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Development of a Quality Management System for a Semiconductor Research Institute

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Zusammenfassung

Herstellungsprozesse in Halbleiterindustrien sind auf Massenproduktion ausgelegt, um die Produktionskosten jedes Chips so gering wie möglich zu halten. Im Allgemeinen werden Prozessparameter im Zuge der Massenproduktion selten variiert. Allerdings gestaltet sich die Situation im Rahmen von Halbleiterforschungsinstituten anders, da mehrere Prozesse simultan durchgeführt werden, was häufige Änderungen der Prozessparameter und Betriebsbedingungen erfordert. Durch kontinuierliche Änderung der Prozessparameter können höhere Schwankungen im Endergebnis beobachtet werden. Ziel dieser Arbeit ist es, ein Qualitäts-Management-System (QMS) zu entwickeln, welches Schwankungen im Endergebnis reduziert und dadurch die Gesamtqualität der in Forschungsinstituten hergestellten Produkte erhöht. Das QMS besteht aus einem Content-Management-System, welches die Geräte- und Prozessdaten des Instituts speichert und organisiert. Ebenfalls besteht es aus Experimental-Design- und Datenanalysesystemen, welche für die Realisierung eines vollfunktionstüchtigen QMS für Forschungsinstitute unabdingbar sind.

Die effiziente Nutzung der QMS-Komponenten hat geholfen, die Prozesse am Institut für Physik (EIT2) an der UniBw zu verbessern. Das Content-Management-System hat die Organisation der Daten verbessert, welche im Zusammenhang mit dem Wartungsverlauf der Geräte und infrastrukturellen Angelegenheiten der Labore und Reinräume standen. Design-Of-Experiments-Techniken (DOE) wurden genutzt, um die Inputfaktoren systematisch zu variieren und dadurch den notwendigen Output zu erhalten. DOE hat dabei geholfen, die Inputparameter für einen benutzerdefinierten Output noch vor dem eigentlichen Test am Gerät vorherzusagen, was zu einer Reduktion der Schwankungen des eigentlichen Experiments führte. Das Datenanalyse Tool stellte Informationen bezüglich der Verlässlichkeit des Gerätes zur Verfügung und legte Richtlinien vor,

die während Änderungen der Prozessparameter für die Durchführung des Experiments einzuhalten sind. Die Nutzung des Datenanalyse Tools stellte sicher, dass die Ausgangsschwankungen selbst bei häufigen Änderungen der Prozessparameter minimiert werden. Es wurden experimentelle Ergebnisse für Prozesse, die vor und nach der Implementierung des QMS am EIT2 durchgeführt wurden, verglichen. Es konnte beobachtet werden, dass die Nutzung des QMS am EIT2 dabei half, Schwankungen zu reduzieren und die Prozessqualität kontinuierlich zu verbessern.

Abstract

Manufacturing processes in semiconductor industries are performed on a large scale to keep the production cost of every manufactured chip as low as possible. Process parameters are seldom varied when manufacturing is performed on a large scale. However, the situation is different in a semiconductor research institute wherein multiple processes are performed simultaneously, which require frequent changes in the process parameters and operating conditions. Due to continuous changes in the process parameters, higher variability in the output can be observed. The goal of this thesis is to develop a quality management system (QMS) to reduce the variations in the output and hence improve the overall quality of the manufactured devices at research institutes. This QMS consists of a content management system to store and organize the equipment and process data of the institute. It also consists of experimental design and data analysis systems that are essential to make a fully functional QMS for a research institute.

The efficient usage of the components of the QMS helped to improve the processes performed at the Institute for physics (EIT2) at UniBw. The content management system improved the organization of the data associated with the maintenance history of the equipment and infrastructural issues concerning the laboratories and cleanrooms. Design Of Experiments (DOE) techniques were used to systematically vary the input factors to obtain the necessary output. DOE helped to predict the input parameters for a user defined output value prior to performing the actual test on the equipment resulting in a reduction of variability for the actual experiment. The data analysis tool provided the information regarding the reliability of the equipment and presented the guidelines to follow while making changes to the process parameters for performing the experiment. Usage of the data analysis tool ensured that the output variations are

minimized even with frequent changes in process parameters. The experimental results for processes performed at EIT2 before and after the implementation of the QMS were compared. It was observed at EIT2 that using a QMS helped to reduce the variability and continuously improve the process quality.

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Nomenclature

ANOVA	Analysis of Variance
APC	Advanced/Automatic Process Control
ATE	Automatic Test Equipment
CMP	Chemical Mechanical Polishing
CMS	Content Management System
CSV	Comma Separated Value
CVD	Chemical Vapour Deposition
DoE/DOE	Design of Experiment
ECMS	Enterprise Content Management Systems
EIT2	Elektrotechnik und Informationstechnik - Institute of Physics
FET	Field Effect Transistor
GIF	Graphic Interchange Format
Gmbh	Gesellschaft mit beschränkter Haftung (Limited Liability company)
IC	Integrated Circuit
ISO	International Standards Organization
IT	Information Technology
JPEG	Joint Photographic Experts Group
LCL	Lower Control Limit
LSL	Lower Speciation Limit
mm	Millimeters
MSA	Measurement System Analysis
NET	Network Enabled Technologies
nm/min	Nanometers per minute
O_2	Oxygen

OFAT	One Factor At a Time
OS	Operating System
PC	Personal Computer
PDCA	Plan-Do-Check-Act
PMMA	Poly-methyl Methacrylate
QA	Quality Assurance
QI	Quality Improvement
QMS	Quality Management System
R2R	Run to Run
RMS	Root Mean Square
SCCM	Standard Cubic Centimeters per Minute
SD (σ)	Standard Deviation
SEMATECH	Semiconductor Manufacturing Technology
SPC	Statistical Process Control
UCL	Upper Control Limit
USL	Upper Speciation Limit
WMS	Web or Portal Content Management Systems
ZMI	Zope Management Interface

Chapter 1

Introduction

1.1 Summary

A major objective of a manufacturing process is to produce high quality products. The variability of all the intermediate processes in production must be reduced to ensure that the product meets the required specifications.

Semiconductor manufacturing involves operating complicated production systems consisting of multiple processes and requiring colossal capital investments. A major portion of the investments are used for setting up the manufacturing facilities and for purchasing the equipment to perform various processes. In a research institute, it may not be practical to purchase and allocate equipment for individual processes due to high costs. Consequently, there are generally many users who are often required to perform multiple processes on the equipment. Therefore, the users require clear guidelines concerning the equipment operation. This makes it inevitable to have proper documentation of the processes and expected failures associated with the different equipment.

1.2 Semiconductor manufacturing

Semiconductor fabrication is one of the most complicated manufacturing processes and employs continuously advancing process technologies performed in large foundries. Semiconductor manufacturing processes require advanced equipment that costs several million dollars [1]. Semiconductor fabrication also requires a cleanroom environment [2]. The standard ISO 14644-1 defines a clean-

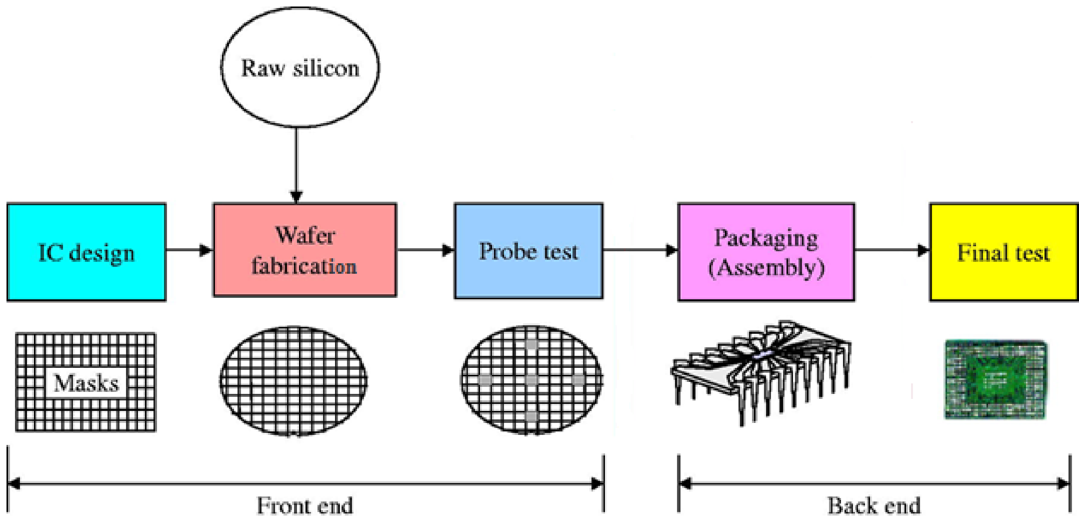


Figure 1.1: Semiconductor manufacturing process [3]

room as a room in which the concentration of airborne particles is controlled, and which is constructed and used in a manner to minimize the introduction, generation, and retention of particles inside the room and in which other relevant parameters like temperature, humidity, and pressure, are controlled as necessary [2]. The main stages in the manufacturing processes are illustrated in Figure 1.1.

The Integrated Circuit (IC) design process starts with defining a given set of requirements for realizing the product [4]. In IC design stage, a schematic of the particular logic and circuit design techniques which is required to design the integrated circuit is created [4]. The consequent stages of the process to achieve the design are then developed prior to the fabrication stage. The wafer fabrication is done in a cleanroom environment in semiconductor foundries on the raw silicon wafer. The chip manufacturer receives the silicon wafer from a wafer supplier. Wafer fabrication processes can roughly be subdivided into four main groups that are used to [5]:

- Transfer geometrical patterns onto the wafer surface.
- Build material layers atop the wafer surface.
- Etch and remove material from the exposed part of the wafer.
- Apply doping in the wafer bulk.

Pattern transfer	Optical Lithography, Electron-Beam Lithography
Layer growth	Epitaxy, Thermal Oxidation, Spin-On, Chemical Vapor Deposition (CMP), Physical Vapor Deposition
Etching	Wet/Chemical Etching, Chemical Mechanical Polishing, Physical/Chemical-Physical Dry Etching
Doping	Ion Implantation, Diffusion

Table 1.1: Main wafer fabrication processes [5]

These common fabrication processes are summarized in Table 1.1. Once the fabrication stages are completed, all individual integrated circuits that are present on the wafer are tested for functional defects by applying special test patterns and verifying the results. Wafer testing is performed using a test equipment called wafer prober [3]. All the stages up to the probe testing are termed as front-end wafer fabrication stages and the subsequent stages as back-end stages. The process of putting the integrated circuit inside a package to make it reliable and convenient to use is performed in the semiconductor package assembly or assembly stage [6]. The main objectives of the assembly stage are to [6]:

- Provide the integrated circuit with a structure to operate in.
- Protect the integrated circuit from the environment.
- Connect the integrated circuit to the outside world.
- Help optimize the operation of the device.

Due to the multitude of processing steps involved in the manufacture of IC chips, process deviations and other sources of errors are bound to happen [1]. Final test is performed to ensure that the ICs work as per the customer requirements. The final test is conducted using Automatic Test Equipment (ATEs) that tests the ICs at different temperature conditions.

1.3 Research institutes and industry

The primary manufacturing areas in a semiconductor cleanroom are divided by functions such as photo, films, etch, CMP, assembly etc. and this type of division is referred to as the farm layout [7]. Semiconductor Manufacturing Technology (SEMATECH), which is an association of semiconductor companies [8] representing about half of the world's semiconductor production, recommends farm layout in manufacturing to its members [9]. Farm layout or a modified type of farm layout is generally used by nearly all the semiconductor companies in its cleanroom for large scale wafer fabrication [10]. In a farm layout, each of the equipment is allotted a specific function and the equipment specifications are generally not varied in large scale semiconductor manufacturing process [9]. The process variations are reduced due to minimal changes in equipment specifications and operating conditions. Industries employ many other techniques to control variations in process. An example from Intel's semiconductor manufacturing uses a technique called "Copy Exactly!" at all its manufacturing facilities [11] [12]. This technique uses the same equipment, the same materials, and workers performing the same tasks in the exact same order [13].

Owing to the variations introduced with changing equipment specifications, manufacturing process is continuous and equipment settings are not usually modified in the industry until a new customer order for a different process is received [14]. Hence, it is practical to perform specific processes with particular equipment rather than to perform multiple processes with it. However in a research institute, many new processes are often continuously performed on the same equipment. The high costs of the equipment that can exceed millions of dollars [1] restricts the number of equipment that are available in the cleanroom of a research institute [14]. Also, there are many older equipment that are present in research institutes on which Advanced Process Control (APC) techniques are not easy to implement. The process settings of some of these machines may be changed by using knobs which users are expected to do manually. The older generation equipment might thus have higher sources of output variation caused by human errors while modifying the settings. In equipment where the output is dependent on the past processes, output consistency might be affected when processes performed on the particular equipment are varied. The differ-

<table>
<tr><th>Industry</th><th>Research institute</th></tr>
<tr><td>There will be one specialist working on the equipment.
Orientation and training about equipment and processes are generally provided to new staff by a specialized trainer or the equipment vendor.
Valuable information is still available with experienced staff when an issue with the equipment arises.
Process settings are not usually varied since equipment is mainly used for mass production.
Implementation of Statistical Process Control and quality control is easier.</td><td>There are inexperienced users working on the equipment.
There is generally no specialized training offered and the new member has to learn from colleagues and instruction manuals.
Loss of key information about specific issues with equipment when the main user leaves the institute.
Process settings may be varied for different experiments based on requirements.
Implementation of Statistical Process Control and quality control is difficult.</td></tr>
</table>

Table 1.2: Comparison between the industry and a research institute [15]

ences in conditions between industry and research institute are highlighted in Table 1.2.

1.4 Motivation

Nowack et. al [16] used a knowledge management system which primarily consists of a content management system. The content management system was proved an important component to improve the education and research activities at a research institute [16]. A constituent to help achieve high product and

output quality is process quality management [17]. To enable process optimization and process quality management, design of experiment (DoE) was identified as an advanced design technique by Kros [18] who investigated the use of DoE in semiconductor manufacturing. Industries use APC techniques in semiconductor manufacturing [19] like Run to Run (R2R) control, wherein a process control system uses data from past experimental runs to adjust the equipment settings for the next run [20]. The process control must be robust enough to make actions when a variability is detected which requires multiple levels of detection and may require a high budget. Implementation of APC techniques in the entire manufacturing line is expensive, costing millions of dollars [19]. In an industry, the implementation of APC is justified due to the high return on investment [19]. However, a research institute does not require a robust control since manufacturing is not performed on a large scale and also a high budget for a process control system is not acceptable [14].

1.5 Scope of the thesis

This work is intended to implement and improve upon a knowledge management system developed at the Technical University Munich by Nowack et. al [16]. The knowledge management system was identified as an important constituent of any QMS [16]. The idea to use a QMS in addition to knowledge management is to improve the process output in semiconductor manufacturing within a research institute. An overview of the structure of Institute für Physik in Universität der Bundeswehr (EIT2) is shown in Figure 1.2.

The institute is broadly divided into three areas as shown in Figure 1.2. The main focus of EIT2 is in semiconductor research, that requires a cleanroom environment. EIT2 consists of two cleanrooms that are called Cleanroom 100 and Cleanroom 300. The cleanrooms are named after the building number that they are located in. There are additionally four laboratories that are part of EIT2. The Analytics and Electrical measurements laboratories are used for performing the electrical characterization and measurements. The development activities for sensors are carried out in the Sensorik lab. In the X lab or Experiments laboratory, semiconductor processes are tested before being implemented in the cleanrooms. Processes that do not require stringent cleanroom requirements are

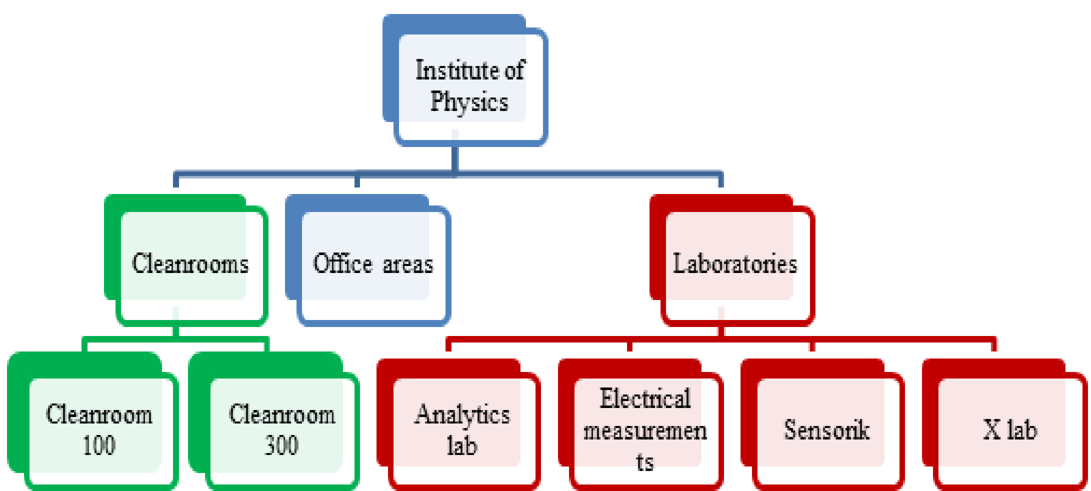


Figure 1.2: Organizational layout of EIT2

also performed in the X lab.

1.6 Organization of the thesis

An introduction to a quality management system (QMS) is made in Chapter 2. This chapter presents the essential components of quality management which are proposed to be implemented in the QMS developed in EIT2. Chapter 3 introduces a content management system that is an essential component of the QMS. This chapter also provides instructions to use the Content Management System (CMS) solution called *Plone* that is selected as the CMS for EIT2. The concepts of experimental design are explained in Chapter 4 and the tool for performing Design of Experiments called *Cornerstone* is presented along with instructions on using the tool. Statistical process control and process capability are described in Chapter 5. Process control and data analysis are an integral component of a QMS and the analysis tool developed in EIT2 is also explained in Chapter 5. A process flow using the components of the QMS is designed and presented in Chapter 6. This chapter also lists all the stages that are essential to ensure that the process output from the available equipment would possess minimal amounts of variation when performing an experiment with any equipment in EIT2. All the data tables that are used for plotting the control charts are available in the Appendix.

Chapter 2

Quality Management

This chapter provides an introduction to quality management. The chapter also presents an overview of the essential components of quality management that are given by ISO 9000 standards. The objectives of ISO 9000 standards with respect to content management and process quality improvement are used to implement the quality management system in EIT2.

2.1 Introduction

The primary goal of every manufacturing industry is to produce a product that satisfies its customer requirements. This means that the manufactured product must have a good value for the money paid. The product should be able to perform its stated purpose and should continue to do so over a given period of time. To manufacture a product that confirms to its specifications, it is necessary that all the processes involved give the required output as per specifications. The quality of a product is defined as its conformance to specifications [21] or its fitness for use [22]. ISO 9000 [23] defines the term "quality" as the degree to which a set of inherent characteristics fulfil the requirements. Product quality can be evaluated in many ways. The differentiation of the components of quality, or the dimensions of quality are provided by Garvin [24] [25]. They are summarized as follows [25].

- Performance (indicates how well the product does its intended function).

- Reliability (if the product does its intended function with less failures).

- Durability (effective life of the product).
- Serviceability (ease and promptness at which a product repair can be made).
- Aesthetics (the visual appeal of a product).
- Features (what more does it have in comparison to other similar products).
- Perceived quality (reputation of the product and organization).
- Conformance to Standards (if the product is made exactly as intended).

A product manufacturer must strive to produce high quality products. If the product does not confirm to the specifications, then it is deemed as a poor quality product and the products must be disposed or sold for a lower price. This results in the wastage of resources that are utilized during the manufacturing process. The minimization of waste and hence the reduction of variability in processes and products is termed Quality Improvement [25].

By summarizing the definitions of quality and requirements from ISO 9000:2000, the expression for quality is the degree to which a set of inherent characteristics fulfils a need or expectation that is stated, generally implied or obligatory [26].

An illustration using the above quality definition is shown in Figure 2.1.

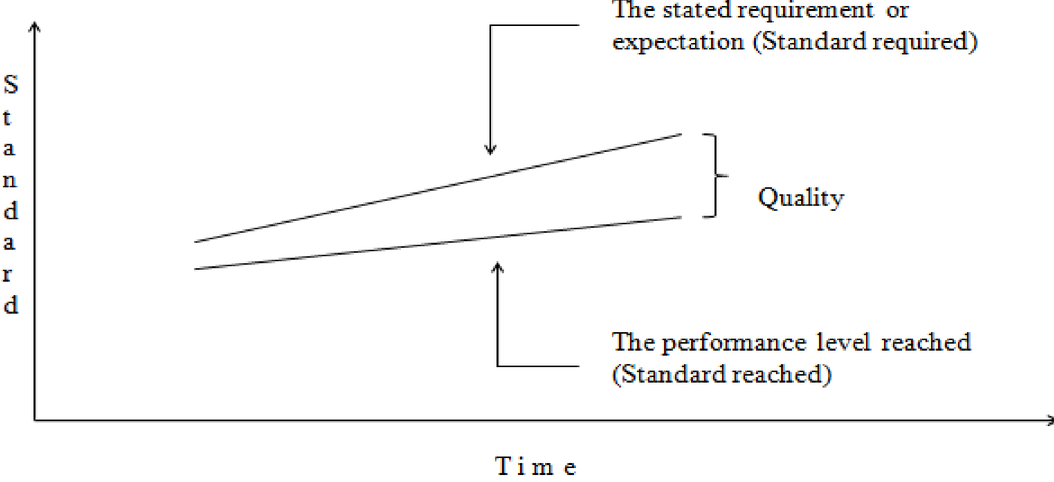


Figure 2.1: Meaning of Quality [26]

Figure 2.1 implies that quality refers to the extent or degree to which a requirement is met. A wide gap is an indication of poor quality. Semiconductor

manufacturing involves a large number of intermediary processes performed over time before the final product is produced. As a result, the gap will widen over time if quality checks are not performed after every critical stage. For an organization to improve the quality of its product or service, the gap between the standard required and the standard reached must be minimized. To achieve this objective, an organization needs to incorporate quality into all the areas connected with the manufacturing of the product. The quality of the process and the product has to be monitored closely to ensure that the required standards are reached. Monitoring a system to maintain stability and consistent performance is termed process control [27]. It should be ensured that the process is always stable with minimal variations [28].

A Quality Management System (QMS) is beneficial in ensuring that end product meets the expected quality standards. Moreover, when quality is the key to the success of the company, quality management systems allow organizations to meet current quality levels and satisfy the consumer requirements for quality [29].

2.2 Quality Management Principles

A quality management system is defined by ISO 9000 as a management system to direct and control an organization with regard to quality [26] [30]. A quality management system serves to establish a framework of reference points to ensure that the same information, methods and controls are applied and used in a consistent manner each time a process is performed [31]. The system must have a proper documentation of the information pertaining to the processes that can be performed with the equipment. This can be used by the employees of the organization and the system can be improved when the users update their findings and issues faced. By elaborating on the definition of quality management by ISO, Hoyle [26] mentions the key quality functions as quality planning, quality control, quality improvement and quality assurance.

2.2.1 Quality Planning

The definition of quality planning is given by ISO 9000 and is defined as a part of quality management focused on setting quality objectives and specifying

necessary operational processes and related resources to fulfil the quality objectives. A sequence for quality planning summarized for research institutes is given below [22].

- Set up a target or goal depending on the requirements.
- Identify the processes or entities affected by the set target.
- Ascertain the needs of the process or entities.
- Develop the process that fulfils the needs of the above mentioned entities.
- Introduce process control and make arrangements to transfer process to operation.

2.2.2 Quality Control

According to ISO 9000, quality control is the part of quality management focused on fulfilling requirements. Quality controls are necessary to prevent undesirable changes in the manufacturing process that may affect the quality of the final product. Even if the planning has been carried out in the best possible fashion, there are bound to be issues in the actual production stage. In production process, installing controls at every stage is beneficial in ensuring that the produced products perform as per requirements. When controls are not present, the gap between the standard reached and the standard required widens as shown in Figure 2.1 and the number of quality products produced reduces. Some of the problems in which defects are introduced in the production stage after quality plan are provided below [32]. The issues are summarized for semiconductor production.

- Flawed process setting devised in the planning stage.
- Error making the required setting on production equipment due to instability issues for the equipment at the selected setting.
- Deviation from output specification limits.
- Errors introduced by a fault of the operator.

