily inspected items status to assess the facility AOQ. This is of particular interest to the quality assurance team for it helps them to identify the source of diminished performance.
   - The second contribution is the second method. This method is more complicated than the previous one but it requires less data and gives almost the same accuracy. This method is of particular interest to management because it provides an instantaneous assessment to the current level of AOQ.
   - The third is the simulation model that is constructed to provide a means to compare various methods of assessing AOQ. The model can be used extensively in this regard and with little modification could cover an even wider range of uses.

9.3 Future Directions of the Research

There are a number of directions this research could be extended to. In general, the directions could follow three main streams. First, the identified critical problems could be expanded by identifying more problems in more fields especially under the new changes in metrology like the need now to do measurements in the nano-scale. Second, formulate and solve other variations of the already solved problems; namely scheduling, CI and AOQ. New variations could be obtained by changing the objective function or changing the parameters of the problem. Finally, continue solving the other identified problems. there are currently seven more unsolved problems. There are other additional directions that could also be followed but these are currently of less importance than the above mentioned ones. These are identifying new metrology fields, new calibration concepts, new metrological constraints and new standards documents. These could potentially impose some new requirements in terms of potential problems or in other words create new set of problems that need optimization.

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APPENDICES

LINGO Model

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MODEL:
SETS:
Operators/1..6/:V, A, E, F,G;
Jobs/1..60/:SN, K,T,W,C,P;
Standards/1..10/:S_C;
Resources/1..4/:R_C;
Areas/1..9/;
Complexity/1..2/;
Priorities/1..3/;
Hours/1..8/;
Days/1..1/;
Shifts/1..2/;
Ind/1..9/;
JobStd(Jobs,Standards):S;
JobRsc(Jobs,Resources):R;
JobOperator(Jobs,Operators):Q;
JobOperDayHour(Jobs,Operators,Days,Hours):X;
JobOperDayInd(Jobs,Operators,Days,Ind):Z;
ENDSETS
!Variables Types;
@FOR(Operators:@GIN(G));
@FOR(JobOperator:@BIN(Q));
@FOR(JobOperDayHour:@BIN(X));
@FOR(JobOperDayInd:@BIN(Z));
!Objective Function;
Max=@SUM(Operators(O):@SUM(Jobs(J):
(va1*W(J)+va2*P(J))*Q(J,O)));
!Constraint Set (1);
@FOR(JobOperator(J,O):C(J)*Q(J,O)<= E(O));
!Constraint Set (2);
 @FOR(JobOperator(J,O):(K(J)-A(O))*Q(J,O) <= 0);
!Constraint Set (3);
@FOR(Jobs(J):@SUM(Operators(O):Q(J,O))<1);
```

```
!Constraint Set (4);
@FOR(Operators(O):@SUM(Jobs(J):T(J)*Q(J,O))<V(O));
!Constraint Set (5);
@FOR(Standards(M):@FOR(Days(D):@FOR(Hours(H):
@SUM(Operators(O):@SUM(Jobs(J):
S(J,M)*X(J,O,D,H)))<S_C(M))));
!Constraint Set (6);
@FOR(Resources(N):@FOR(Days(D):@FOR(Hours(H):
@SUM(Operators(O):@SUM(Jobs(J):
R(J,N)*X(J,O,D,H)))<R_C(N))));
!Constraint Set (7);
@FOR(Jobs(J):@FOR(Operators(O):
@FOR(Days(D):@FOR(Ind(I)|I#LE#(9-T(J)):
@SUM(Hours(H)|H#GE#I #AND# H#LE# (I+T(J)-1):
X(J,O,D,H))>T(J)*Z(J,O,D,I)))));
!Constraint Set (8);
@FOR(Jobs(J):@FOR(Operators(O):
@SUM(Days(D):
@SUM(Ind(I)|I#GE#1 #AND# I#LE#(9-T(J)):
Z(J,O,D,I)))=Q(J,O)));
!Constraint Set (9);
@FOR(Operators(O):@FOR(Jobs(J):
@SUM(Days(D):@SUM(Hours(H):
X(J,O,D,H)))=T(J)*Q(J,O)));
!Constraint Set (10);
@FOR(Operators(O):@FOR(Days(D):@FOR(Hours(H):
@SUM(Jobs(J):X(J,O,D,H))<=1)));
!Constraint (11);
@FOR(Operators(O):@FOR(Days(D)|D#EQ#1:
@SUM(Jobs(J):@SUM(Hours(H):X(J,O,D,H))) < 8));
!Constraint Set (12);
@FOR(Operators(O):@SUM(Jobs(J):
T(J)*Q(J,O))=G(O));
!Constraint Set (13);
@SUM(Jobs(J):@SUM(Operators(O):
Q(J,O)))=JA;
!Constraint (14);
@SUM(Operators(O):G(O))=gg;
```