Depending on the nature of the organization, the nature of quality control employed may be different. Hoyle [26] mentions that quality control can be done

- Before the event.
- After the event.
- During the event.

Organizations may choose to select one of more control events depending on the process in consideration and the costs associated with the quality control. The reliability can be predicted by making use of a control before the process occurs. This is often done using the data from previous processes. In some cases, a deviation from the tolerance limit can be corrected in the subsequent stages and in this case, quality control after the event would be beneficial. “During the event” control is useful when continuous monitoring of parameters can be made and inconsistencies can immediately be corrected when they arise. An example for this type of control is designing components to function only when inserted in the correct orientation.

2.2.3 Quality Improvement

Quality Improvement is defined by ISO 9000 as the part of quality management focused on increasing the ability to fulfil quality requirements. Improvement is achieved by raising the standards that a process is capable of meeting. This can be achieved by improving the existing methods or by devising a new one which is more efficient and effective. The plan-do-check-act (PDCA) developed by Shewhart and popularized by Deming [33] is used as a systematic procedure in organizations to initiate, track and review improvements [34].

The PDCA model and the Deming or Shewhart cycle for continuous improvement is shown in Figure 2.2. The requirements are usually provided in the “Plan” segment shown in Figure 2.2. The process is performed in the “Do” segment and the output is verified at the “Check” segment for conformance to specifications. The “Act” segment is where the problems identified from the cycle can be used for improving the method. It also allows the users to take corrective and remedial actions if the output is non-confirming to requirements. The standard achieved with the method adopted can be used as the

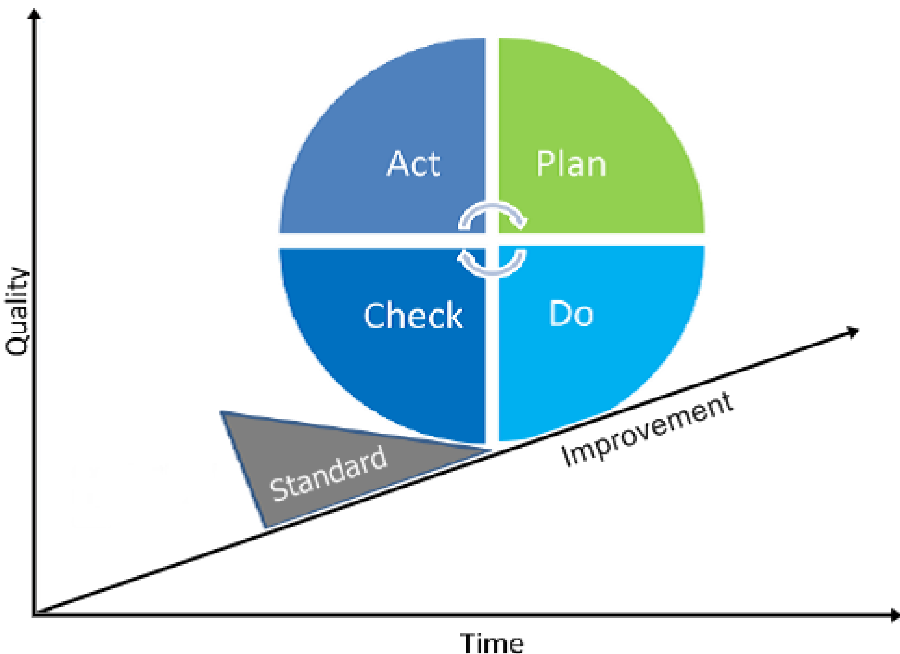


Figure 2.2: PDCA model for quality control and continuous improvement [35]

current benchmark as shown in Figure 2.2. Repeating the PDCA continuous improvement cycle gradually accumulates practical knowledge about the system resulting in better results for quality over time [36]. Repetition of the continuous improvement cycle also helps to raise the standard level in Figure 2.2 towards the direction of improvement. In this scenario, quality improvement is carried out by raising the process performance standards and setting higher goals or targets. The improvement plan by Hoyle [26] can be used for the overall process. Firstly, a feasibility study will be required once a new target is determined to see if achieving the target is feasible. It must also be ensured that the benefits from attaining the new target would outdo the costs incurred in achieving the new target. Once the target is finalized, the improvement plans can be specified on how the target will be achieved. A solution from possible options must be identified and actualized. When the solution concerns a process, the process parameters must be adjusted to reflect the new changes needed. The final part of the improvement plan is to revise the controls for attaining the new level of performance.

Continuous improvement also includes using techniques like PDCA cycle to solve the problems when they arise. Improving the PDCA cycle is used by organizations for problem solving [37] and is shown in Figure 2.3.

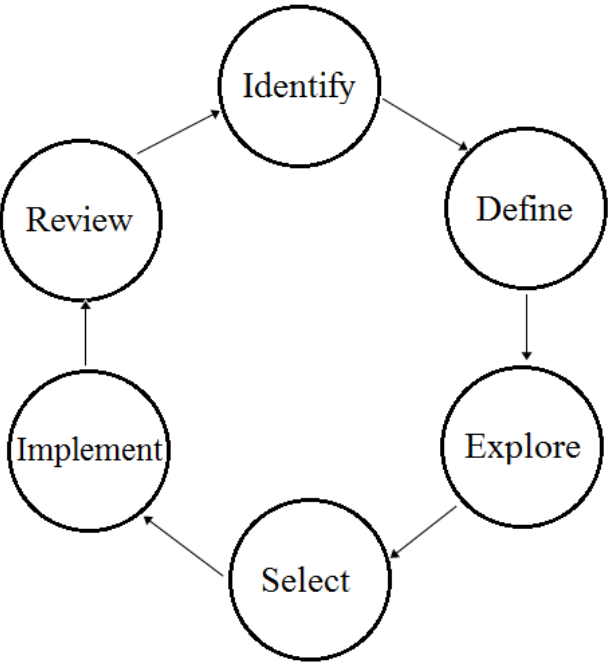


Figure 2.3: Problem solving cycle [37]

The different stages of the problem solving cycle is described below [37]

- The first stage called the "Identify" stage is the stage where the organization realizes that there is a problem to solve.
- The next stage called "Define" stage is where the problem is defined more clearly. The problem may be divided into smaller sub-problems which can be tackled easier during this stage.
- The "Explore" stage involves exploring the ways to solve the problem. Brainstorming is done within the group that is investigating the solution, as well as involving members from cross functional teams to generate as many potential solutions as possible.
- The "Select" stage is the stage where favorable solutions are tried out. It involves evaluating all possible solutions, thereby designing and selecting the best possible solution for the problem to be solved.

- The solution is tested and implemented in the “Implement” stage.
- In the “Review” stage, the results of the tested solution are evaluated to determine if the solution can be finalized or if it must be improved upon.
- The cycle is then repeated to improve the solution or to identify and solve other problems that exist in the manufacturing process.

2.2.4 Quality Assurance

ISO 9000 defines quality assurance as the part of quality management focused on providing confidence that the quality requirements will be fulfilled. An assurance of the quality of the manufactured product is necessary for any organization to obtain customer trust. The strategy for quality assurance in manufacturing is to ensure that bad output is not passed to the next process [38]. Several organizations try to make quality as an integral part of each stage of the design and production process replacing the traditional “after-the-fact” inspection oriented quality process [39]. ReVelle [38] has also stated that an important strategy in quality assurance is to use a preventive maintenance system and perform a process with fewer complexities to identify the quality issues in the process. However, the labelling of prevention activities as quality assurance is criticized by Hoyle [26]; since it could mean that the role of quality assurance department in an organization is to prevent issues from happening in manufacturing process. Hoyle [26] mentions that implementing a quality management system gives an assurance of quality, but the true meaning of assurance comes from the knowledge and what is being done or has been done rather than doing something. Hoyle [26] lists the steps to attain an assurance of quality that are given below

- Acquire the documents which contain an organization‘s plans for achieving quality.
- Define the stages of the quality assurance plan that states how an assurance of quality will be obtained.
- Organize the resources to implement the quality assurance plan.

- Confirm whether the proposed process possesses characteristics that can satisfy the quality requirements.
- Assess the organization‘s operations to determine the existing quality risks.
- Perceive if the identified risks can be controlled, eliminated or reduced with the developed organization plan.
- Determine the degree to which the organization‘s plans are being implemented and risks confined.
- Confirm that the final product or output considered has the desired characteristics.

Some of the techniques that may be used for quality assurance include auditing, planning, analysis, inspection and test. The key quality functions discussed in this chapter should be used by semiconductor research institutes in order to improve the quality of their manufacturing process.

Chapter 3

Knowledge Management

This chapter emphasizes the importance of knowledge management and the role of a content management system as an essential component of QMS. The web-based content management systems are compared and *Plone* is selected among them owing to its ease of use and adaptability for EIT2. The CMS interface is customized for EIT2 and content management using *Plone* is explained. The improvements with regard to knowledge management at EIT2 are also highlighted in this chapter.

3.1 Introduction

Knowledge management is defined as any process or practice of creating, acquiring, capturing, sharing and using knowledge to enhance learning and performance in organizations [40]. Processes such as acquiring, creating, sharing knowledge and the technical foundations that support them is focused in knowledge management [41]. Knowledge about a process comes from individuals and the goal of an organization is to use this knowledge effectively. Knowledge management is defined from an interdisciplinary perspective as the effective learning processes associated with exploration, exploitation and sharing of human knowledge that use appropriate technology and cultural environments to enhance an organization‘s intellectual capital and performance [42]. A system that focuses on organizing and managing an organization‘s knowledge is termed a knowledge management system [43].

3.2 Knowledge management in a research institute

In a research institute, knowledge management is important to improve the information sharing among the staff, researchers and students, thus helping in improving the education and research activities at the institute [16]. An effective method for knowledge management in research institutes is to use a content management system [16]. A content management system is a web publishing and management system that allows content creators to create, submit and publish their content directly within a website [44].

3.2.1 Advantages of a content management system

A content management system can make knowledge sharing simpler and more efficient. The content editors who serve as the knowledge source add contents which can be used globally within the network by other users. Some of the advantages of the CMS are listed below [45] [46]:

- The main advantage of using a CMS is to consolidate the content into one powerful repository that facilitates sharing among the users. A good content organization helps to avoid clutter and content duplication.

- Having a good content organization also helps to ensure that only the updated information is available about a process or equipment. This helps to avoid confusion regarding multiple versions of a document containing details about the same process.

- A CMS also allows setting user permissions. This allows only users with sufficient privileges to access specific contents in the system.

- CMS can also incorporate a work flow system and facilitate the collaborative efforts of the members in creating, editing, and approving the content before it gets published. This guarantees that only the content approved by the team or a key user gets published.

- Search functionality within the CMS makes it easier for finding the required information about a process or equipment.

A CMS helps organizations with many contributors for knowledge sharing. The approval of the added contents can be delegated to specific users depending on the process concerned. Earlier, students were required to send the contents through email or other means to their supervisors, who then had to correct the document and resend to the students to make the necessary changes. The workflow is easier with a CMS. The document can be uploaded by the students. The supervisors will be notified when a new document is made available to publish. The supervisors can make the changes to the same document and publish it directly or notify the students to make the necessary corrections within the CMS.

3.2.2 Classifications of CMS

Content management systems may be divided into several categories. The most important of these categories are Enterprise Content Management Systems (ECMS) and Web or Portal Content Management Systems (WMS) [47]. The objective of the ECMS is to make sure that there is an effective method of saving, delivering, managing, and capturing large amounts of data beneficial to the organization [48]. An ECMS is needed for a big enterprise where integrated document management is needed with the highest audit and control requirements [47].

WMS is a web application that provides an interface for users to create and manage contents with relative ease [47]. In most cases, popular CMS are termed concurrently as CMS and WMS [47] [49]. However, in some cases WMS and CMS are considered as separate entities [50], with CMS vendors offering web content management within the CMS. As of 2013, the most popular content management systems in terms of market share for websites were *WordPress*, *Drupal* and *Joomla* [49]. *Plone* has a lower market share but outweighs them by a secure CMS, a strong community backup and an abundance of add-ons [51].

3.3 Pre-requisites

The fundamental requirement for having a web based content management system is to ensure that the network connectivity is well established within the organization or a research institute. EIT2 has an internal server named “Balu”.

All the entities of EIT2 (office sections, cleanrooms and laboratories) are connected to this internal server. The data backup is routinely done from the internal server to the central server to ensure that the data will not be accidently lost. The internal server can be accessed from any browser by entering *"http://balu/"* using any PC connected to the Intranet. The page contains links to the knowledge management system, the wafer database and an equipment booking system. In this thesis, knowledge management is done with the help of a web based content management system called *Plone*. *Plone* is hosted on the internal server and runs on a web application framework called *Zope* [52]. The wafer database is used to check the available wafers in stock and order the wafers if needed for experimentation. The equipment booking system is used by the institute staff to book the time slot for using the equipment.

3.3.1 Requirement analysis

The following were the major requisites that were considered for selecting a CMS for EIT2.

Ease of usage and support

The primary selection criterion for a CMS was that it should have an easy-to-use interface. A CMS requiring less maintenance was also preferred, since there was no member explicitly assigned to maintain the system in EIT2. A popular content management system with good online support was needed to obtain easy support when problems arise. A review of the most popular content management systems [53] was used to make the initial list for selecting the right CMS solution.

Security

An important requirement was that the CMS must be robust and offer high security. This was necessary since the CMS is used to store the internal data and research proposals that need to be securely stored.

Managing content

The users in EIT2 belongs to different groups like professors, staff and students. A CMS is required to have a good degree of control for managing contents and permissions to restrict access to the contents by group.

Speed

Another key requirement from a CMS was that accessing contents and searching for the required content must not be time consuming. A web based content management system was preferred since the resource usage on the local user PC is minimized.

3.4 Knowledge management in EIT2

The final list of the content management systems included *Wordpress*, *Joomla*, *Drupal* and *Plone*. In terms of speed and popularity, *Wordpress* was found to be the best option [53]. Adding and managing contents is easier in *Plone* when compared to CMS like *WordPress* or *Drupal* [51]. The Institute of Physics consists of non-technical members aside from technical staff, researchers and students and the concept of accessing contents by group permission in *Plone* is an advantage. *Plone* was found to be a better choice as a content management system in EIT2 for many other reasons. *Plone* is a powerful and flexible, enterprise-quality CMS that is easy for developers to download and install, and easy for end-users to use [52] [54]. *Plone* lets non-technical people create and maintain website content with the help of a web browser and offers capabilities for public websites, private intranets and collaborative workspaces [54]. *Plone* offered the users an easier interface with the folder layout and where the basic operations similar to a file system environment like cut, copy and paste were possible [47]. Some of the staff in the institute have prior experience using *Plone*. Tasks like password recovery could be directly made by users with the *Plone* system that influenced the experienced *Plone* users in the institute to consider it. A summary of the advantages of *Plone* are given below:

- *Plone* system is based on the concept of permissions for performing the basic operations and which can be granted to groups or users [55]. For a

research lab, the system works well to conceal some contents depending on the group. Other CMS tools like WordPress requires installing an add-on for this feature [56].

- During the selection of a content management system, *Plone* offered the best security with lesser vulnerabilities when compared to other popular CMS [51].

- A big advantage that *Plone* offers is the intelligent searching and indexing of the information [57]. The built-in search feature of *Plone* can search within documents [57] and this built-in search is better than most CMS tools [58].

By considering all the factors, it was seen that *Plone* offered all the advantages of other popular CMS tools. *Plone* was also recommended by the staff at EIT2 who had experience in using a CMS and was thus preferred over other CMS for knowledge management at EIT2.

To develop *Plone* into a functional CMS, the main stages identified were:

- Initializing the website.
- Website customization.
- Organizing contents.
- Creating users and groups and delegating the roles.
- Getting user feedback and constantly improving the system.

The stages are explained in further detail below.

3.4.1 Initialization

Plone is built on a web application server called *Zope* which is written in the programming language *Python* [52] [59]. The relationship among *Plone*, *Zope* and *Python* is shown in Figure 3.1.

Since *Plone* is built on *Zope* and *Python*, it is necessary that the latter two are installed before the installation of *Plone*. However, an automatic installation of *Plone* installs Python, *Zope* and then *Plone* [59]. The operating system of

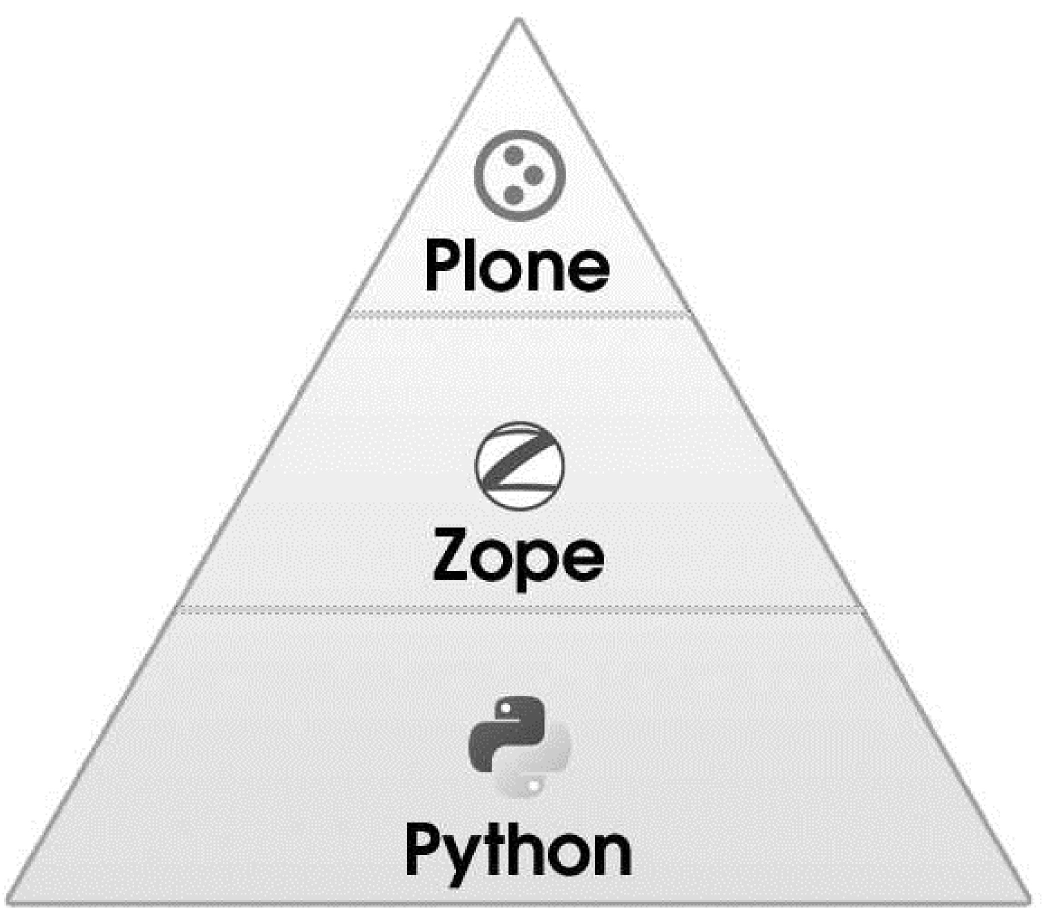


Figure 3.1: Connection between *Plone*, *Zope* and *Python* [59]

the internal server "Balu" is *Ubuntu*. The detailed instructions for installation are available online in the developer section of *Plone* web-page [60]. Once the installation is completed with the default settings and *Plone* is started [60], the site can be accessed from a browser by entering the server address as *"http://balu.et.unibw-muenchen.de:8080/eit2physik/"*. The default *Plone* page with a welcome message is displayed. A login tab is available at the left side of the page. The "admin" login credentials that were set during the installation are provided to login. After logging in, the "admin control panel" is available from the configuration section accessible from the site navigation tab.

3.4.2 Site customization

Plone "control panel" is accessible to users with administrator privileges and it contains necessary controls to make changes to the layout, user list, language and

other configuration settings that are desired. “Zope management interface” or “ZMI” page needs to be selected to customize the appearance of the website. It is used to make the changes that apply to the whole CMS. This page can also be accessed by entering *“http://balu.et.unibw-muenchen.de:8080/eit2physik/manage”* directly in the browser. The “portal” page in ZMI is used to customize the appearance of the website. The default logo located at “portal_skins” in ZMI is replaced by the institute logo. Some other changes were made to the site theme and the navigation bar following the instructions available in the *Plone* documentation to customize the website for EIT2 [61].

3.4.3 Organizing contents

After customizing the *Plone* page, organizing the contents in a user-friendly manner is necessary. This required suggestions from all researchers and staff of the institute. A collective decision was made to create a hierarchical organization of the contents which is equivalent to folder view in a personal computer. An initial set of folders for the general categories were first set up. This included the “Events”, “News” and “Institute” folder. The “Institute” folder is the main folder to include all the information relating to the institute. Depending on the requirements put forward by the users, the “Institute” folder was subdivided into 9 sub-folders as shown in Figure 3.2.

The overview of the institute folder is shown in Figure 3.2. The first sub-folder is the “Institute Info” page. It contains information about the institute. The members are listed in the “Group” page and information about the activities and ideas for master and diploma thesis are put up in “Innovation Center” page. The second sub-folder of the “Institute” folder is called “Infra”. Infrastructure related issues are provided in this sub-folder. The “Events” page in this sub-folder has a calendar layout where the designated members in charge of the institute infrastructure have to enter the updates regarding infrastructural issues. The room list and floor plan are entered in the “Raum und Bau” page. The page is also used to provide details like the purchase of new equipment and the essential infrastructure requirements. The changes to the existing laboratory set up that are required are also updated in this page. In the case of laboratories, sub-folders are provided for the specific requirements concerning the particular laboratory. The most important of these are the safety instructions for the users

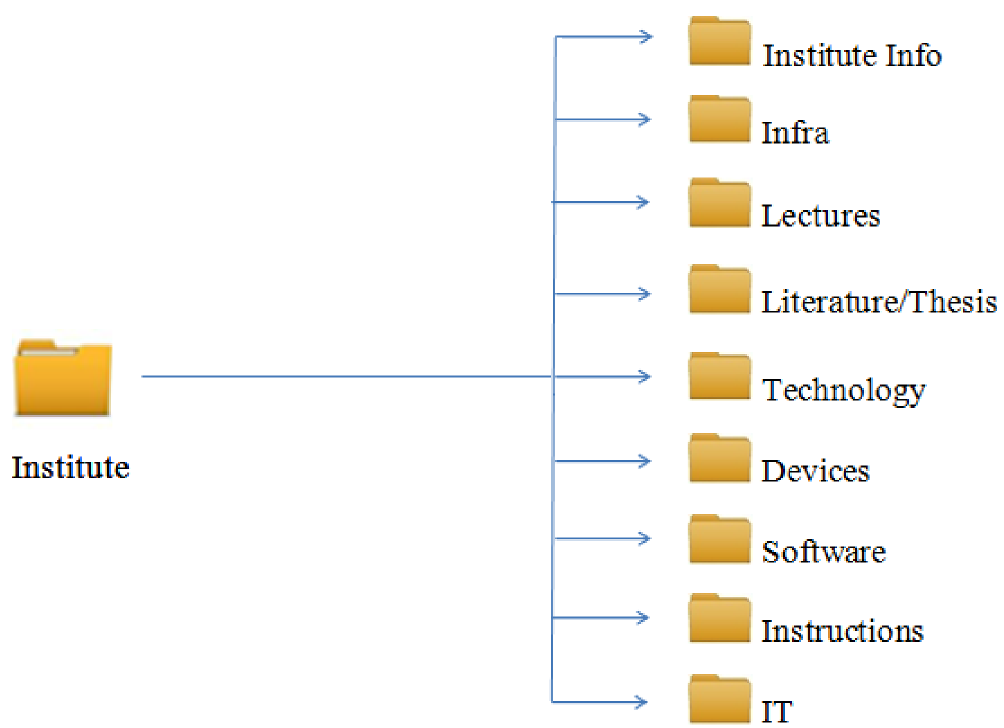


Figure 3.2: Subfolders in the institute folder of CMS

and the details about the supply of materials and gases. The required templates are available for each of the laboratories and cleanrooms. It enables users to add the vital contents at a later stage.

The "Lectures" sub-folder consists of pages for "Practicals", "Theory" and "Exams". The "Literature/Thesis" page is used to list all the scientific journals and the Diploma/Master/PhD thesis from the institute. A section for the thesis proposals is also available in this page. The proposals listed in this page are the selected project proposals from the list in "Innovation center" sub-folder within the "Institute info" folder. A page for listing external thesis relating to the projects done at EIT2 is also available.

The sub-folder "Technology" is the most extensive sub-folder in the CMS. It comprises the folders "Tools", "Processes" and "SPC". The "Tools" folder lists the laboratories and cleanrooms of the institute namely the "Analytics lab", "Cleanroom 100", "Cleanroom 300", "Electrical measurements lab", "Sensorik lab" and "X lab". Each of these sub-folders consists of the list of available equipment in the respective laboratories and cleanrooms. The "Equipment" folder comprises of different sub sections to further explain the details of the equip-

ment. A screen shot of the page for "Annealing furnace Carbolite" equipment is shown in Figure 3.3.

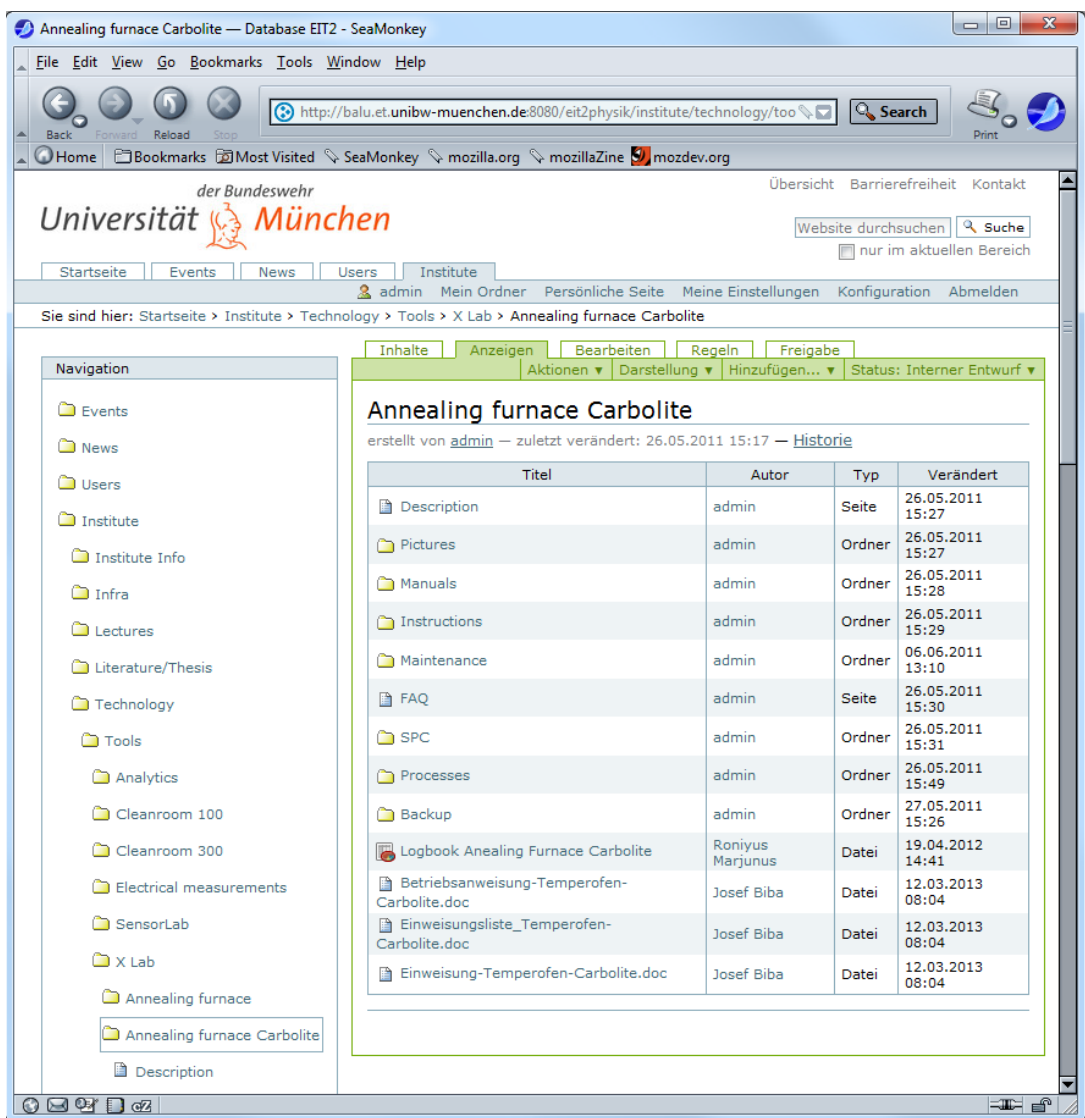


Figure 3.3: Annealing furnace page in CMS

The primary details of the tool/equipment are provided in the "Description" segment of the "Equipment" folder which includes the equipment description like manufacturer, type, serial number, date of installation etc. to name a few. An example for such a folder shown in Figure 3.3 contains the pictures, manuals, operating instructions, safety instructions, maintenance history, servicing details, log book listing the experiments performed, statistical process control data and a list detailing the processes that can be performed with the equip-

ment. The "Processes" page of the technology sub-folder lists the semiconductor processes performed in the institute. The "Processes" page may contain additional sub-folders depending on the process type concerned. The "SPC" page in the "Technology" sub-folder helps to provide an introduction to statistical process control and explains the procedures to perform SPC on the equipment.

The "Devices" sub-folder comprises of the pages for "Test Structures", "Diodes" and "FETs". The specific device types and their comprehensive information including the theory, simulation, fabrication and the actual measurements performed on the device are available in this sub-folder. The "Software" sub-folder is used to list and provide the operating instructions of the simulation tools used in the institute. The pages "Instructions" and "IT" are used to provide the instructions for using the CMS and the institute IT infrastructure respectively.

3.4.4 Creating users and groups

Once the website customization is completed, the next stage is to make the user list and divide users by groups. Users with administrator privileges are able to view the "control panel" of the *Plone* CMS which has a page called "Users and groups" for the creation and management of users and groups. To access the contents and manage the security for information in the CMS, specific groups were made and access rights are given to members depending on their inclusion in the corresponding group. The groups were broadly classified as:

- Administrators (Have access to all areas of the CMS and can manage users and contents).
- Professors (Have access to all contents and have rights to publish any information without additional permissions needed).
- Institute staff (Have access to all contents that are not explicitly hidden. They are also allowed to publish information but restrictions apply to edit contents created by other users).
- Researchers (Have same rights as the staff with the additional permission to approve the content posted by students for publishing).
- Students (They have access to only the open and specific sections of the website. They are allowed to add information in the areas designated to

them, but the content needs to be approved by a member with higher rights to be published).

The user accounts are first created and then added to the corresponding groups. Users who do not belong to any group are only allowed to view the open contents in the internal pages. During account creation, the CMS is configured to send an email to the email address of each member automatically with instructions to reset the password. After password reset, the member can login to the CMS with their user credentials. For the password recovery, the user can select the "Forgot Password" option in the login screen and a new mail will be sent to the email address that was provided during account creation to reset the password.

Plone allows giving special privileges to users in addition to their pre-assigned rights in the CMS. Specific users can be given complete privileges in a folder, wherein they have control of all the contents within that folder to edit all contents or to create the list of other users who are allowed to view or edit the contents. As part of the existing quality management initiative in the institute, researchers are given complete responsibilities of managing data for equipment assigned to them. In this regard, the user is given the additional responsibility for content management in the CMS for areas corresponding to the equipment or processes that lie within his/her area of responsibility. The responsibilities include creation of the instruction manuals, training new users, verifying the experimental results and managing the maintenance activities.

3.4.5 Continuous improvement

The concept of continuous improvement applies to any system and the CMS is no exception. Training on using the CMS was first provided to the institute members. The institute members were asked to test the CMS and to provide feedback about the system. Weekly meetings were held to receive user feedback of the CMS. After receiving the feedback, the contents in the CMS and the folder layout were standardized. To add a new process or equipment, the delegated users are required to use the existing parent folder of the equipment or process as a template. Additional tools needed for specific functions were also added depending on user feedback. To make the initial set of changes, the CMS was configured to "debug mode". This is the preferred mode to carry out the site

developments in a *Plone* CMS [62]. After the first set of user feedbacks were received and the changes were made, the CMS is switched back to "production mode".

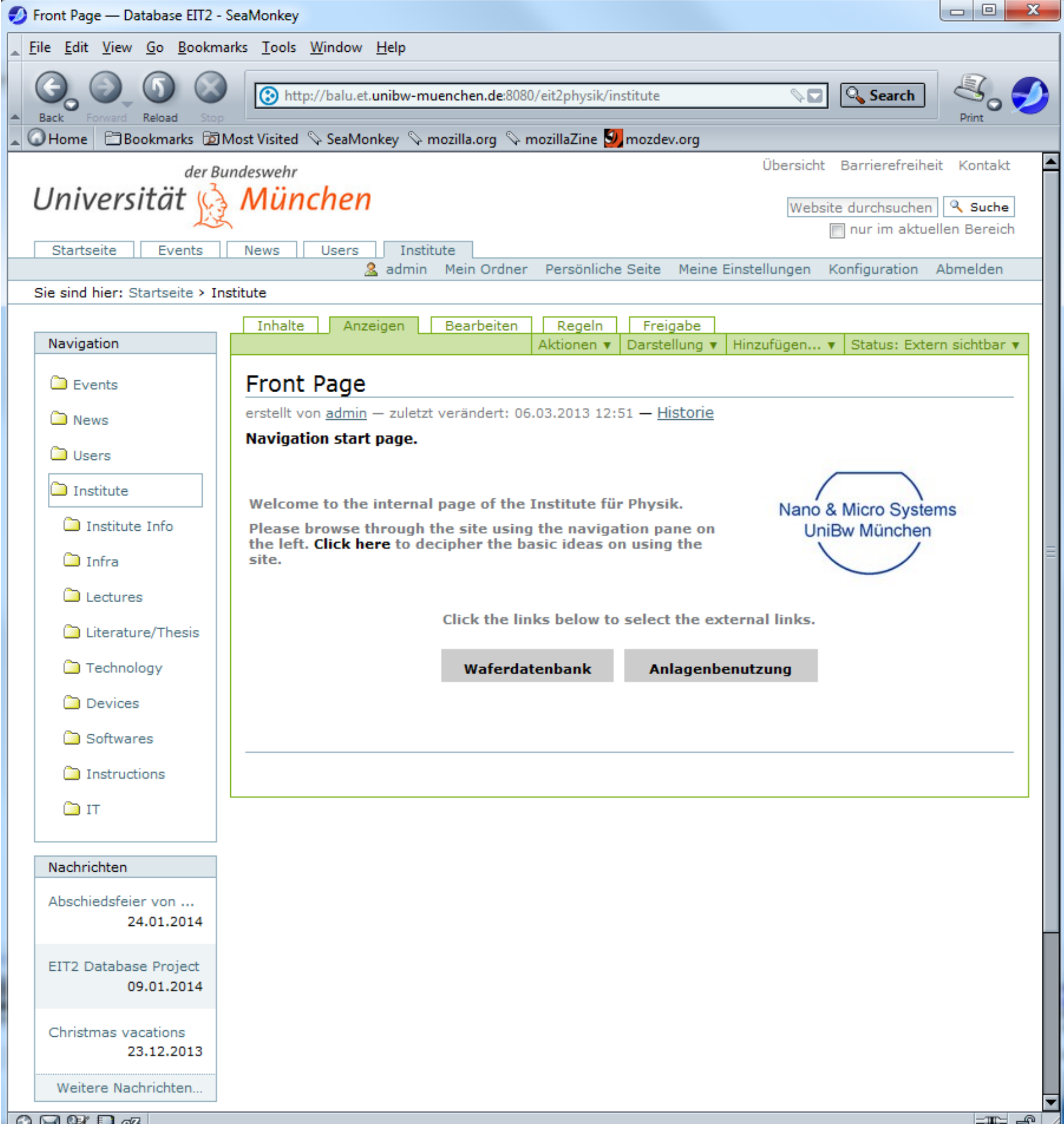


Figure 3.4: Institute folder of CMS

The "Institute" folder of the CMS in production mode is shown in Figure 3.4. The sub-folders are visible only to logged-in members of the institute.

3.5 Using the CMS

This section describes the CMS in "production mode" after the completion of the stages described in section 3.4. The users are required to access the user interface of the CMS for the first usage. The CMS can be accessed by entering the url *"http://balu.et.unibw-muenchen.de:8080/eit2physik/"* in the address bar of any internet browser. The homepage providing a brief introduction to the institute will be loaded. The "Events", "News", and "Institute" folders in the navigation bar are also visible. An introduction message is displayed on selecting the "Institute" folder. The CMS is configured to be displayed in German language. To view additional details in the "Institute" folder, users are required to login. The login field is available below the "Navigation" link. Login is done by providing the username and password in the "Benutzername" and "Passwort" text fields respectively. The additional sub-folders of the "institute" folder as shown in Figure 3.4 are displayed once the user is logged in, depending on user privileges. The user can access the internal pages of the institute after logging in and browsing to the required area of the CMS. The users are then able to use the "Meine Einstellungen" tab under the site logo shown in Figure 3.4 to set their personal preferences. This area allows the user to provide their personal information and also to customize the settings regarding the preferred document editor and if they would like to be listed in the user list.

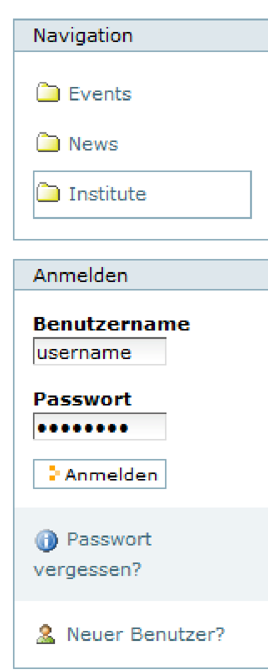


Figure 3.5: Login section of the institute CMS

3.5.1 Managing documents

An institute member can add contents to any folder where the site administrator has given the rights. *Plone* allows addition of different types of contents and therefore the correct content type needs to be added online or uploaded from the local PC. This would ensure that the contents can be viewed in the best way that is supported by *Plone*. The following content types are provided by

Plone [59] and approved to be added into the CMS.

- Event: An upcoming event, meeting, conference, etc...
- File: A piece of content such as a movie, sound clip, text file, spreadsheet, compressed file, etc ... Multiple file upload is possible by appending "@@upload" in the address bar at the end of the site address.
- Folder: This is similar to a folder on a hard drive.
- Image: An image, such as a GIF or JPEG file.
- Link: A link to another item which can be internal or external.
- News Item: A document about new information (e.g., a press release) which is normally shown under the "News" navigation tab.
- Page: To present static information to the user.

If a member has the required permission to add contents in a folder of the website, the folder will be displayed with a green border around the top. The user must select the "Hinzufügen" option to add a new document. A drop-down menu opens and the user needs to select the content type to be added. To add a page, the option "Seite" needs to be selected. It loads the add page panel shown in Figure 3.6.

A page can be created or edited using the default editing tool of *Plone* within a web browser. A title needs to be provided since it is a compulsory field. The "Zusammenfassung" or summary field is used to give a quick indication of the content of the item and will appear in content listings and search results [59]. The largest field "Haupttext" is the body text field where the main information or content needs to be entered. The inbuilt text editor can be used to format the text. The "Änderungsnotiz" field helps to note the changes made to an existing document. This is beneficial in situations where many users are allowed to edit a document and a change note can be used to store essential memos. The "Speichern" or save button is used to save the document after all the changes are made. Users can also make other changes like specifying a publishing date and also the list of users who are allowed to view and edit the document.

To add a picture or file from the computer, the corresponding choice needs to be selected from "Hinzufügen" option. A page similar to Figure 3.6 loads with

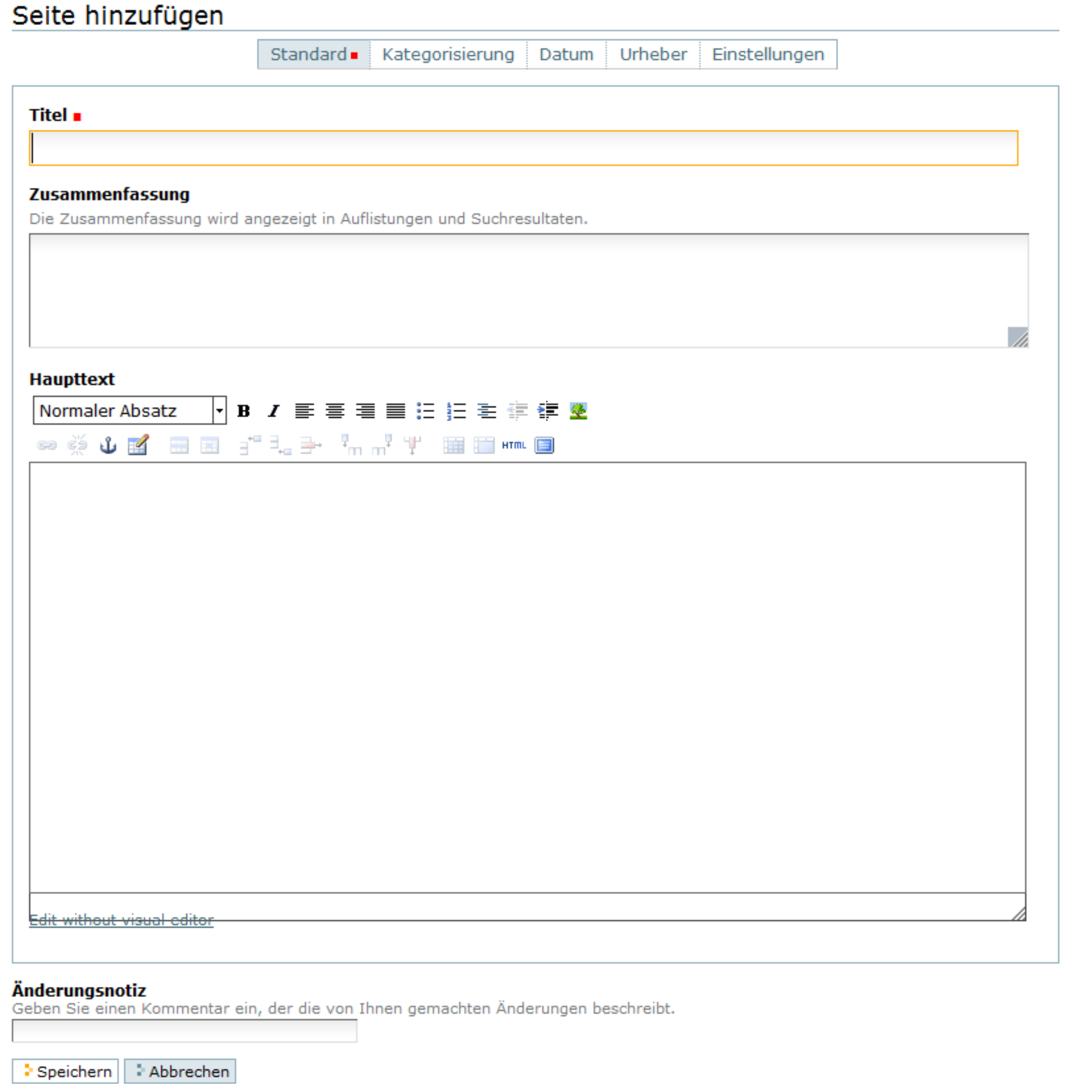


Figure 3.6: Visual editor to add a new page in *Plone*

a title, description and an upload field. The "Browse" button in the upload field is used to browse through the local hard drive and select the file or image to upload. Adding other *Plone* content types is also straightforward for a new user to understand. All details about adding and editing contents are available in the "Instructions" page of the "Institute" folder. If a user is working on an item that other users are also allowed to edit, the item automatically becomes locked. Another user who wants to edit the document sees the name of the user who locked the item as well as the locking time. This helps to ensure that the document is not modified at the same time.

3.6 Improvements with CMS

The main improvement brought about by the *Plone* CMS was in the area of knowledge management. The Institute users found it easy to add and edit contents on the database. As a result the database usage has increased and its contents are seen to increase over time. The infrastructure issues are listed in the “Events” page of the “Infra” folder (shown in Figure 3.2) and a screenshot of the page is shown in Figure 3.7 below.

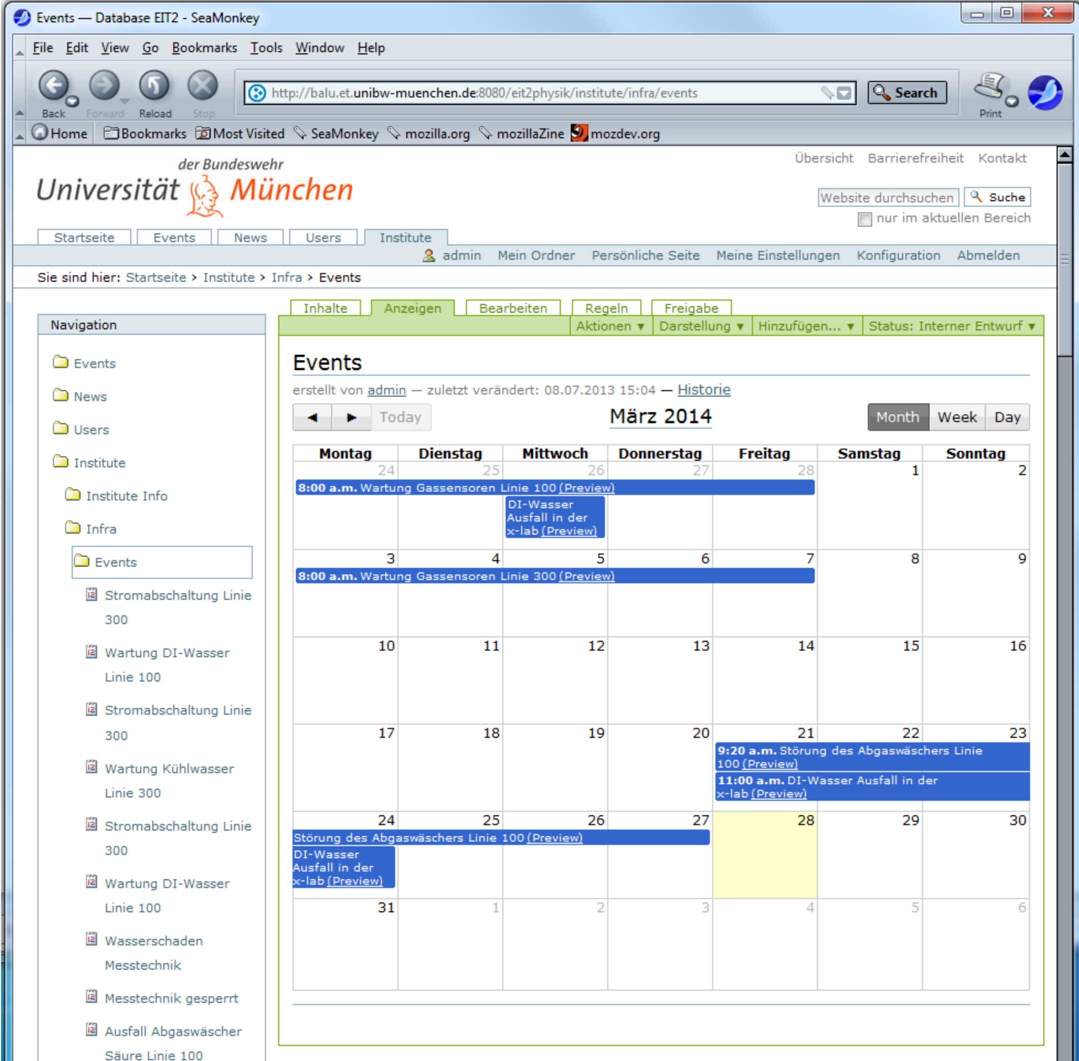


Figure 3.7: Events page listing infrastructural issues on a calendar

As seen from Figure 3.7, the infrastructure issues are logged into the “Events” page. The entries are listed by their date of occurrence in the calendar. Additional details of an event can be seen by clicking on the event name in the

calendar. The discussion of the infrastructure issues every week during the department meeting ensures that the institute members are informed of the issues in the laboratories and cleanrooms. The user interface enables easy addition of new events during the course of the meeting.

The safety instructions and operating instructions of the equipment in the institute are available in the database. Maintenance history, processes and process parameters along with pictures of the important components of the equipment are also maintained. The documents are checked regularly to ensure that only the latest versions of the operating instructions are kept in the database.

3.6.1 Usage statistics

The benefits of using a QMS are only realized if the system is used by all the users. The usage history of the content management system was collected over a period of one year to check if the system is accepted and used by the members of EIT2. The CMS was released in January 2013 for the members to enter the equipment and process data in EIT2. By end of March 2013, the majority of the equipment and process data were entered in the system. Once the data was available, only the newer processes and issues concerning the infrastructure and equipment maintenance were required. A cumulative graph displaying the number of available documents is shown in Figure 3.8.

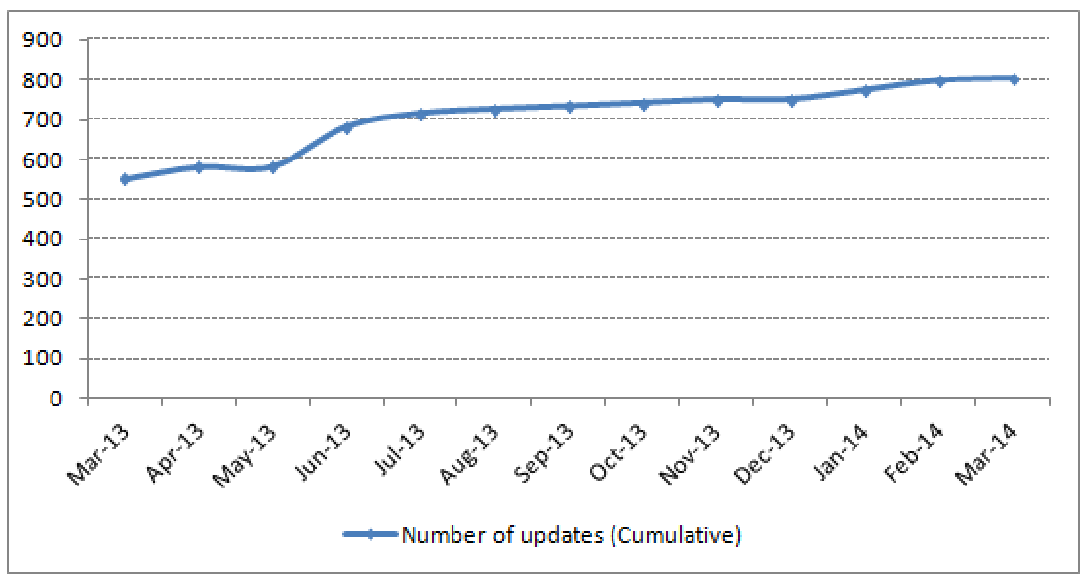


Figure 3.8: Usage statistics of the knowledge management system

As seen from Figure 3.8, the number of data files entered in Mach 2013 was 551. The figure gradually increased up to 804 by March 2014. An increase of 253 data items over a year shows that the CMS is used in a fairly good manner by the members in EIT2. Usage of the system by all the staff and users could eventually make the CMS, the solution to all the training activities in the institute. The availability of the actual data of the process can also make the data analysis and implementation of statistical process control techniques easier.

Chapter 4

Design of Experiments

This chapter introduces the concept of experimental design and presents the software tool *Cornerstone*, which is used to perform Design of Experiments (DOE) at EIT2. A screening experiment for determining the significant input factors is performed with DOE. Fractional factorial and other computer generated models which are used for DOE are presented. These models are used to analyze the input factor effects and simulate the output value for a given input setting.

4.1 Introduction to experiments

Any industrial process is made up of input variables, process variables and output measures. A process can be envisioned as a combination of materials, machines, methods and people. A process variable refers to any varying operational and physical conditions associated with a process [25]. Process variables or factors can be classified as controllable and uncontrollable. The controllable process factors refer to any factor whose value can be controlled and measured accurately. Uncontrollable factors are external factors such as temperature changes, material contamination etc. Some of these uncontrollable factors can be measured and some are unknown and cannot be measured. The uncontrollable factors are often referred to as noise factors [25]. An output measure has one or more observable quality characteristics or responses. Based on the process definition as a combination of materials, machines, methods and people, a process diagram can be constructed as shown in Figure 4.1.

The objective of a process is to improve the output measure or the response.

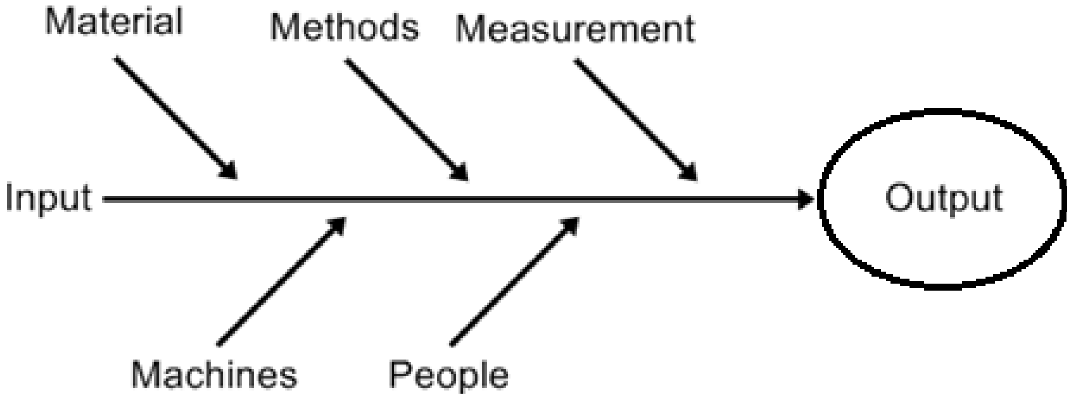


Figure 4.1: Components of a process [63]

An experiment is performed with the following objectives [25]:

- Determine the process factors that are most influential on the response.
- Determine the specifications of the influential factors to make the output near the required levels.
- Determine the influential factor specifications so that the output variability is less.
- Determine the influential factor specifications so that the effects of uncontrollable factors are minimized.

To achieve the process objectives, an experiment is conducted to determine the best values of parameters that minimize the variability of the output or the performance characteristic considered. The experiment must be designed in such a way that will provide the experimenter with information necessary for making appropriate decisions [64]. By performing designed experiments, key variables that influence the quality characteristics of a process are discovered. Experimental design methods are used in process development or process troubleshooting to improve the process performance or to obtain a process that is robust and insensitive to external variability sources [25].

4.1.1 Process Model

In a process, variations in the input parameters can lead to undesired output variations. An ideal process must give the output response as a direct function

of the input factors. Using DOE, a quantitative connection between the factors and responses can be obtained [65]. The process model can be reconstructed with the factors and responses as shown in Figure 4.2.

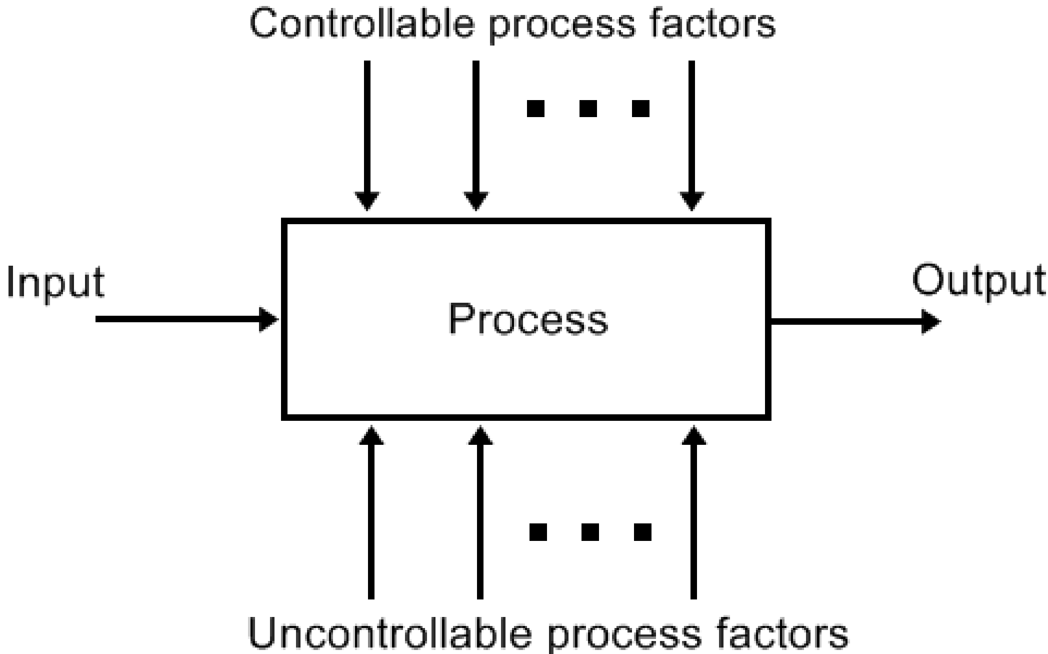


Figure 4.2: General model of a process [25]

In a real world scenario, there would be many sources of variations in the input factors, whereby the process deviates. Owing to this deviation, the process cannot be modelled easily. The deviations can arise due to the chosen experimental method or because the machines might not function as intended, or the output being measured is not accurate. These sources of variations constitute statistical errors. The presence of statistical errors reduces the accuracy of the output prediction when creating a process model. The mathematical model of the process model should thus take into account the measurable input factors and the error factor to give the desired response. This mathematical model can be represented as

$$y = f(x_1, x_2 ... x_n) + e,$$

where x_1, x_2 refers to the input factors and e is the statistical error.

4.1.2 Measurement System Analysis

Measurement System Analysis (MSA) is an experimental and mathematical method of determining how much the variation within the measurement process contributes to overall process variability [66]. Measurement is an integral part of any experiment. The total process variability is the sum of the process variation and the measurement system variation [67]. No measurement process is perfect and variations may even arise when the same part or sample is measured more than once. Variations may be caused by measurements being made by different people, gauges or even by the same person using the same gauge. If the measurement system variation is reduced, the variations reflected by the collected data would only result from process variation. MSA is performed to ensure that the information collected from the measurement system is a true representation of the process output and serves to address the following concerns [67]:

- Capability of the measurement system for the experiment.
- Intensity of the measurement error.
- The amount of uncertainty required when interpreting the measurement from the system.
- If measurements are being made with measurement units that are small enough to reflect the variation present.
- Determining the sources of measurement errors.
- Detection of process improvement when it happens.
- The stability of the measurement system over time.

The measured values provide a feedback of the process performed to re-adjust process settings, to replace tools or to determine if the current process can run without modifications. In this regard, it is also necessary to analyze the source of variation in the data, since data validity directly affects validity of process improvement decisions. Automotive Industry Action Group specifies the general rule of thumb for measurement system acceptability as [66] [68]:

- Error less than 10% is acceptable.

- Error of 10% - 30% is acceptable depending on the importance of application, cost of measurement device, cost of repair and other factors.
- Error over 30% is unacceptable and the measurement system is unfit for use unless its measurement error is reduced.

While performing MSA, there are five parameters to be investigated, which are bias, linearity, stability, repeatability and reproducibility [68]. Sources of variation can be found by analyzing these five parameters. The variation sources resulting from measurement errors can be classified into two general categories called precision and accuracy [67]. Precision is a measure of the spread of readings that results from successive measurements of the same part or sample [67]. For precision measurements, when successive measurements are made by the same person using the same equipment, it is termed repeatability measure; and when it is made with different hardware, people or environment, then it is a measure of reproducibility [67]. Accuracy or bias of a measurement is a qualitative indication of how closely the result of a measurement agrees with the true value of parameter being measured [68]. A measurement can be highly precise or reliable, but not accurate or valid at the same time [69]. A distinction between accuracy and precision is depicted in Figure 4.3.

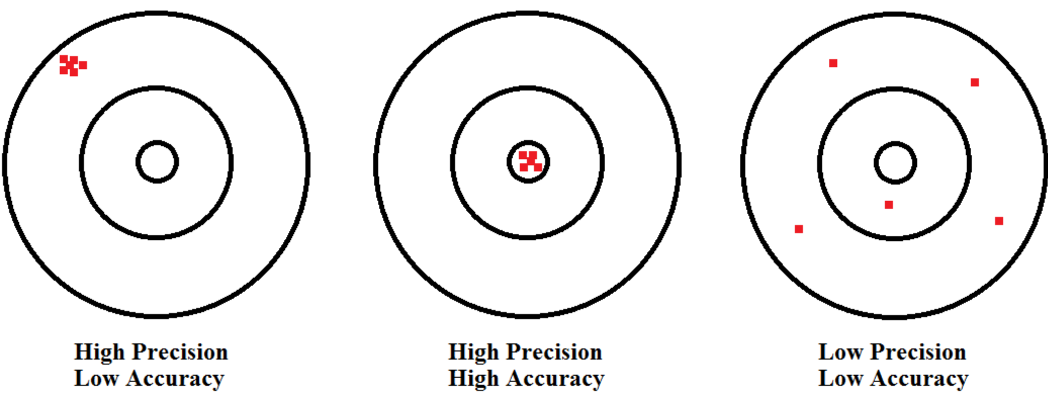


Figure 4.3: Three features of measurements [69]

On the first concentric ring in Figure 4.3, all four points lie in close proximity to each other, but to the left of the ring. This represents the case of high precision and low accuracy. On the second concentric ring, all four points lie in close proximity to each other, and all are inside the innermost ring. This represents the case of high precision and high accuracy. On the third concentric ring, the

four points are distributed widely around the target. None of these points lie within the innermost ring. This represents the case of low precision and low accuracy. MSA is performed using an Interferometer (discussed in section 6.1) and the calculations and results are summarized in Chapter 5.

4.2 Experimental Design

Once the MSA is performed and the measuring system errors are accounted for, the other uncertainties in the process can be studied. A powerful approach to improve a process is by means of designed experiments. Experimental Design, also called Design of Experiment (DOE) is a technique used to systematically vary the controllable input factors in the process and determine their effects on output [25].

The output effects can be classified as main effects, interaction effects, quadratic effects and cubic effects. In an experiment, the "Main effect" is defined as the change in response produced by a change in the level of one of the primary factors in the experiment [25]. In some cases, the difference in response between the levels of one factor is not the same at all levels of the other factors and there exists an interaction between factors. This effect is called the "Interaction effect" [25]. "Quadratic effects" and "Cubic effects" are second order and higher order effects of the same factor. These factor levels and a combination of levels of factors is known as a treatment combination or run [30].

There are often many factors in an experiment of which some have no influence on the output. It is desirable to reduce the factors to a small set to focus on controlling only the important factors. Screening experiments with minimal runs helps to determine the important factors and to make a Response Surface Design [70] [71]. Response Surface Design is a procedure to make process improvements and optimization [71]. The idea behind Response Surface Methodology (RSM) is to develop an approximating model for the true response surfaces [72]. The initial stages in DOE consists of [71]

- A screening experiment to select the main factors.
- A response surface experiment to determine the shape of effects.

4.2.1 Screening experiment

A screening experiment is necessary in situations where there are many factors affecting a response. Screening experiments helps to find the important factors that have to be taken into consideration for DOE. However, it should be noted that in the screening experiment discussed below, only the main effects have been considered and the model is assumed not to have any factor interactions. The technique using the Taguchi matrix [73] can be used for screening experiments and would be beneficial to determine the factors that do not contribute much to the output value.

A screening experiment was performed with a plasma etcher at the EIT2. Three input factors of the plasma etcher were considered and the screening experiment was done to study the effect of each of the factors on the output. The identified input factors were O2 flow rate, power required for the plasma generation and height of the sample from the base of the plasma chamber. These input factors are represented by Standard Cubic Centimeters per Minute (SCCM), Watts and Millimeters respectively. When the plasma etcher is started, a faint light is seen in the vacuum chamber. In some input setting combinations, the light in the plasma chamber flickers. The output taken when the light flickers is unstable and has a very high variation [74]. The adjustment of power setting for the plasma generation to a higher or lower value helps to address this issue. "Power (Theoretical)" and "Power (Actual)" depicted in Table 4.1 is used to show the adjustment of power settings to obtain a stable output. The screening tests were done using Taguchi matrix [73].

Each of the input factors must have two or more levels so that the effect of change in factor setting on the response can be examined. As is evident from Table 4.1, each of the three main factors are set at three specification levels to exemplify high, medium and low levels of the input factors. However, the actual value of power setting is different from the required theoretical value in some cases. This makes the Taguchi matrix unsuitable for usage while designing a complete model for simulation purposes which requires accurate values for a specified level. Taguchi matrix is more suited for calculating the main effects of the factors which are shown below.

	Factors				Output
Run number	O_2 level (SCCM)	Power (Theoretical) (Watts)	Power (Actual) (Watts)	Height (mm)	Etch rate (nm/min)
1	6	50	52	0	12.43
2	6	200	241	9.7	211
3	6	350	350	19.4	406.3
4	9	50	50	9.7	6.85
5	9	200	230	19.4	106
6	9	350	320	0	92.45
7	12	50	50	19.4	6.05
8	12	200	250	0	6
9	12	350	350	9.7	16.38

Table 4.1: Taguchi matrix for plasma etcher output

The effects are calculated by taking the output values corresponding to a particular factor and a level. A factor effect can be represented as

$$f_0 = (y_{01} + y_{02} + y_{03})/3, \tag{4.1}$$

where f_0 is the factor representing a factor level of "low", "mid" or "high" and y_{o1}, y_{o2} and y_{o3} are the experimental outputs at the considered factor levels respectively. For example to calculate the effect of O_2 at 6 SCCM, to represent a "low" factor level of the oxygen flow, the output values can be substituted in Eq. (4.1) to give,

$$O_2\,(\text{Low}) = (209.91 + 68.43 + 9.48)/3 = 200.43.$$

The values are calculated and are summarized in Table 4.2.

From Table 4.2, it can be concluded that for the given levels of the factors, difference in the output value by varying O_2 is the highest. The effect of height difference is seen to have the least effect on the output.

Factors	Effect (Low) (nm)	Effect (Mid) (nm)	Effect (High) (nm)	Difference (nm)
O_2	209.91	68.43	9.48	200.43
Plasma Power	8.44	107.67	171.71	163.27
Height	36.96	78.08	172.78	135.82

Table 4.2: Effects of factors on the response.

4.2.2 Response Surface Design

The response surface method is used after the important factors are ascertained from the screening experiment. A response surface experiment is performed to create a prediction model to detect interactions among factors and optimize the process [71]. Some of the important characteristics and goals of a response surface design are as follows [70] [72]:

- Design a good fit of the model to the data and hit the target value continuously.
- Provide an estimate of the pure experimental error.
- Be insensitive to presence of outliers in the data.
- Be cost-effective.
- Reduce the variations in the process.

According to Telford [71], the response surface can be estimated as,

$$Y = \beta_0 + \sum_{i=1}^{p} \beta_i X_i + \sum_{i=1}^{p} \sum_{j=1}^{p} \beta_{ij} X_i X_j + \sum_{p=1}^{p} \beta_{ii} X_i^2 + e, \tag{4.2}$$

where

β_0 = the overall mean response,
β_i = the main effect for each factor $(i = 1, 2, ..., p)$,
β_{ij} = the two-way interaction between the ith and j^{th} factors, and
β_{ii} = the quadratic effect for the ith factor.

4.3 Factorial Experiments

When there are many input factors affecting a response, experimental design is performed using factorial experiments. The experiments involving the study of the effects of multiple input variables or factors on the experiment outcome or the response are called factorial experiments [75]. The easiest method to handle many factor problems is called One Factor At a Time (OFAT). In a OFAT experiment, the user or experimenter seeks to gain information about one factor in each experimental trial [75]. OFAT was used in earlier times to design experiments but its usage has decreased due to the following reasons [25] [75]:

- OFAT requires more runs to estimate the process model in comparison to factorial methods.
- Relations between the various input factors cannot be evaluated.
- In factorial methods, random experimental runs are made and OFAT plans can be susceptible to bias due to time trends.
- It is possible to miss the optimal settings of the factors to get the required response.

For all the reasons mentioned above, factorial design must be used instead of OFAT when there are several factors of interest in an experiment.

4.3.1 Types of factorial designs

Factorial experiments are more effective to detect interactions between factors, since the corners of design space needed for interactions are not considered by OFATs [65]. In each complete trial or replicate of the factorial experiment, all possible combination levels of the factors are investigated [30]. For a factorial experiment with three levels, the number of runs escalates from 27 to 729 as the number of factors increase from 3 to 6. For this reason, even though a full factorial design involves all possible treatment combinations, it involves many experimental runs which are not feasible with more factors. A fraction of the full factorials are thus chosen in an economical and efficient way and the design is called fractional factorial design. Fractional factorial designs with a higher resolution are desired and they require higher number of runs [30] [76]. There

can also be process settings that are not feasible or are impossible to run with a selected fractional factorial design [76]. In such cases, design types called optimal designs are more effective.

Optimal designs are computer aided designs that are based on a particular optimality criterion and are generally better for a specified model [77]. The design treatment runs that are generated by the algorithms are chosen from a set of possible treatment combinations [77]. This helps to ensure that all the runs specified by the models are feasible. D-optimal design or Determinant-optimal design is a type of computer-aided design based on a criterion to reduce the generalized variance of the parameter estimates of a pre-specified model [77]. D-optimal designs are independent of the model that needs to be estimated (first order with or without interactions, quadratic etc.). The model that needs to be estimated first needs to be specified for D-optimal designs and computer algorithms provide the optimal settings for the required runs [76].

4.3.2 Choosing the factorial design model

To choose an appropriate model type, knowledge of the factors is very essential. After the primary factors have been screened, it is common to consider the main effects of the factors. The response surface methodology discussed in Section 4.2.2 can be used to determine the shape of the effects and to check the significance of interaction and quadratic effects of the factors to be considered for design [71]. The main factors that influence the decision to choose the model type are the cost and resources needed for an experimental run. When high amount of time and money are involved for performing the experiment, the goal is to make the DOE with minimal amount of runs.

4.4 DOE with Cornerstone

At EIT2, DOE is performed by using the software tool *Cornerstone* developed by Camline Gmbh [78]. *Cornerstone* has a special focus on DOE and can be used for data analysis and model building [78]. *Cornerstone* has a simple user interface referred to as the “workmap” and the DOE module of *Cornerstone* can directly be accessed from the *Cornerstone workmap*.

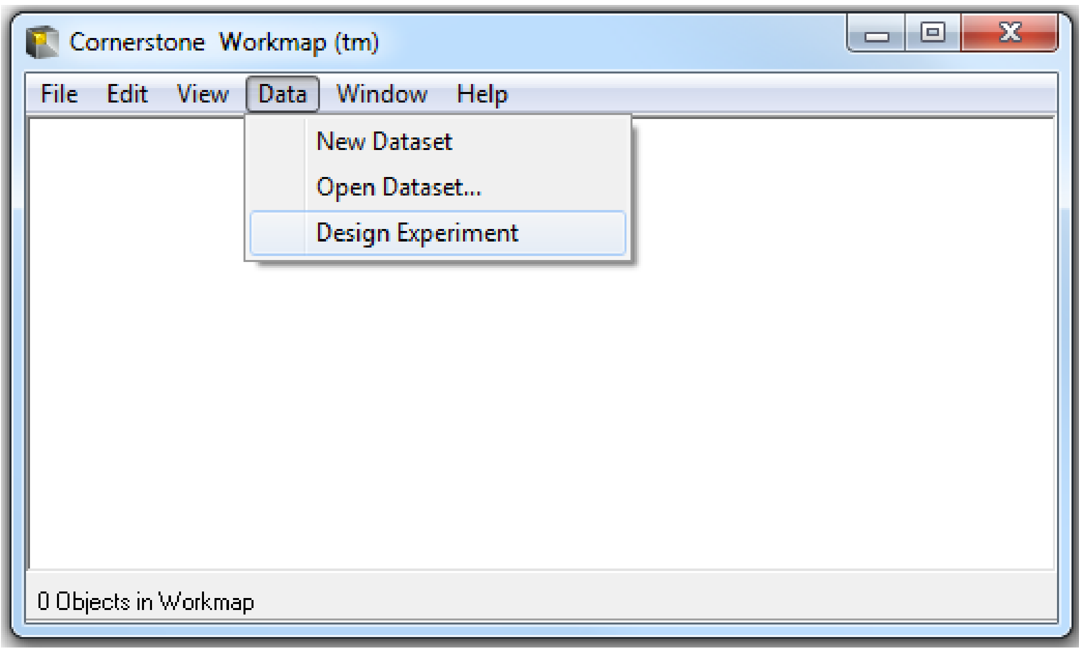


Figure 4.4: Cornerstone Workmap

The DOE section of *Cornerstone* can be selected directly from the "workmap" as shown in Figure 4.4. Before performing DOE, it is important to have a clear idea of the objective of the experiment, factors to be studied, conditions for conducting the experiment and a qualitative understanding of the data analysis [79]. The DOE tool *Cornerstone* is used with the recommended procedure for designing an experiment as summarized below [25] [79]:

4.4.1 Recognition of the problem

This stage involves soliciting information from all concerned parties connected to the process. A clear statement of the problem must then be prepared and the experiment objectives must be stated to understand the process better and find the eventual solution of the problem.

4.4.2 Choice of factors and levels

The factors to be varied in the experiment and the range over which the factors will be varied must be selected. A practical experience and theoretical understanding of the process is required. All the important factors required to obtain the desired result needs to be investigated. Process characterization must be

performed wherein the number of factor levels need to be kept low. In EIT2, the factors are defined for DOE with three levels pertaining to high, medium and low factor levels. The factors can be defined in the "Define" module of *Cornerstone* and is shown in Figure 4.5.

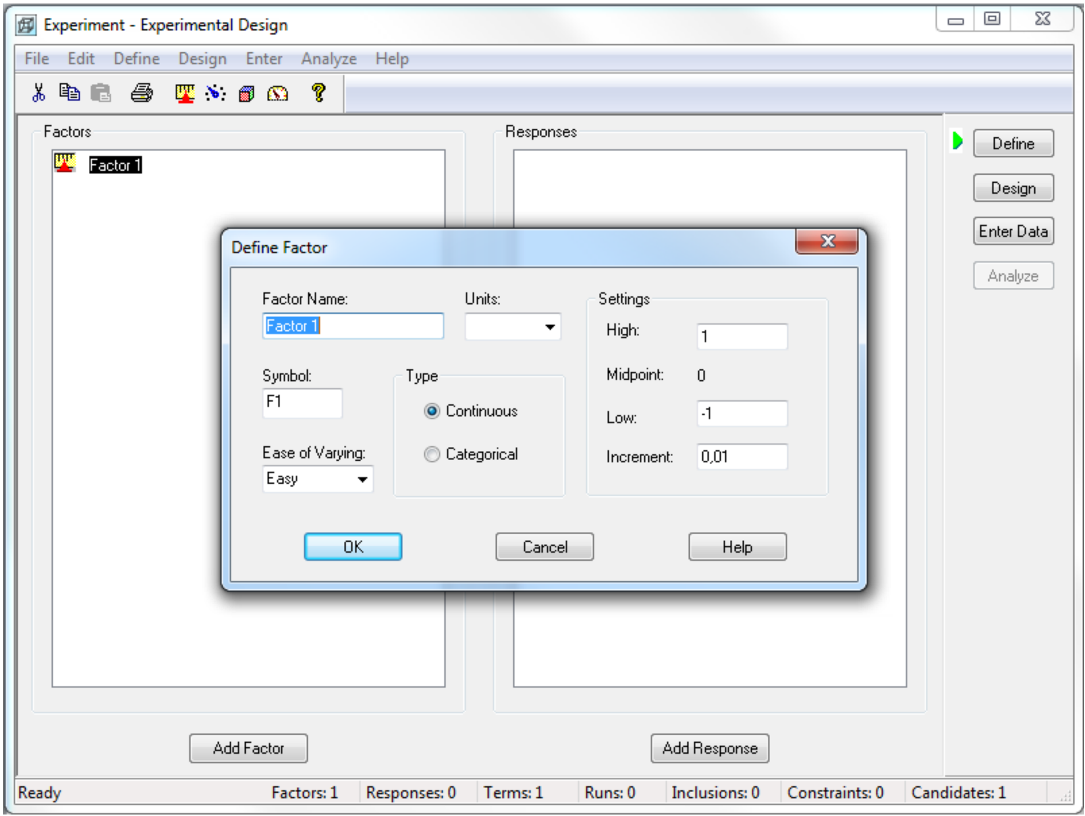


Figure 4.5: Define module of *Cornerstone* experimental design

Factors can be categorized as scaled/continuous factors and categorical factors. Continuous factors can be measured on a linear or non-linear scale and can take on positive or negative values [80]. In many situations, there are differences in trials that cannot be put on adequate scale like alternative equipment, different chemical substances or elements and material types. Such factors with discrete non scaled levels are called categorical factors [80].

The factors and responses are provided in the "Define" module of *Cornerstone* as shown in Figure 4.5. On clicking "Add Factor" button, a new factor is added. Double clicking the factor name, opens the "Define factor" screen as shown in Figure 4.5. The factor name, unit, symbol for representation and the type can be specified. The "Ease of Varying" text field is used to define whether

the variable or factor under consideration can be varied easily for a process. When an experiment is designed, the algorithm computes the sequence of experiments depending on its ease of factor variation. This means that for DOE, the experimenter needs to make less adjustments for the factor that is difficult to vary for subsequent experiments. The maximum and minimum levels for the factors can be specified in the fields under “Settings” for continuous factors as well as the different ranges for categorical factors.

4.4.3 Selection of the response variable

The variable that provides useful information of the process under study must be selected as the response variable. An average or standard deviation of the measured characteristic is generally used as a response variable [81]. Gage capability, which is the analysis of the variability associated with the repeatability and reproducibility of the measurements with an instrument [81] is an important factor. If gage capability is poor, then only relatively large factor effects will be detected by the experiment or additional replication will be required. The response variable can be added in the “Define” module of DOE and the “Define Response” dialog box can be selected by double clicking the added response name.

The “Define Response” dialog box is shown in Figure 4.6. The parameters for response name, symbol and units can be entered in this dialog box. The “Goal” field is used to specify the objective of the experiment. *Cornerstone* computes the optimized settings for the input factors to obtain the desired response using the DOE data. “Measurements per run” field is used to specify the number of measurements that are taken on a sample at the end of each experiment. Selecting “Multiple” option activates the “Analyze” field. Parameters like mean, variance, standard deviation etc. of the measured output value can be analyzed by selecting the equivalent option if “Multiple” option is selected for “Measurements per run”. The specification limits of the required response can also be provided in the corresponding section.

It is also possible to specify constraints during the design phase for the factors from within this section. Constraints can be provided to *Cornerstone* by users to define the points that are excluded from the D-optimal designs; used to define which points are excluded during optimization of the responses. The

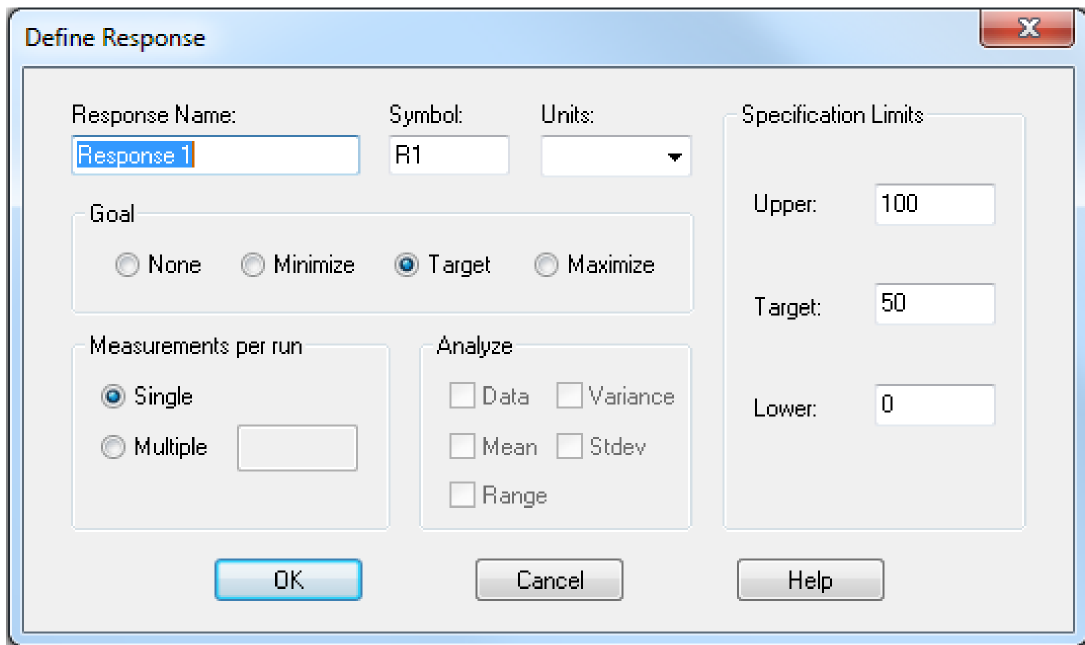


Figure 4.6: Define Response dialog box of *Cornerstone* experimental design

combinations of input factors with which an experiment cannot be performed can be specified as constraints, so that these settings are not generated for DOE.

4.4.4 Choice of experimental design

Choice of design involves consideration of sample size or the number of replicates, selection of a suitable run order for the experimental trials and whether blocking or other restrictions are involved. The "Design" toolbox of *Cornerstone* can be used for experimental design. It consists of fields for specifying the model type and design type which are shown in Figure 4.7.

The "Model Type" can be selected depending on the conditions given in Section 4.3.2. In Figure 4.7, an "Interaction model" is selected and four factors are specified for the experiment. Based on this information, the tool computed four "main effects" or "linear effects" and six "interaction effects" in the model. In the "Design" module, the "Run order" can be specified to perform the experimental runs as randomized, standard or according to the ease of varying the factor levels. Selecting the "Change Design" option first opens the dialog-box where the maximum and minimum number of runs can be specified. This in-

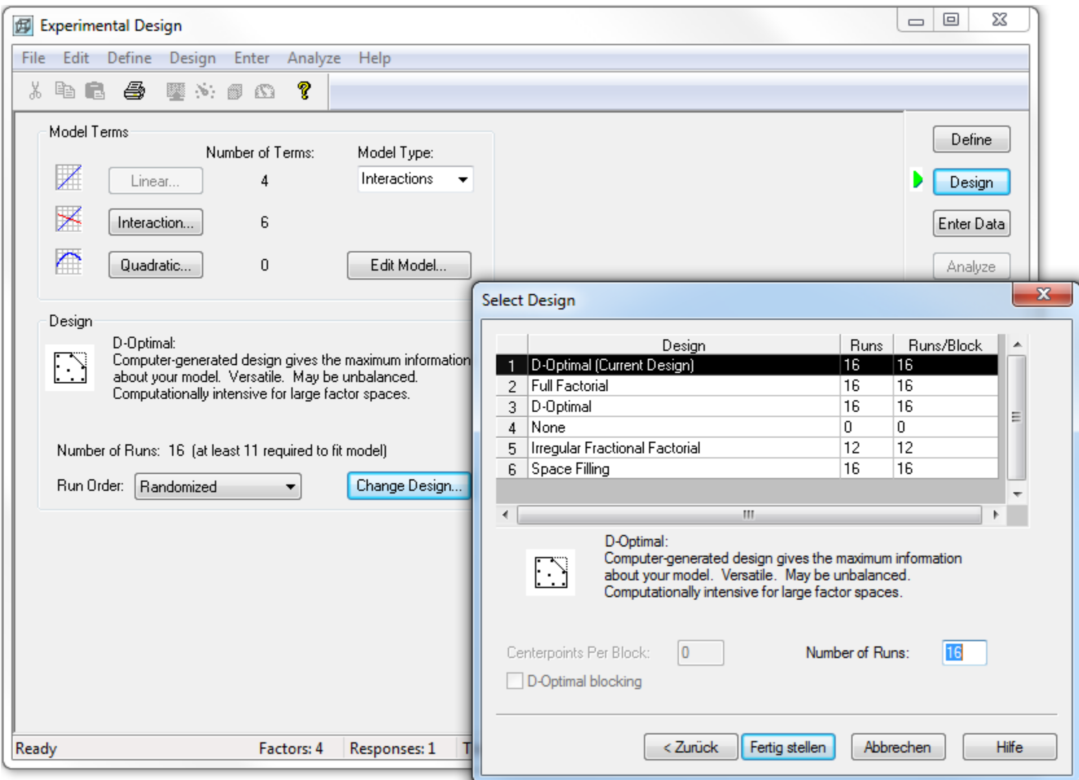


Figure 4.7: Design module of *Cornerstone* experimental design

formation is used to generate the possible design types. The block size can also be specified in this area wherein the experimental runs can be divided into homogeneous blocks. The next page opens the “Select Design” dialog-box shown on the lower right in Figure 4.7. A number of design types are made available for selection depending on the number of factors and the type of factors specified. An option to select “None” exists, wherein the user can manually enter the specifications for the experimental runs. For DOE tests aimed at reducing the output variability in the process, the D-optimized design is recommended [77] and will be used in this study. The number of runs can also be specified if the user requires higher or lower runs from the recommended number of runs. An option called “Inclusion”, which is accessible from the “Design” drop down menu is available. With this option, it is possible to enter any previously completed runs to the design. By including the previously conducted experiments along with the recommended runs, the accuracy of the model is improved [86]. Also, the additional number of runs needed to estimate the selected model are reduced if the user wants to perform only the required number of experiments.

4.4.5 Performing the experiment

Once all the previous stages have been carried out, the actual experimental run can be made. The actual process needs to be monitored carefully to ensure that each step is made according to plan. The experimental procedures must be performed as per the requirements and necessary precautions must be taken to prevent error sources that could nullify the validity of the experiment. In *Cornerstone*, the sequences of experimental runs are provided by accessing the "Enter Data" module shown in Figure 4.8.

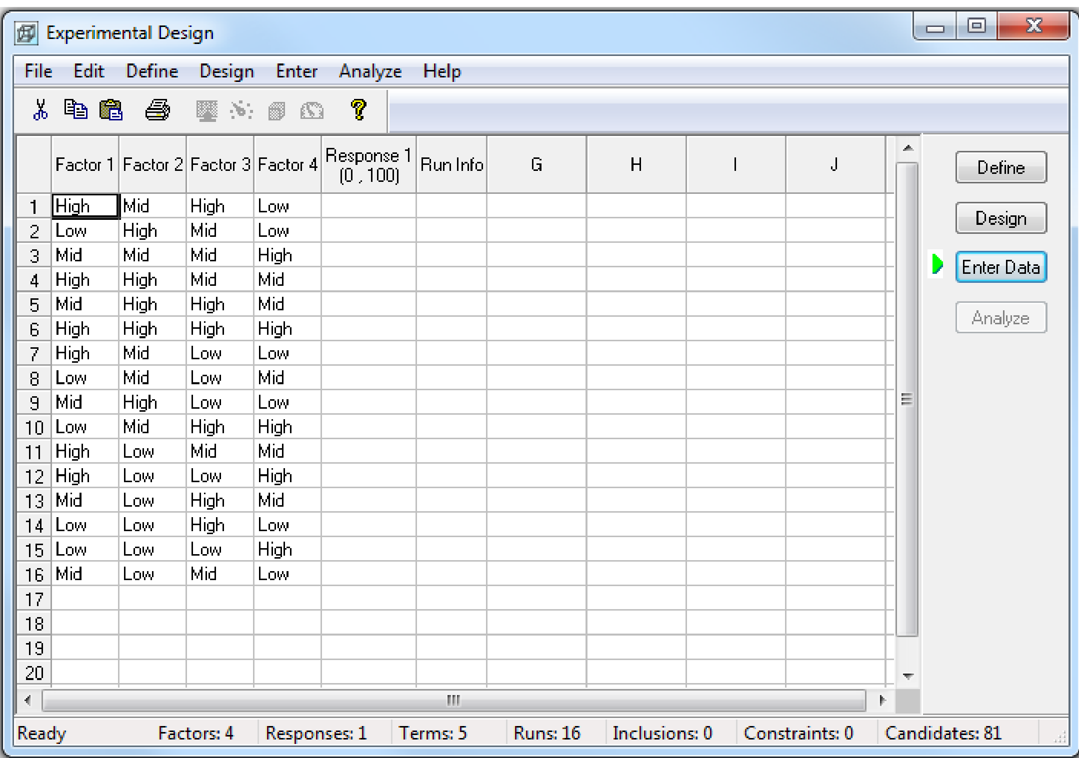


Figure 4.8: Enter Data module of *Cornerstone* experimental design

Figure 4.8 shows the "Enter Data" window where the specifications of the experimental runs are provided to the experimenter. The settings here are shown for an experimental design with four categorical factors and three variation levels within a factor. The experimenter is required to perform the runs in the run order specified and enter the results in the "Response" field. Any other information about the run can be provided in the "Run Info" field. Additional runs that are deemed necessary can also be appended into the run list and their responses can be provided. Once all the experimental runs have been successfully

completed and the responses are noted, the "Analyze" option will be activated automatically. Clicking the "Analyze" button opens the window where data analysis can be performed.

4.4.6 Data Analysis

To arrive at conclusions and results of the DOE objectives, statistical methods must be used to analyze the data. The type of statistical methods required is not complicated if the experiments are designed correctly and performed according to the design. Regression analysis is one of the most widely used techniques for multi-factor data analysis and is a statistical technique for investigating and modeling the relationship between variables [82]. An important objective of regression analysis is to estimate the unknown parameters in the regression model and this process is called fitting the model to the data [82]. Once a model is simulated, model adequacy checking is done where the appropriateness of the model is studied and the quality of fit is determined [82]. The RMS error is used to measure the difference between the value predicted by the model and the observed value [65]. R-square or coefficient of determination indicates the quality of fit of the data points to the statistical model and depending on its value, the model is adopted or modified to improve the fit [82].

The "Analyze" module of *Cornerstone* contains options to assist in data interpretation. Regression analysis is performed on the dataset and a table is generated which lists the factors and their significance along with the R-square and RMS error. The "Analyze" module with the available options is shown in Figure 4.9.

As seen in Figure 4.9, *Cornerstone* allows five data analysis options.

- "Coefficients table" shows the coefficients and their standard error for each term.
- "Effects Graph" shows the effects of each factor towards the output. It is very useful in screening experiments to identify the most important factors that contribute towards the output and filter out the less significant factors.
- "Interaction graph" is used to see the interaction between the input factors.

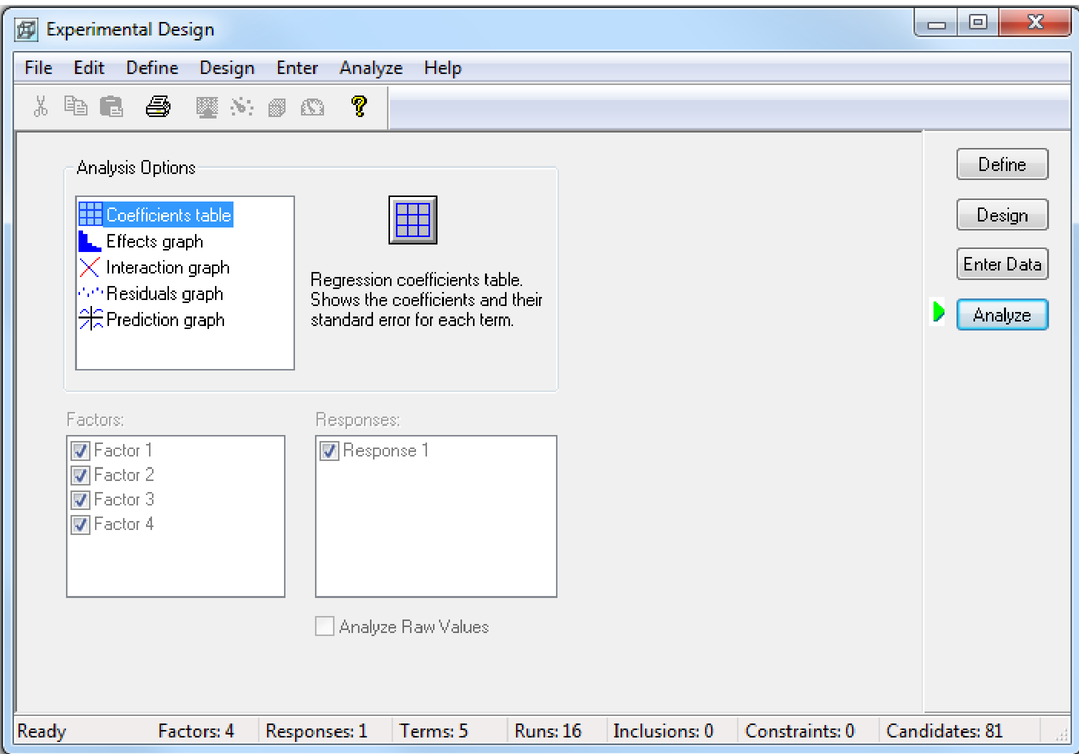


Figure 4.9: Data analysis options in *Cornerstone*

- "Residuals graph" plots the residuals on the vertical axis and the run numbers on the horizontal axis. It helps to determine the model which estimates the response better [82]. If the points in a residual plot are randomly dispersed around the horizontal axis, a linear regression model is appropriate for the data; otherwise, a non-linear model is appropriate [83].

- "Prediction graph" shows the response graph for the given input settings of the factor. An experimenter is able to determine the output with the specified input factor combinations along with the confidence intervals for the output prediction. The term "confidence interval" indicates the amount of uncertainty with which output can be predicted [65]. *Cornerstone* includes an option called "optimize" in the prediction graph to determine the optimum input settings to perform an experiment to get the required response with the least amount of variation.

The "Analysis option" for data analysis, shown in Figure 4.9, provided by *Cornerstone* generates the "Regression coefficients table".

The "Regression coefficients table" lists the significance of each input factor

for obtaining the output response as shown in Figure 4.10. Values of R-square and RMS errors are also listed in the table. R-square indicates the goodness of fit of the model and RMS error is a measure of how accurately the model predicts the response [84]. A lower value of RMS error indicates a better fit [84]. Plots and summaries of the dataset can be generated in the regression module by opening the "Graphs" and "Summaries" tabs in the menu bar of the module displayed in Figure 4.10.

Other graphs that are used in the data analysis from the "Regression" module are the

- Residual probability plot.
- Box-Cox transformation plot.

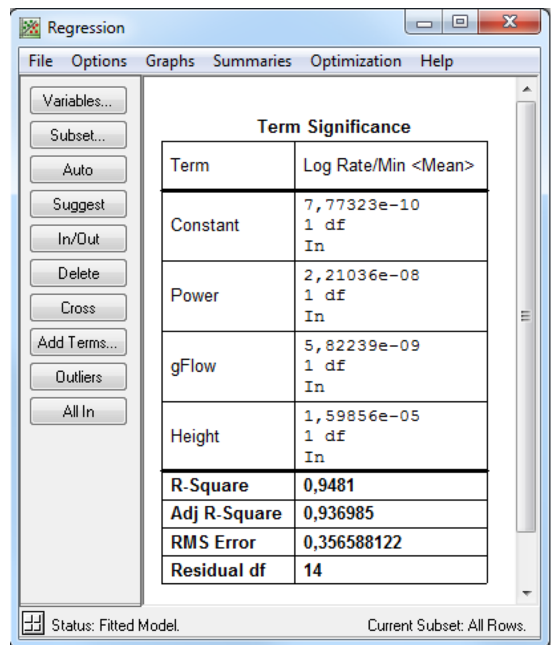


Figure 4.10: Regression module of *Cornerstone*

The plots can be accessed from the "Graphs" menu in the regression module that is seen in Figure 4.10. The residuals probability plot helps to determine how the error terms are distributed. If the error terms are normally distributed then a straight line can be drawn through the points [85] and outliers, which are the points that deviate markedly from the other points can be identified.

"BoxCox" transformation plot helps to measure the normality of the plot and indicates if a different type of transformation would result in a better fitting model [65]. However, RMS error value must not be the only deciding factor for a Box-Cox transformation [65]. The user is able to identify a better fit based on the process knowledge in addition to the RMS error value and can then select the transformation that offers the least RMS error. The prediction graph can also be accessed which shows the output prediction for the input factor values. The user is able to drag the line corresponding to each of the input factors in the prediction graph and determine the output response. Alternatively, if a

target value and goal is specified in the “Define” segment of the “Experiment” module, the “Optimize” option available from “Options” tab can be used. The “Optimize” option helps to automatically specify the input settings for obtaining the specified output. The output is optimized by keeping the variations in the output prediction low while considering the constraints specified for the experiment. The predicted output graph is generated with additional data points by performing more runs than the required minimum number of trial runs to fit the model. Performing higher number of runs generates a better experimental model that improves the accuracy of the output prediction [86].

4.4.7 Analysis of Variance (ANOVA)

After DOE is performed and an appropriate model is simulated with the factors and responses, actual runs can be performed on the equipment used for the study. The prediction graph from *Cornerstone* can also be used to determine the input factor settings for obtaining the required response. However, there would be differences in the predicted and the actual output data from the process due to statistical errors in the model. While performing multiple runs with the same input settings, differences in the values of the response are observed. The scatter, spread or variability in a distribution is expressed by the variance σ^2 and is defined as [25]:

$$\sigma^2 = \begin{cases} \int_{-\infty}^{\infty} (x-\mu)^2 f(x)\,dx, & x \text{ continuous} \\ \sum_{i=1}^{\infty} (x_i-\mu)^2 p(x_i), & x \text{ discrete} \end{cases} \tag{4.3}$$

Experimental runs are performed in groups consisting of a fixed number of runs over a period of time. ANOVA test is used to compare the difference between the different groups of the experimental runs [87]. The groups are made independent and ANOVA test analyses the variance if the means are unequal [87] [88]. ANOVA is done for data analysis but is used mainly for categorical factors in contrast with regression analysis that is used for continuous factors [65]. When one or two categorical factors are analyzed at a time, it is referred to as one-way or two-way ANOVA respectively [88].

4.4.8 Conclusions and recommendations of DOE

After the data has been analyzed, the practical conclusions about the results must be drawn and a course of action must be recommended. The results must be presented to all the concerned parties connected with the process. Follow-up runs and confirmation testing should also be performed to validate the conclusions from the experiment.

Chapter 5

Data analysis

Chapter 4 provides some insights into data analysis using the experimental design. This chapter focusses on data analysis and process control on the actual experimental data. Statistical process control tools and the analysis of process capability are explained. A data analysis tool called *DataEntry* which is a constituent of the QMS and developed at EIT2 is also presented in this chapter. This tool functions as a logbook for the equipment and helps to monitor the reliability issues with the equipment when the equipment is used for multiple processes.

5.1 Introduction to Statistical Process Control (SPC)

The key objective of a manufacturing process is to produce a high quality product. The variability of all the intermediate processes in the production must be reduced to ensure that the product meets its required specifications. Statistical process control refers to a powerful collection of problem-solving tools used to achieve process stability and reduce variability [89]. From an industry standpoint, usage of SPC aims to reduce the variations in the products, delivery times in materials and the attitude of people involved [90]. SPC is vital, since incapable and inconsistent processes render even the best designs unacceptable [90].

5.2 SPC Tools

Variations exist in every process and they need to be understood in order to be managed. SPC can be applied to any process and its seven major tools are [90] [91]:

- Process flowcharts (to understand what is done).
- Check sheets (to check how often it is done).
- Cause and effect or fishbone diagrams (to determine what causes the problem).
- Histogram (pictorial representation of the variations).
- Pareto chart (for prioritizing the variations).
- Scatter diagram (to explore the relationships in variations).
- Control chart (to monitor the variations over time).

These tools are intended to make statistical analysis less complicated and to provide good visual aids to make statistical and quality controls more comprehensive.

5.2.1 Process flowcharts

A flowchart is a means of visually presenting the flow of data through an information processing system [92]. Flowcharts assist in providing a better understanding of the system or process under study [90] and helps to identify areas for improvement. Flowcharts can also serve as the documentation of a new process that aid in the identification of design flaws and hence prevent problems once the new process is put into use. A team working on process improvement can use the flowcharts to analyze and document their findings to identify [90]:

- Problems and weaknesses with the current system.
- Unnecessary stages or duplication of effort.
- Objectives of the improvement effort.

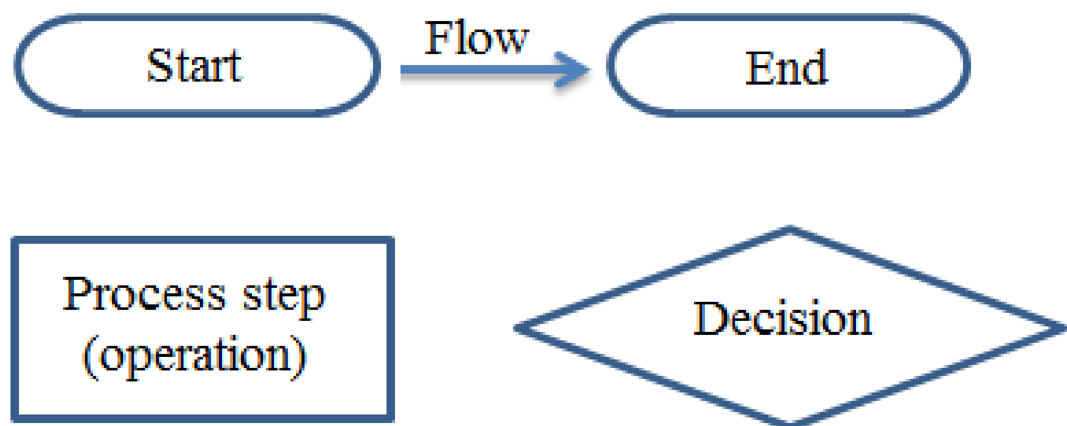


Figure 5.1: Commonly used flowchart symbols

The most common flowchart symbols that are used are shown in Figure 5.1. By using the flowcharts, knowledge of the various levels of a process is improved which can in turn be used to improve the overall process. A flowchart helps to identify unnecessary components in a process that can be removed to reduce wastage of resources.

5.2.2 Check Sheets

Data forms the basis of analysis, decision and action of a process and it is often necessary to collect historical or current operating data about a process under investigation. Check sheet is a tool to aid data collection activity [25]. Check sheets allow data to be collected in an easy, systematic and organized manner. Check sheet is generally a form designed for easy and efficient recording of the required information. The information is mainly collected to identify the actual situation of the process. Opportunities for process improvements are based on information obtained from the data collected in the process. For check sheets to be beneficial, it is important that the collected data is accurate and relevant to the process issue that is being analyzed [92]. A data collection plan is devised in order to collect reliable data and serves the following purposes [92]:

- Establish the purpose of data collection.
- Define the type of data that will be collected.
- Determine who will collect the data and when the data will be collected.

The check sheet is used to collect data at the location where the data is generated in real time and are classified into five types [92]:

- Classification check sheet (To reflect traits like mistakes or failures).
- Location check sheet (Physical location of the trait).
- Frequency check sheet (Shows absence or presence of a trait and number of occurrences).
- Measurement check sheets (Indicates measure on a scale divided by intervals).
- Check list (List with items to be performed like a to-do list).

5.2.3 Cause and effect or fishbone diagrams

In some situations when the causes of process variation are not known, cause-and-effect diagram is a formal tool employed to examine the potential causes [25]. A cause and effect diagram has two sides called the effect side and the cause side. The right side in the diagram lists the problem under consideration and the primary causes of the problem are listed on the left hand side of the diagram [92]. Fishbone diagrams helps to identify, explore and graphically display all the possible causes related to a certain effect in a process. The steps in constructing the cause-and-effect diagrams are as follows [25]:

- Define the problem or effect that needs to be analyzed.
- Create a team of users to perform the analysis. This is to aid in brainstorming to discover potential causes.
- Draw the effect box on the right hand side of the diagram and a center line to list the causes on the left side of the center line.
- Specify major potential cause categories and connect them as boxes to the center line.
- Identify possible causes and categorize them into the major cause categories listed in the previous step. New categories can be created if needed.

- Categorize the causes by priority to identify the ones that are most likely to impact the problem.
- Take corrective action.

The tool serves to define the problem, identify possible and probable causes and highlight the major causes.

5.2.4 Histogram

A histogram is a specialized type of bar chart used to graphically summarize and display the distribution of a process data set [92].

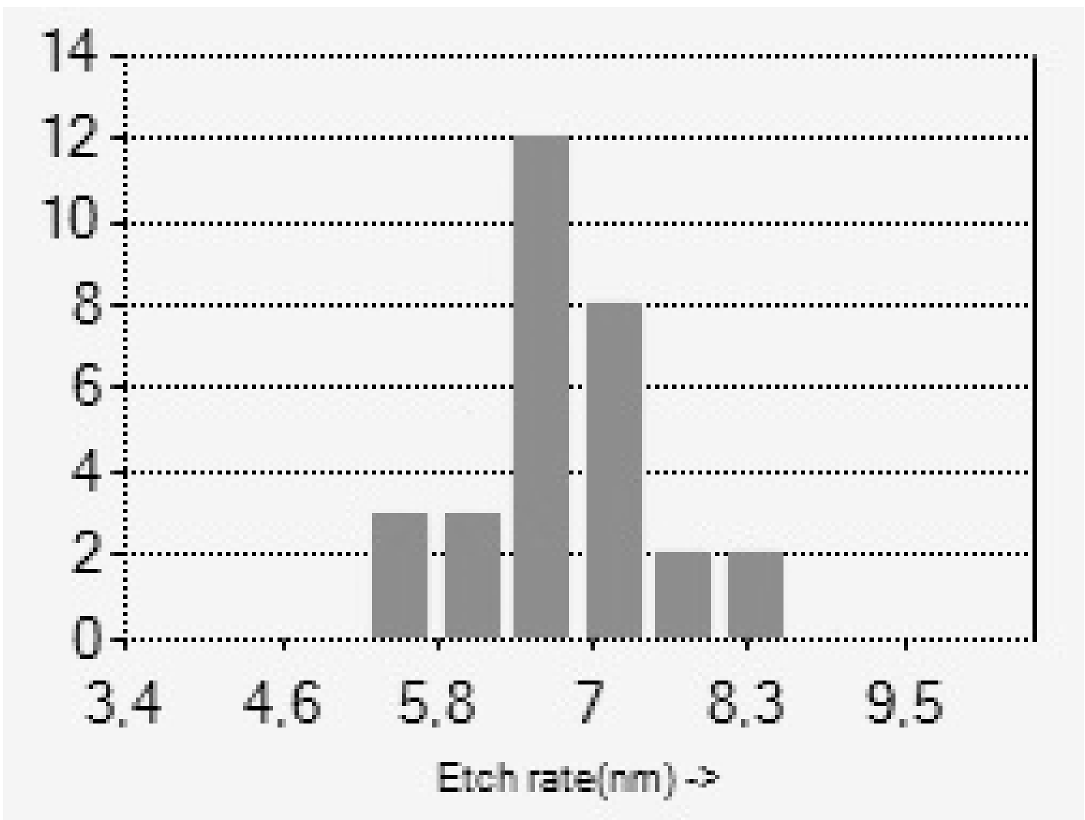


Figure 5.2: Bar chart showing the distribution of etch rate as output parameter [15]

A histogram illustrates the centering, spread and shape of the distribution points of the data and helps to address the following questions [92]:

- What is the most common system response?

- What type of distribution is possessed by the data?
- Is the data symmetric or skewed to the left or right?
- Does the data contain outliers?

An example of a bar chart with the response data from the plasma etcher for a predefined standard setting is shown in Figure 5.2.The bar chart illustrates the distribution of the etch rate in nanometers per minute performed at the standard setting defined for SPC on the Technics plasma etcher. The etch rate in nanometers per minute is shown on the X-axis and the number of output points falling in the range on the Y-axis. This helps the experimenter to determine whether the output falls around the 7nm range for the given input setting.

5.2.5 Pareto chart

Pareto chart is a frequency distribution or histogram of attribute data arranged by their importance [25]. It is difficult to tackle all the issues affecting a process or a product and Pareto charts helps prioritize the issues that need to be addressed [92]. Pareto charts are used to find out the most frequently occurring issues in a product or process under consideration. By making use of DOE, Pareto charts are used at EIT2 to display the most significant factors affecting the response. Therefore, the experimenter is able to visually identify the most important factors. The "Effects Pareto chart" of DOE tool *Cornerstone* is used at EIT2 for Pareto analysis. An example using the data from the Technics plasma etcher is shown in Figure 5.3.

Figure 5.3 is the "Effects graph" taken from the "Analyze" section of *Cornerstone* described in section 4.4.6. The model considered here is a quadratic model with second order effects and interaction effects taken for every factor. Since the etch rate decreases with an increase in the flow of O_2 (represented by gFlow), its effect is shown as negative on the graph. Taking the absolute values of the terms, it can be deduced that the main effects are O_2 flow, power setting of the plasma etcher and height of the sample from the base of the plasma chamber. These factors along with the interaction effect of O_2-flow and Power are the important factors which affect the output response.

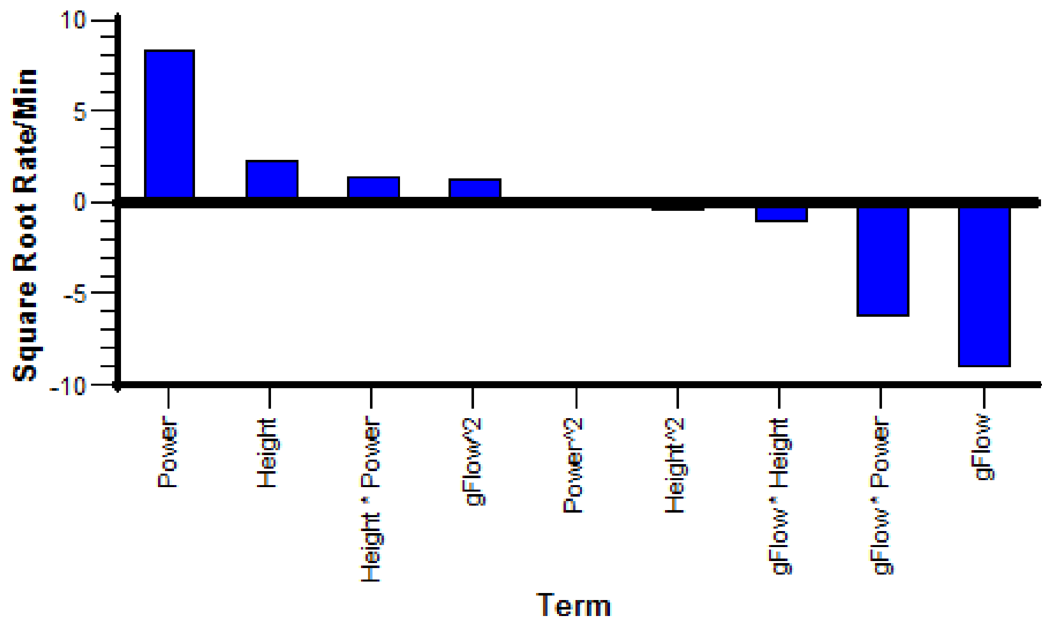


Figure 5.3: Effects Pareto chart of Technics plasma etcher

5.2.6 Scatter diagram

Scatter diagrams are used to identify a potential relationship between two variables. The shape of the scatter diagrams often indicates the type of relationship that exists between the two variables. The interaction graph of *Cornerstone* (discussed in section 4.4.6 of Chapter 4) serves to find the relationship between the factors. The relationship can be positive, negative or none. For a positive correlation, the data points are clustered along a trend line with an upward slope [92] and along a downward slope to indicate negative correlation. When the data points are scattered, then no correlation exists between the variables.

5.2.7 Control Charts

One of the prime SPC tools is control chart and by making use of control charts, variability in the process can be analyzed and controlled [91]. The occurrence of shifts in process performance are detected using control charts so that corrective actions may be taken to bring an incorrectly behaving manufacturing process back under control [89]. This is necessary to ensure that the manufacturing process is stable, repeatable and yields products with acceptable performance.

Bissel [93] listed four aspects pertaining to the use of control charts:

- To measure the performance of the process. Control charts indicate the extent to which the process is stable or *in control* and indicate the presence of special causes of variation.

- To indicate deviations from target conditions permitting prompt correction or investigation of the reasons for the deviation from target performance.

- To provide the pointers necessary for improving the process performance in terms of process yield, capability to a specification, reduced interruption levels or other aspects.

- To continue the flow of information relevant to maintaining control and making decisions related to process.

Sources of variation

In any production process, there is a high probability of variation that is inherent or natural. This natural variability is the effect of many small but unavoidable causes regardless of how well the process is designed. In statistical quality control, this variability is called a stable system of common causes and a process operating with only common causes is said to be in statistical control [25]. A second kind of variability arises from improperly adjusted or controlled machines, errors from experimenter, or with the material used for the process. This variability is significantly larger than the variability due to common causes and is called special cause variability [25]. A process that operates in the presence of assignable causes is said to be *out of control* [25].

Components of a control chart

The schematic of a typical control chart is shown in Figure 5.4. The chart displays a quality characteristic that has been measured from a sample plotted with respect to time. The basic elements of the chart are [89]:

- A centerline corresponding to the process average or mean of the measured characteristic of a process.

- An upper and lower control limit represented as UCL and LCL respectively. These control limits are selected such that the entire sample points will lie between them if a process is in statistical control.

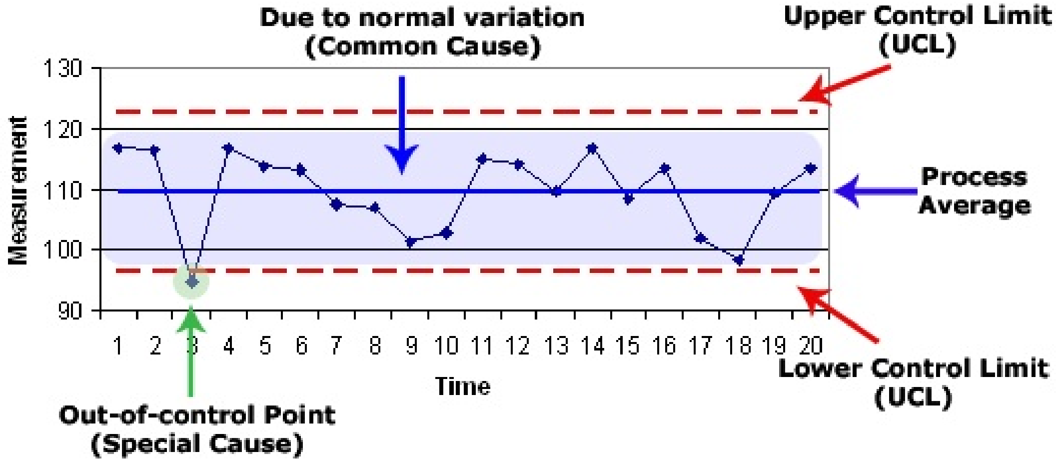


Figure 5.4: SPC control chart [94]

The control limits (UCL and LCL) are taken at three times the standard deviation (σ) from the mean value. Value of σ is calculated from the available sample data. The common cause and special cause of variation are also shown in the chart. Since the measured value due to the special cause lies outside the control limits, the point is referred to as *out of control* point. There are some patterns in a control chart that indicates an *out of control* state for the process. In order to detect such non-random patterns, a set of rules are provided in Western Electric Statistical Quality Control Handbook [95]. These guidelines state that a process is out-of-control if [95] [89]:

- Any point lies outside the control limits or 3σ limits.
- Two out of three consecutive points lie outside the 2σ limits.
- Four out of five consecutive points lie beyond the 1σ limit. Nine consecutive points lie on the same side of the centerline.
- Six consecutive points increase or decrease.
- Fourteen consecutive points alternate up and down.
- Fifteen consecutive points lie on either side within the 1σ limit.

Types of control charts

Control charts are associated with attributes of data and continuous variables [96]. The attribute charts are used to monitor the incidence of particular occurrences of an event. The groups for the attributes are taken periodically and the incidences of the attributes are counted and compared to the control limits. The control limits in the chart are generally based on an initial sample of similar groups. An example of this is an attribute chart to count the number of defective devices in a lot of a particular product type.

The control chart for continuous variables is used when the fitness for use of an item considered is a function of one or more numerical dimensions as it can be represented numerically [96]. In quality control environments, variable charts are more common [96] since in most cases they can provide more information regarding manufacturing process performance than attribute control charts [89]. Control chart of the mean is achieved using a chart called the $\bar{x}$ chart and the variance is monitored using either the standard deviation (s chart) or the range (R chart) [89].

Calculation of control chart elements

The calculation of the parameters below applies to continuous variable control charts. If x_1, x_2, ..., x_n are the readings taken from an experiment then, the basic elements of the control chart are calculated using the formulae given below [89]: Mean

$$\mu = \frac{(x_1 + x_2 + \cdots + x_n)}{n},$$

where n is the total number of experiments and standard deviation is

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}}$$

The Upper Control Limits and Lower Control Limits are given by $UCL = \mu + 3\sigma$ and $LCL = \mu - 3\sigma$.

Special conditions in control charts

In control charts, it must be noted that there are circumstances when the conditions for an *in control* process maybe violated even though no special cause is

present. This is referred to as the Type I error leading to a false alarm and a corrective action may prove to be unnecessary [93]. There are also cases in which a special cause may be present but may not be indicated due to interference with a common cause. This is referred to as a Type II error and can result in a poor quality process occurring until an out-of-control condition is satisfied [93]. When following a control chart for process monitoring and control, the existence of these risks must be noted. Using the readings from the control charts and the historical data, the experimenter is able to identify the likelihood of a Type I or Type II error to avoid over-control and under-control of the process. An average of the last few readings must be used rather than individual values for making adjustments when an out-of-control case is identified. Another option is to set warning limits and recheck the sample if warning limits are violated or use readings from the next sample before the process is declared out-of-control [97].

Using control charts in a research lab

Type I and type II errors were also seen at EIT2 and the frequency of their occurrences were high. A reason for this is due to the fact that in a research institute, the processes that are performed on the equipment are often varied unlike in the industry where the process parameters are not usually varied. This issue is further discussed in section 5.4.1.

5.3 Process capability

Control chart is seen as a good indicator for determining the process stability. Control charts can also be used as an estimation tool where certain process parameters such as the mean, standard deviation, fraction non-conformance etc. can be estimated from a control chart of a process that are in statistical control [25].

Another determinable quantity using control charts is process capability. A process capability index is a numerical summary that compares the behavior of a product or process characteristic to engineering specifications [98]. Process capability quantifies what a process can accomplish when it is *in control* [89]. The capability indices are represented by C_p and C_{pk}. The probable process capability, C_p indicates the spread of data within control limits and C_{pk} or

the actual process capability indicates how centered the process is with respect to mean [25]. From an industry standpoint, a good process capability index is obligatory for a product to meet customer requirements [99]. It must be ensured that the manufacturing process under consideration is *in control*, since capability figures are applicable only to a process which is in a state of statistical control [25]. Even if a process has poor capability but is in statistical control, then process capability can be improved by reducing the variability [89] [100]. The probable and actual process capability figures are calculated using the formulae below [89]: Process capability

$$C_p = \frac{(USL - LSL)}{6\sigma}$$

Process Capability

$$C_{pk} = \min\left(\frac{(USL - \mu)}{3\sigma}, \frac{(\mu - LSL)}{3\sigma}\right)$$

Here μ is the mean of the current process output, σ is the standard deviation and LSL and USL are the lower and upper specification limits. Specification limits are the tolerances from the mean value that are allowed for a response. The specification limits differ from the control limits and are externally imposed on the manufacturing process, whereas control limits are derived from natural variations inherent in the process [89].

When a set of specifications about a process are obtained from a customer, the process parameters must be varied to reflect the requirements of the new process. After the changes are made for the new process, the process capability study indicates if the process is capable or incapable. If the process is incapable, steps are taken to identify the parameters that make the process incapable. Once the parameters that cause the incapability are identified and corrected, SPC charts are established for the new process to understand, control and improve the key process parameters causing the variations [101].

An example showing the difference between control limits and specification limits is illustrated in Figure 5.5. The equipment used is the Technics plasma etcher. The mean of the equipment at a specified factor setting is specified as Mean (Tool). The upper and lower control limits that are calculated are given as UCL (Tool) and LCL (Tool). The process output that is required by a customer is shown as Mean (Cus). The lower and upper tolerance values that are allowed

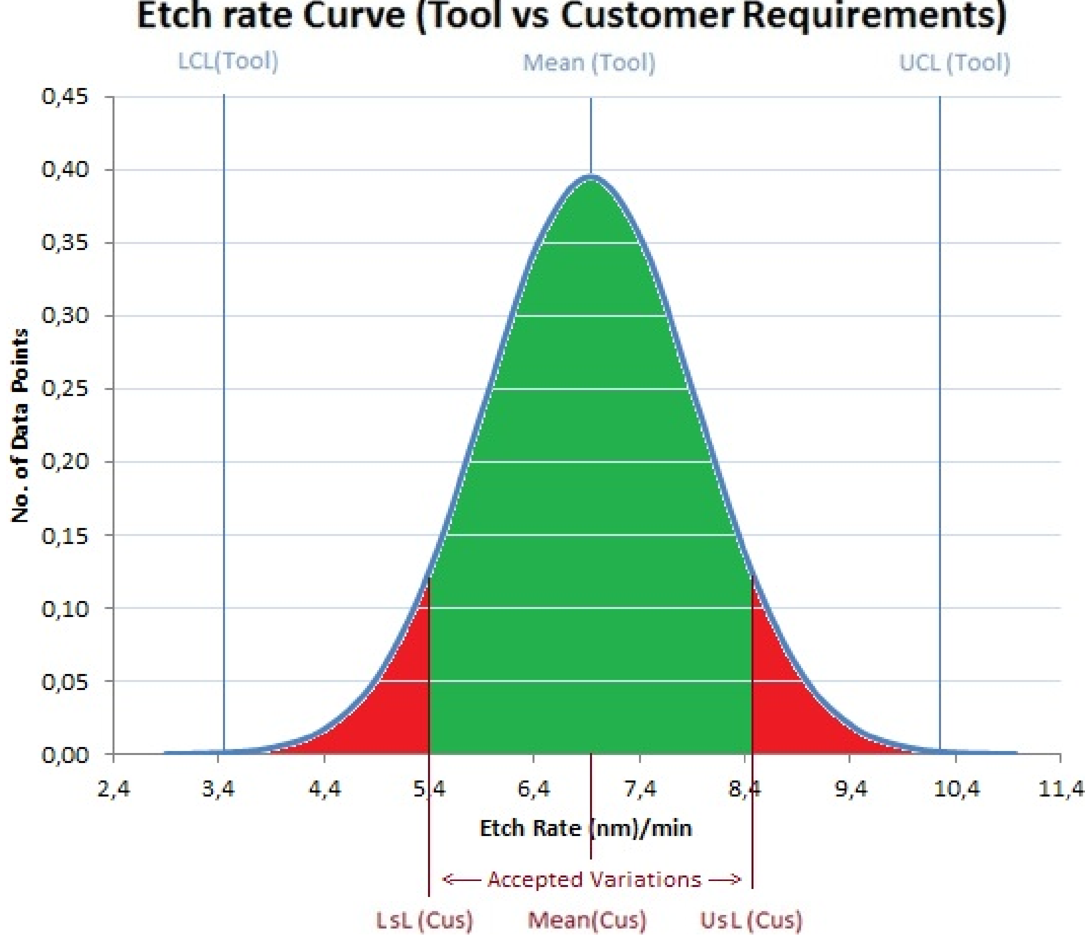


Figure 5.5: Control limits and specification limits

by the customer are given as LSL (Cus) and USL (Cus). As can be seen from Figure 5.5, the current process variability is more than customer tolerances. The products with the measured output that falls outside the customer specifications are not accepted. That implies that in Figure 5.5, only products with the output indicated in the green area on the normal curve would be accepted and the remaining products will be disposed. A process capability study would deem the current process incapable. The process must thus be improved to meet the specification limits. The following are some of the benefits of process capability studies [101] modified to reflect semiconductor manufacturing:

- Acquiring of process knowledge that will facilitate problem solving and introduction of new processes.
- It provides the means to easily qualify new materials for the process that

may or may not be utilizable in case of product variation. When a new material is considered, a process capability study can be performed comparing the results using the new material and the existing material.

- Some new product lines and associated processes may quickly be determined to be unstable or incapable and not ready for production.

Another advantage of using the process capability studies is to obtain the numerical quantity to determine the capability of the process. In Figure 5.5, the process can be termed a capable process only when the normal curve of the current process lies within the specification limits. The value of C_p and more importantly C_{pk} determines the capability of the process in satisfying requirements. The difference in the probable and actual process capability for four processes is shown in Figure 5.6.

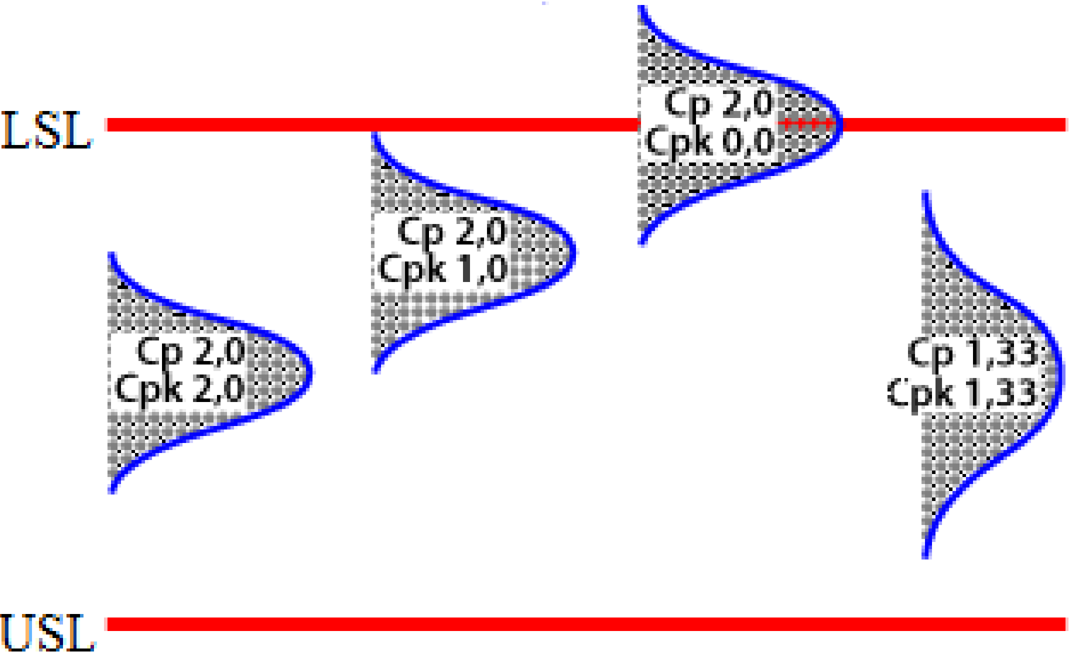


Figure 5.6: Process capability index [102]

It is seen from Figure 5.6 that a higher value of C_{pk} translates to a better process. In this regard, the normal curve of the process shown on the extreme right in Figure 5.6 is considered to be a better process compared to the second and third processes (from left) in spite of having a wider curve. The process curve is set to exactly the middle of the tolerance range if C_{pk} equals C_p [102].

The process can be classified in terms of its sigma limits. Table 5.1 shows the C_{pk} values and the corresponding sigma levels [103].

C_{pk}	**Sigma level**	**Yield**
0.33	1σ	68.27%
0.67	2σ	95.45%
1.00	3σ	99.73%
1.33	4σ	99.99%
1.67	5σ	99.9999%
2.00	6σ	99.9999998%

Table 5.1: Sigma levels corresponding to capability index

A good process must have a C_{pk} that is more than 1.33 [102]. A C_{pk} value of more than 1.33 would translate to 99.99% of the process output falling within the specification limits. A continuous improvement program in manufacturing industries must achieve a C_{pk} greater than 2.

5.4 Pre-requisites for process control

Before the SPC operation is commenced and the usage of control charts for process control is introduced, the following points need to be noted [93]:

- Establish priorities through problem solving techniques like Pareto charts and cause/effect diagrams.

- Decide the parameter to measure or observe. The parameter must be chosen with relevance to end-use and not ease of measurement.

- Setup a system for data collection. Information must be provided to experimenter regarding how, where and when to measure the output response. A log sheet of the process parameters must also be included that might help in the identification of special causes of variation.

- Obtain initial data on the process and record it in the format that will be used for routine SPC records.

5.4.1 Issues in research institutes

In a large scale manufacturing industry, processes are generally not varied. The output would be independent of past processes under normal circumstances when process parameters and operating conditions are not varied. The differences between the industry and a research institute are highlighted in Table 1.2. In a research institute, the number of equipment available are usually limited [14]. This is also true in the case of EIT2. The equipment limitation results in many processes to be made on the available equipment. An example is that of an oxidation furnace that is used to produce a thin layer of oxide on the silicon wafer surface. In an oxidation furnace, the typical processes performed are wet oxidation, dry oxidation and annealing. Table 5.2 gives a list of some of the available equipment and typical processes for which they are used.

Equipment list	Possible Processes
CVD	Oxidation, Nitridation
Oxidation furnace	Wet Oxidation, dry oxidation and annealing
Plasma etcher	Metal, Insulator and plastic etching
Si CVD	Epi Si, poly Si, α Si and doping (POCl)

Table 5.2: The list of available equipment and processes made on them

When multiple processes were simultaneously performed with the same equipment at EIT2, process variations were seen to be higher. It was observed that some equipment shows a higher variation when a process is performed after another process with different specifications. The case study using the oxidation furnace and the plasma etcher is made and the results are summarized in Chapter 6.

5.5 Development of a data analysis tool

In view of the differences between a research institute and industry, a software tool was required to measure the process capability in a research institute. The tool takes into account of the variations in process specifications. The tool caters to the different scenario existing in a research institute, specifically the situation

wherein the current processes depend on past processes. A data analysis tool developed at EIT2 consists of 2 main sections for "entering data" and "viewing the process statistics". The tool is referred to as *DataEntry* and was developed in *Visual Basic 2010* [104].

Figure 5.7: Interface screen of the *DataEntry* tool

The interface screen of the *DataEntry* tool with the 2 main options to enter the data for a new experiment and to view the process statistics are shown in Figure 5.7. *DataEntry* tool was developed as a standalone application and is accessible from the internal server of EIT2 by clicking on the shortcut link available in the desktop of the laboratory PCs. It does not require any installation and runs on any PC with Windows OS and having .NET framework 4.0 [105] or later installed. Instructions on installing .NET framework is available from Microsoft website [106].

5.5.1 Logging experimental data

An important function of the *DataEntry* tool is to enter data about the equipment in EIT2. In the institute, the log data of the process is entered into a logbook after completion of the experiment. The logbooks are placed next to the corresponding equipment in the laboratories and cleanrooms. Users have to enter the experimental data manually into the equipment logbook after completing the experiment. Some of the issues using a paper based logbook are:

- Difficulty in performing data analysis: The data is not available online.

To perform any sort of data analysis, the experimenter has to manually enter the data into the network, which requires a considerable amount of time.

- Costs: Due to stringent cleanliness requirements in cleanrooms, special kinds of paper have to be used in the cleanrooms for the logbook that are expensive.

To facilitate data analysis, *DataEntry* tool serves as an electronic logbook. On clicking the “New experiment” button, users are directed into a form to enter the data. A screenshot of the form with the different sections is shown in Figure 5.8.

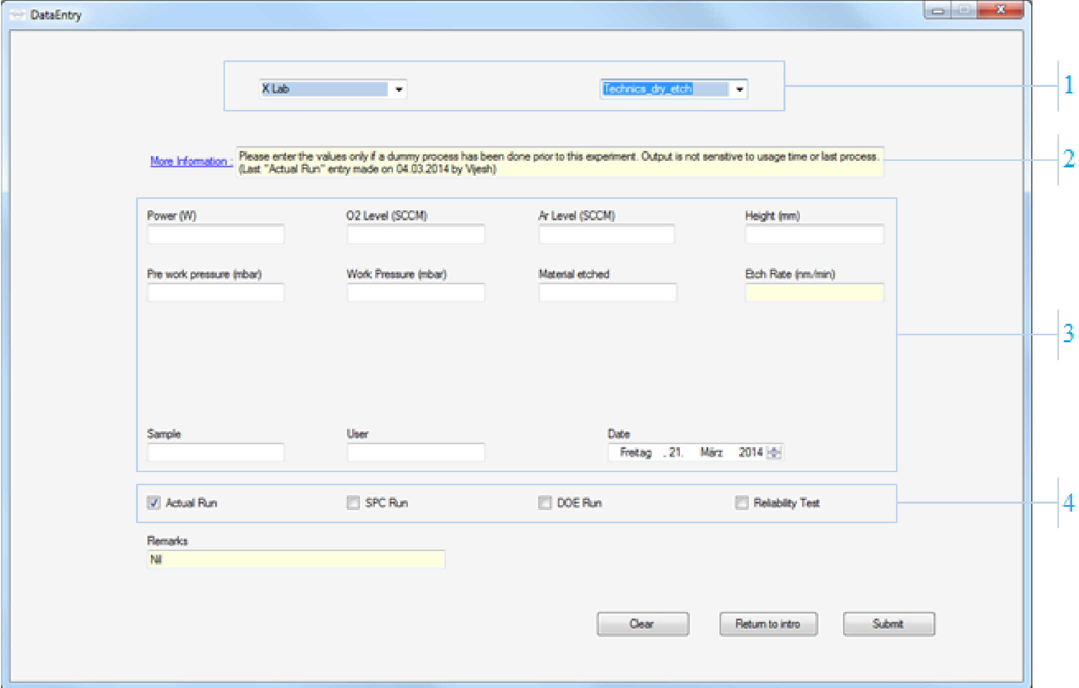


Figure 5.8: New Experiment form in *DataEntry* tool

The different sections of the “New Experiment” form are numbered in Figure 5.8.

- Segment 1 is used to enter the laboratory name and the equipment name using the drop down list. The laboratory name needs to be selected first and the list of available equipment will be updated in the equipment list depending on the laboratory selected.

- Segment 2 provides specific information about the selected equipment. The text box serves to inform the experimenter about issues that need to be taken care of before performing a process or experiment with the selected equipment. If necessary, the segment also provides information of the last process made on the equipment. The "More information" link redirects to the equipment folder in the institute database.

- Segment 3 contains the input fields where the experimenter can enter the process specifications including the factors and the response(s). This segment is also updated depending on the equipment selected. The fields must be filled after the completion of an experiment.

- Segment 4 is used to specify the experiment or run type. "Actual Run" is the default selection and should be selected when a regular experiment is performed with the equipment. "SPC run" must be selected when the experiment performed is a standard process with predefined settings. The settings for the factors are automatically filled in the input fields on selection of SPC run. Selection of "DOE run" must be made when the experimenter is required to make an experimental design. On selection of this option, a button called "Design of Experiment" is made visible. The button redirects to a form providing an overview of DOE concepts and also provides brief instructions to perform experimental designs using the DOE tool *Cornerstone*. The software *Cornerstone* can also be directly opened from the page. The "Reliability test" option is used to get an overview of the reliability and stability data of the selected equipment.

After filling in the input fields at the end of an actual or SPC run, the submit button needs to be clicked. The application makes a basic check of the entered data like the usage of invalid characters or if non-numerical characters are entered in a field where numerical characters are required. The fields with errors are highlighted and the experimenter is asked to recheck the entered data. After the corrections are made, the data would be accepted by the application and would be appended to the equipment specific logbook in the internal server.

5.5.2 Storing experimental data

The data from the *DataEntry* tool is stored in a separate folder in the internal server called "louie". The folder can be accessed from within the institute by opening "*louie**rummel**dataentry*\". The folder consists of 2 subfolders for the logged data and specification files. It also contains the shortcut for the *DataEntry* tool to access the application from the network. The "Log" folder is where the logbooks from the equipment are stored. It consists of the subfolders for the laboratories and the corresponding equipment logbook listed in them.

The second folder named "specification files" contains the necessary files for *DataEntry* to work. The files can be modified by selected users to add a new equipment without understanding the program flow of the *DataEntry* application. The folder is a protected folder accessible only to specified users. The file "Path_specification.txt" is the most important file that *DataEntry* uses to obtain the locations of the specification files. "Path_specification.txt" is a text file and the contents are shown in Figure 5.9.

Input File path:
\\louie\rummel\dataentry\specification files\Input.csv

Output Folder path:
\\louie\rummel\dataentry\Log

SPC File path:
\\louie\rummel\dataentry\specification files\Input_standardprocess.csv

Cornerstone Location
C:

Reliability Data File Path:
\\louie\rummel\dataentry\specification files\Reliability_Test.csv

Figure 5.9: View of Path specification text file

The file and folder locations are specified in "Path_specification.txt" file. The files mentioned in figure 5.9 are explained below.

- "Input file path" specifies the location of the input file that contains the laboratory names, list of equipment in the laboratory and the names of the factors and responses pertinent to the equipment. The input factors shown in this file specifies the number of text fields in "New experiment" form of *DataEntry* (Segment 3 of Figure 5.8). The information available

in Segment 2 of the form is also provided corresponding to the equipment within this file. The file can also be used to accept multiple outputs and to generate a wafer map if needed. With this feature, the outputs at the different sections of a wafer can be entered.

- The "Output folder path" specifies where the equipment log-data needs to be saved. The actual test data is saved by the equipment name at the location and in Comma Separated Values (csv) [107] format. For example, the data from oxidation furnace is available at: "*\\louie\rummel\dataentry\Log\XLab\Oxidation_furnace.csv*". The data for the SPC test of the equipment has a similar naming convention but followed by a "_StdProcess" at the end of the filename.

- *Cornerstone* location can also be specified to open *Cornerstone* from within *DataEntry* application.

The file locations namely "Input file path", "SPC file path" and "Reliability Data File path" are generated by the file "Input.xlsm". "Input.xlsm" is a macro enabled excel file [107] that contains three worksheets for generating the files at the three file paths given in Table 5.3. Data about the equipment can be entered in the Excel table within the file. An example is provided in Table 5.3.

Lab	Equipment	Input1	Input2	Input3	⋯	O/p	Remarks	Link
X Lab	Annealing furnace	Gas	Temperature (°C)	Process Time (min)	⋯	Nil		

Table 5.3: Input specifications worksheet table

Any addition of equipment to the list is made using a "New Entry" button located on top of the table in each of the worksheets. This is to ensure that the data is entered correctly. For equipment, where there is no output quantity that can easily be measured, the output field is given as "Nil" as is the case with the Annealing furnace given in Table 5.3. On clicking the "Save" button in the worksheet, the worksheets are saved as separate csv files at the location specified in Figure 5.9. These csv files are then used by *DataEntry* to generate the equipment list and its input parameters as well as the specification limits

for the SPC charts and the reliability test. The Reliability test option can be selected in the Section 4 of the New Experiment form given in Figure 5.8. On selecting the option, a button named “Reliability check” would be visible that can be used to access the pages for Reliability and Stability test of the selected equipment in “New Experiment” screen.

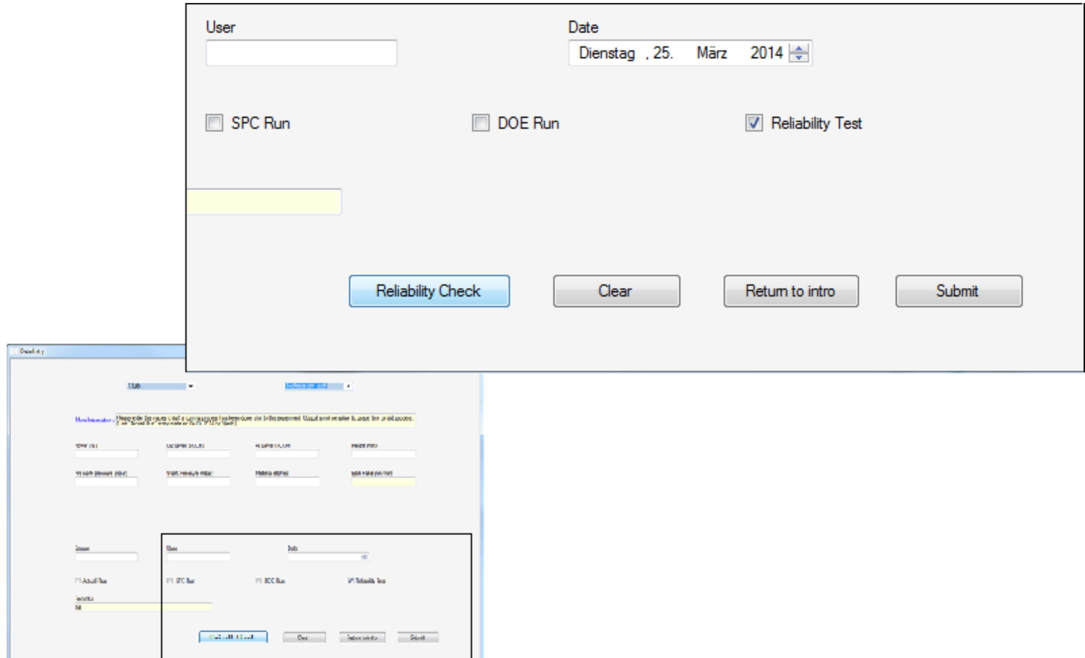


Figure 5.10: New Page form with Reliability Test option enlarged

On clicking the “Reliability check” button shown in Figure 5.10, an instruction sheet is opened that explains the reliability and stability data and charts. Instructions about performing the reliability tests, as well as a brief explanation of the four kinds of processes that are done for the reliability analysis of the equipment are also provided. Clicking the “Overview” button in this sheet redirects to the overview page shown in Figure 5.11.

The reliability and stability studies of the equipment under changes in the operating conditions of the equipment are shown in Figure 5.11. Therefore, different operating conditions are defined as processes for each of the equipment and its stability charts are generated. The stability charts are plotted chronologically in which the experimental runs are performed. In Figure 5.11, four different processes are defined within which the equipment is generally operated.

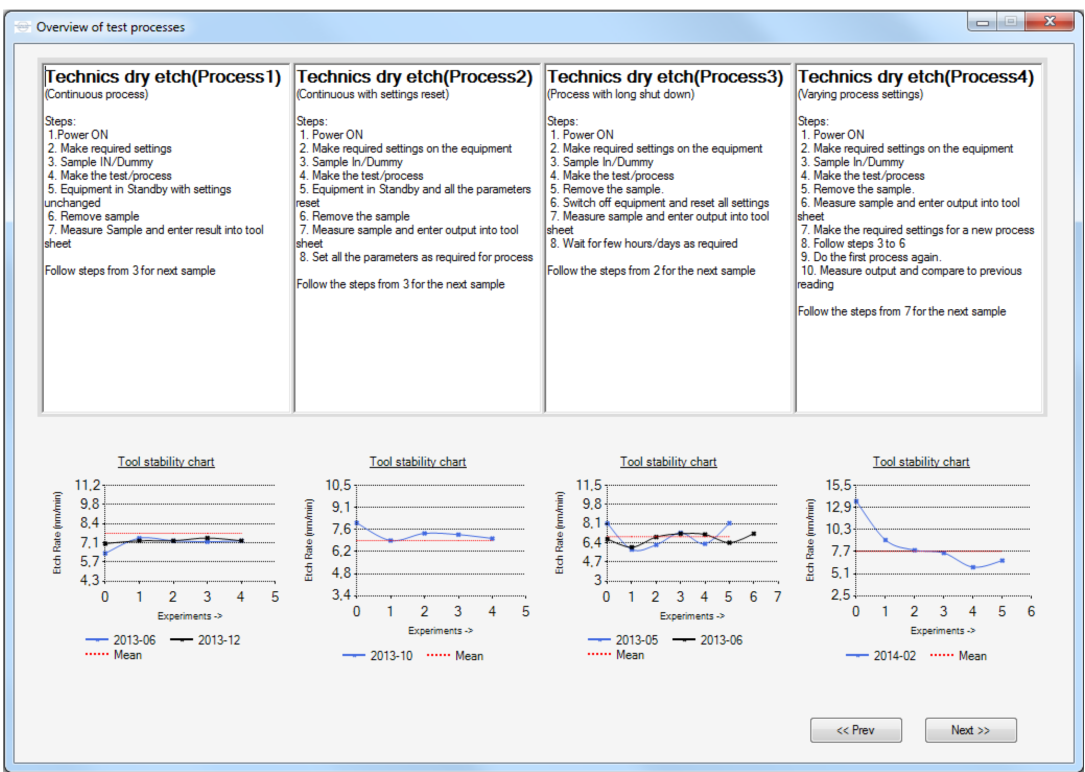


Figure 5.11: Overview page with reliability process instructions and Equipment stability chart

- Process 1 or Continuous process: In this setting, the equipment is operated on a continuous basis. After completion of every process, the subsequent process is performed without varying the settings or turning off the equipment. This is similar to equipment usage in the semiconductor manufacturing industry.

- Process 2 or Continuous process with settings reset: Process 2 is similar to process 1 with the difference that the equipment settings are reset after every process. The equipment is then reset to the required specifications and the subsequent process is made. This test is made to check if the equipment settings always give a true indication of the actual values. This test is mainly aimed at checking older equipment having knobs to adjust the settings.

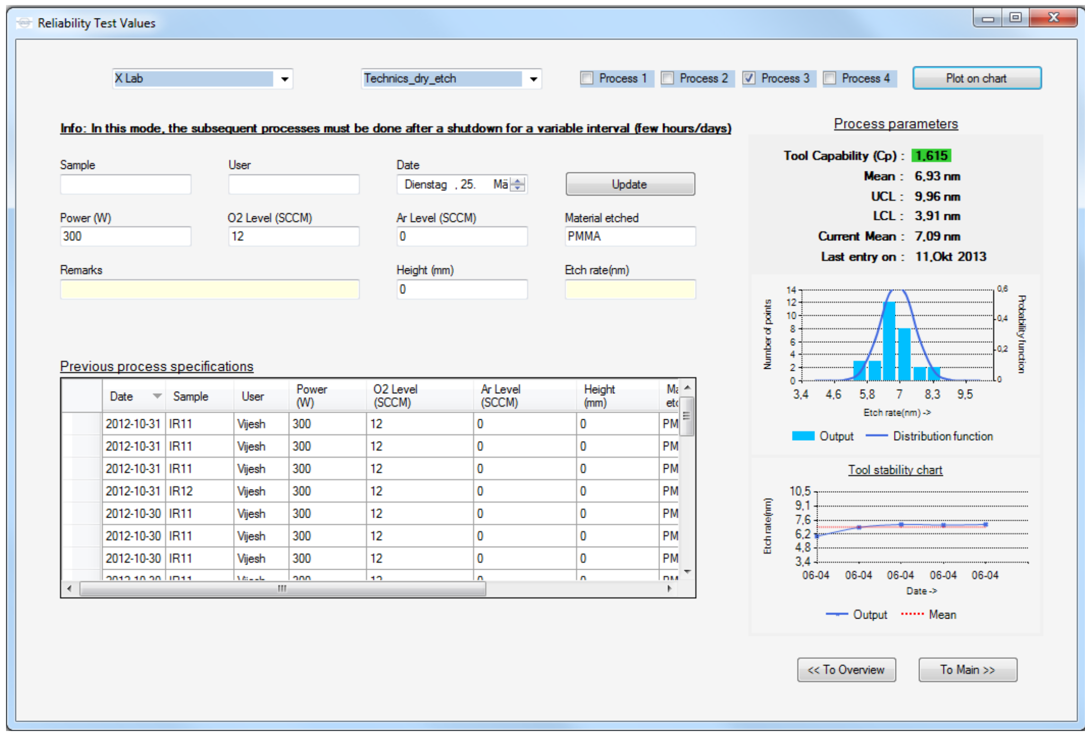
- Process 3 or process with long shutdown: Process 3 is performed to check the long term reliability of the equipment. In this case a process is per-

formed on the equipment and the equipment is switched off for a non-specific time period. The test helps to find out if the equipment is capable of producing a consistent output even after a long delay or if it requires a few initial runs before the output is stable.

- Process 4 or Process with varying process settings: Process 4 helps to identify the dependence of the output on the past processes. In this test, different processes are performed on the same equipment. The processes are performed at different conditions or using different materials and the output of the standard process is checked and plotted on the stability chart.

The data for generating the reliability and stability charts are available from “*\\louie\Rummel\dataentry\Log\XLab\ReliabilityTest*”. The process steps are also extracted from user generated text files available in “Instructions” sub-folder in the “Reliability Test” folder. Reliability Test form is accessible from the “Overview” page and can be opened on clicking the “Next” button. The form can be used to check previous process specifications for reliability test and to view the data variations depending on the process specified in the Overview form. “Reliability Test” form also contains the input sections to enter the data for the tests performed with a specific process type. On selecting the process name, the input factors are automatically entered and an information bar is displayed with a brief instruction on the type of test associated with the selected process. The mean and the control limits of the data corresponding to the process are also updated.

On clicking the “Plot on Chart” button located at the top right of the form shown in Figure 5.12, the additional details of the process type are displayed. The mean of the current dataset is calculated which is used to compute and display the process capability C_p. The process specifications of the previous processes performed on the equipment are also extracted and tabulated as illustrated in Figure 5.12. By default, the data is arranged by date of entry of experimental values and can be changed depending on the parameter provided in the column name. The experimenter can enter the data if an experiment has been completed and update the information into reliability test file available on the internal server “louie”.



Date	Sample	User	Power (W)	O2 Level (SCCM)	Ar Level (SCCM)	Height (mm)	Ma etc
2012-10-31	IR11	Vijesh	300	12	0	0	PM
2012-10-31	IR11	Vijesh	300	12	0	0	PM
2012-10-31	IR11	Vijesh	300	12	0	0	PM
2012-10-31	IR12	Vijesh	300	12	0	0	PM
2012-10-30	IR11	Vijesh	300	12	0	0	PM
2012-10-30	IR11	Vijesh	300	12	0	0	PM
2012-10-30	IR11	Vijesh	300	12	0	0	PM

Figure 5.12: Reliability test data of Technics Plasma etcher

5.5.3 Monitoring process data

In most of the processes performed at EIT2, the quality of the process is characterized by the relationship between a response variable and the factors. Control charts are best suited to identify process quality issues in such cases [108]. The control charts for the institute processes can be accessed from the "View Statistics" form and accessible from the initialization screen of *DataEntry* shown in Figure 5.7. A form is loaded with drop-down menus for selecting the laboratory and equipment list. The equipment usage history in a particular laboratory can be accessed by selecting the required laboratory name in the drop-down list and clicking on the "Overview" button in the form. The form given in Figure 5.13 is loaded that lists the available equipment in the selected laboratory and provides information when the data was last updated on the tool.

The form shown in Figure 5.13 is configured to read the data from the logbook of the equipment and the last date of entry would be taken as the last date of equipment usage. Color codes are given to indicate the recentness of the equipment usage. A green color indicates that the equipment was used within the last two weeks. The yellow color is given to equipment that was used be-

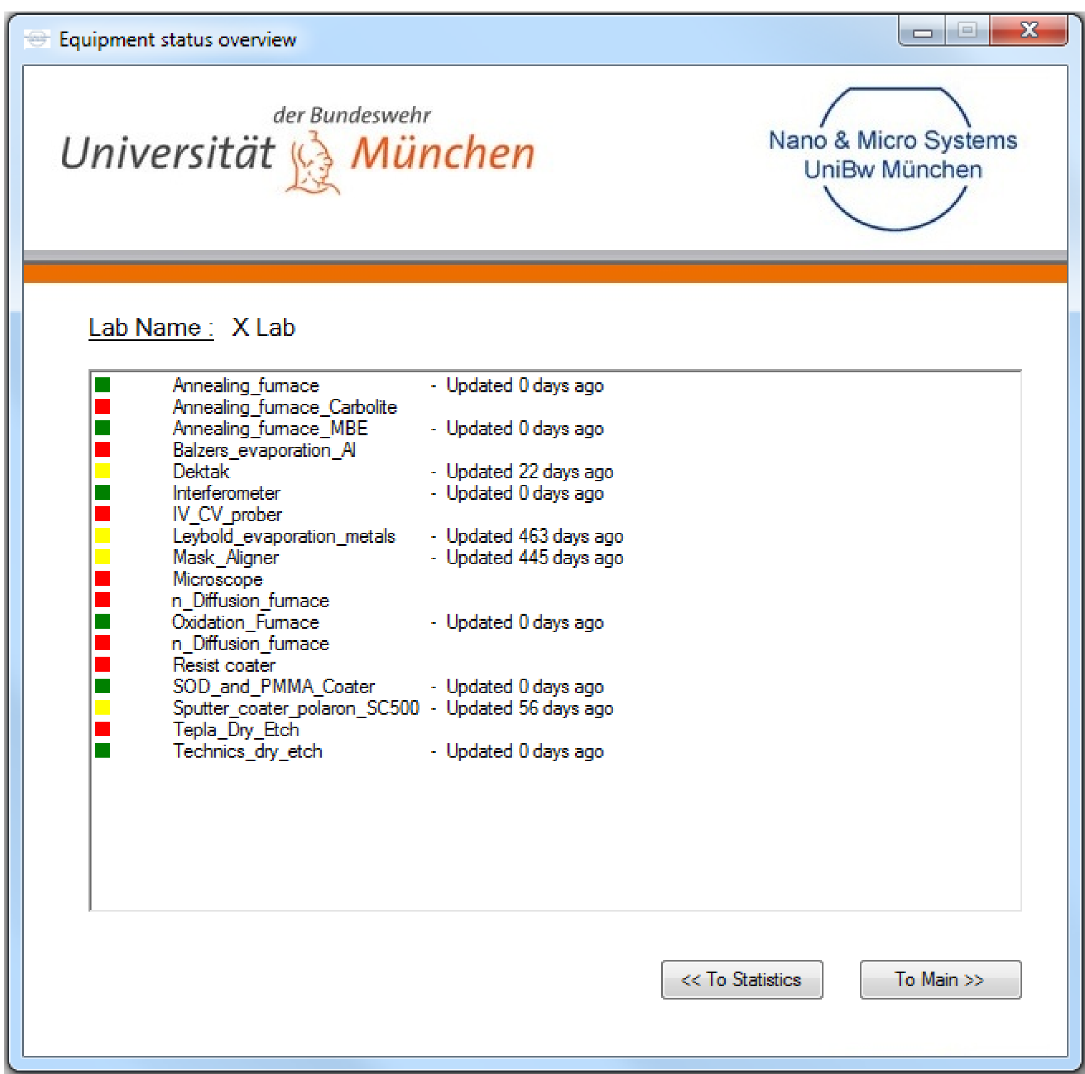


Figure 5.13: Equipment status overview form

tween two weeks and 2 years. A red color is given to the equipment that has not been used for more than 2 years or if no data about the equipment is available in the internal server. Clicking the “To Statistics” button of the form reloads the previous statistics form. Selecting the equipment name from the drop-down list of the Statistics form alters the name of the “Overview” button to “View”. Clicking the View button updates the form with the control charts and process specifications of the selected equipment. The updated form is shown in Figure 5.14.

The Process statistics form, shown in Figure 5.14, contains the control chart of a predefined standard process for the selected equipment. The logbook of

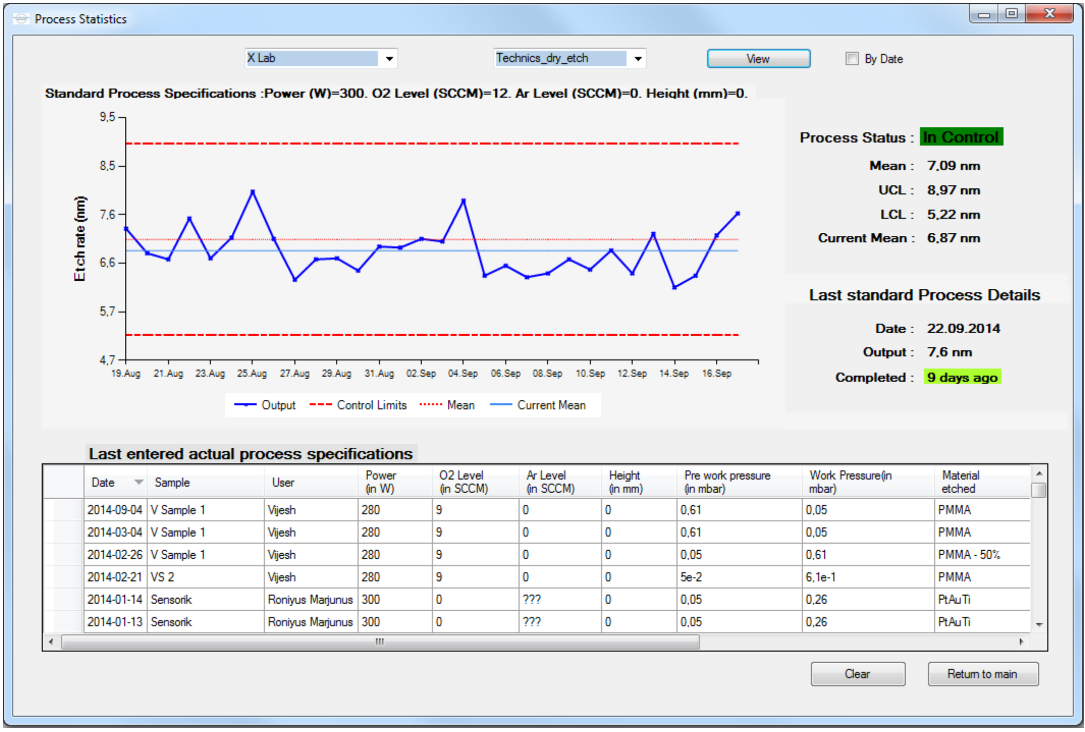


Figure 5.14: Process Statistics form of Technics Etcher

the equipment is also displayed listing all the actual processes performed on the equipment. The input specifications of the standard process are provided above the control chart and the output specifications and the last completed standard process details are given on the right side of the control chart. The process status indicates if the process is *in control* or *out of control*. An *out of control* check is made using the Western Electric guidelines [95]. By default, the control charts shows the output quantity on the Y-axis and the experiment number labelled with the date of experiment on the X-axis. The "By date" selection can be made in the form to update the X-axis of the control chart by date. The current version of the application is unable to identify Type I or Type II errors discussed in section 5.2.7. A further enhancement to the statistics form is to include the Type I and Type II errors to identify if the process is in a state of control.

A form of data verification in *DataEntry* application is to make a condition check for a data point that deviates by more than 50% of the mean value. The next five data points are considered and if there is no other data point that has a similar amount of deviation or shows an increasing or decreasing trend, the value

is considered as an outlier and removed from the calculations and the control chart. An experimenter must however check the dependence of the equipment on past processes or variations in operating conditions before making the SPC test and entering the data. An analysis of the data to find the root cause of the variations must be done only after ensuring that the variations are not due to common causes. The control charts must be used with data from the selected equipment over a wider time period to see the variations over time and to assess the effectiveness of the improvement activities that are taken to improve the process output. The control charts along with other SPC tools like *cause and effect diagrams* are used to study the output response.

Process improvement procedure

The first stage in process improvement is to ensure that the guidelines given in *DataEntry* are properly followed before performing the process. Once the variations due to process change are taken care of, the process improvement strategy can follow the two-steps improvement procedure to [109]:

- Remove the special cause of variations.
- Improve the system from common causes.

The first step involves determining the special causes of variations and removing them. It is also important to ensure that they are not repeated. There are cases in which the assignable causes are identified but may not be controllable. In such cases, these variations must be taken as a part of the system and then an output response must be selected that will make the best use of these variations [96]. The second step involves redesigning the whole system or important parts of it. A general approach is to try and identify the major causes of variation and remove or reduce the variation introduced by them [96].

Chapter 6

Improving processes output

This chapter focuses on improving the process output at EIT2. A process flow is designed to be used at EIT2 using the components of the QMS to ensure that the variation in process output with changing processes are minimal. The measurement system analysis is performed to ensure that the measurement equipment provide accurate values. A comparison of the process capability index before and after using the quality management guidelines is also shown to conclude that the effective use of the QMS improves the process quality.

6.1 Process improvement at EIT2

As summarized in Section 1.2, IC manufacturing involves many processes that are performed in a sequence. Quality control thus requires controlling the variations of all the intermediate processes involved in IC manufacturing. In semiconductor manufacturing industries, the issues of high yield and high quality are addressed to an extent by the development of the following critical process steps [110]:

- Process Monitoring: An important step in process modelling is data collection. As discussed in section 5.3, a system for data collection must be established to simplify process monitoring. A sufficient amount of data about the process is required to design a model. In EIT2, the *DataEntry* tool helps to collect the response data of all experiments conducted.

- Process Modeling: Process modeling permits an experimenter to manipu-

late and optimize the process efficiency with a minimum amount of experimentation [89]. The models are required by semiconductor manufacturers to predict the process behavior under different set of operating conditions. A well-developed process model can in turn be used to generate the ideal process conditions to obtain desired responses. At EIT2, process modeling is done by means of experimental design by using the DOE tool *Cornerstone*.

- Process Optimization: Optimization is designed to produce designated target responses based on the functional relationships between the controllable input parameters and the process responses generated by the models [110]. A systematic methodology that facilitates the design of specific sets of process conditions to achieve desired process objectives is necessary to optimize a given unit process [89].

- Process Control: Once the process parameters have been determined and the process is verified to give the required response, it is necessary to ensure that the process consistently gives the required response. Process control is performed using statistical tools like *pareto charts* and *control charts* as well as the *DataEntry* tool is used at EIT2 as discussed in chapter 5.

- Process and Equipment Diagnosis: Once a process is seen to deviate from its target limits, an analysis of the variation causes is investigated. At EIT2, the experimenter is first required to check the knowledge database for the general variation causes that are specific to the process. These variation causes may be due to the change in operating conditions of the equipment or due to external factors, like irregularities in the gas supply that may not be properly regulated. If the source of variation is identified as an unknown source, the experimenter is required to investigate the issues in the process or equipment. The cause and effect diagram is generally used to identify the root cause of the issue.

Another goal of the QMS in EIT2 is to design a process flow to reduce the variations in the output. A simple guideline was developed to direct the experimenter when performing an experiment with the equipment in EIT2. The QMS developed for EIT2 consists of three main components, specifically the Knowledge database, Data analysis tool and the DOE tool. A simple illustration in

Figure 6.1 shows these basic components and the institute server that is used to provide the interconnection between these components.

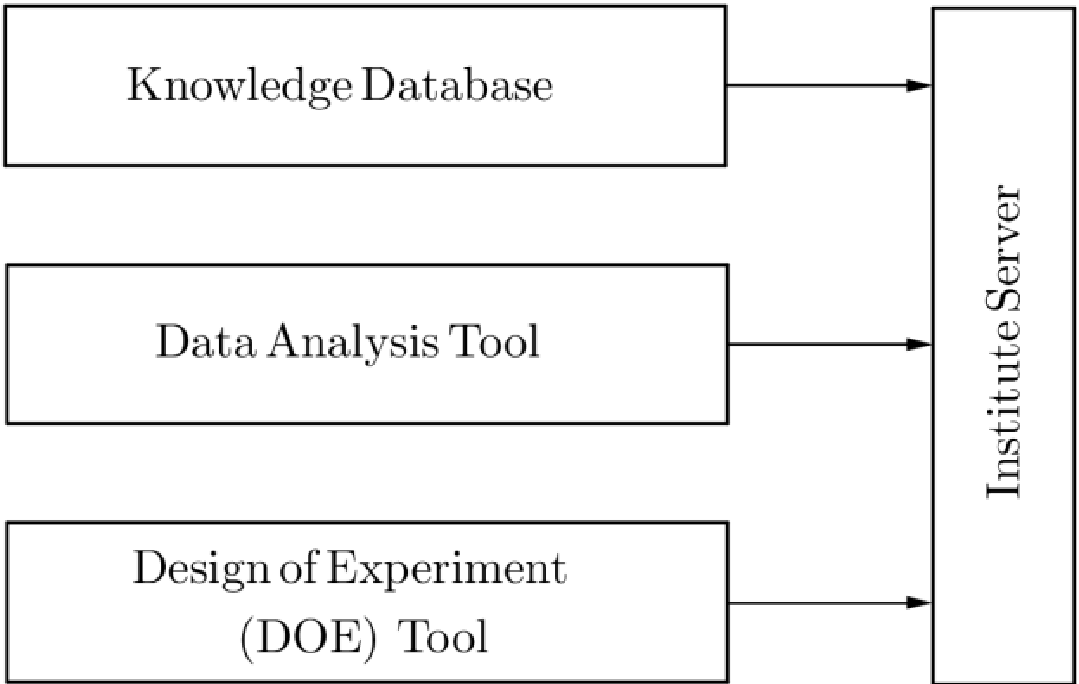


Figure 6.1: Components of the Quality management system

6.2 Pre-requisites

Prior to designing a process plan, it is necessary to verify that the associated equipment is capable of constantly meeting the specifications. All the equipment connected with a process need to be checked for conformance to specifications. A process generally consists of pre-process stages, the main process and measurement stages. To obtain a required response it is necessary to ensure that all the stages preceding and following the actual process are also yielding the required results. Measurement system analysis or MSA, discussed in section 4.1 is used to check the variations in the measurement process. A case study is made with the interferometer which is one of the measurement equipment used at EIT2 for thin film measurements [111].

6.2.1 MSA with interferometer

Interferometers are used for high precision measurements of distances from nanometer range to a few meters and also for measuring surface irregularities [111]. Light is sent to a source material that needs to be measured and the measurement is made by analyzing the reflected light. For thin film measurements, the data of the source wavelength and features of the reflected light associated with a substance, like the shift in the interference patterns, are used to measure the thickness of the deposited layer [112].

Figure 6.2: Experimental set up for the interferometer measurement

The industry name for the interferometer used in this study is "Thin-film-metrology spectroscopic reflectometer" and is developed by "Mikropak". The interferometer data is analyzed using the software tool *NanoCalc 2000* which provides the thickness of a deposited substrate.

The study was conducted with a reference sample and its measurements were made in blocks of 20 readings taken in sequence. The reference sample was made of silicon with a coating of PMMA (Poly-methyl methacrylate) at the surface.

Two sets of readings were taken, the first set in March 2013 and the second set in March 2014. The experimental setup is shown in Figure 6.2. The block marked 1 in Figure 6.2 is the wafer holder. The smaller samples can be placed inside the holder using a special sample holder where the sample can be aligned perfectly into the holder. Block 2 shows where the samples are placed for the measurements. Block 2 consists of a measurement head and the base. The measurement head is movable and contains the light source and detector of the interferometer. The PMMA layer on the sample is non-uniformly distributed. After coating PMMA layer on the sample, the thickness was measured at different points on the sample. The PMMA layer had a maximum thickness of 353nm and a minimum thickness of 317nm within the sample. The measurements were taken at the center point of the sample that had a thickness of 348nm.

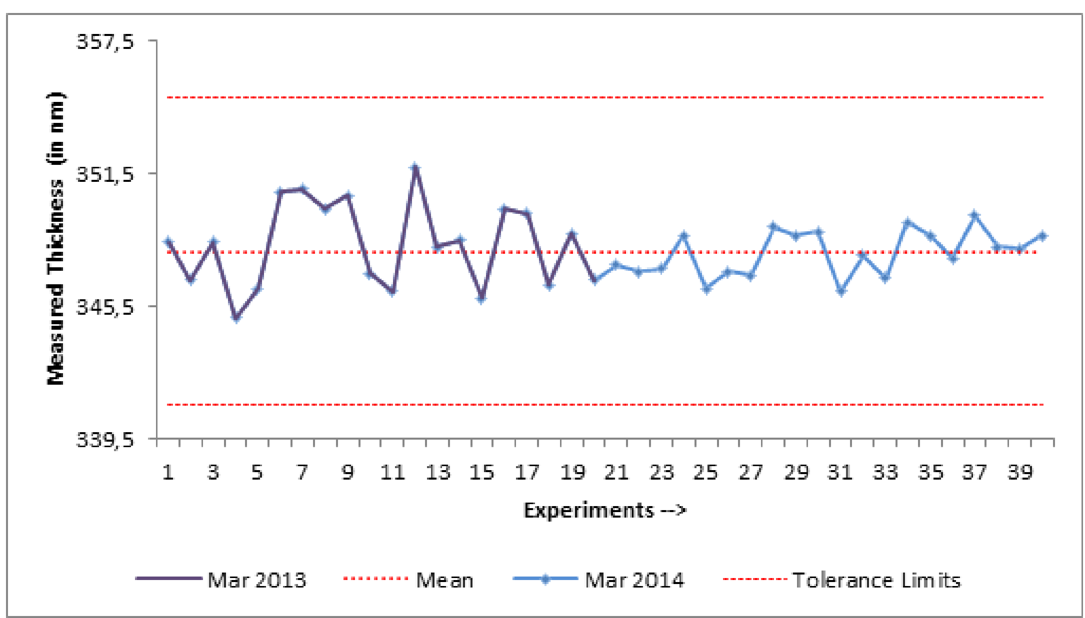


Figure 6.3: Output chart showing measured PMMA thickness using interferometer

The measured thickness of the same reference sample taken during March 2013 and March 2014 are shown in Figure 6.3. The first 20 readings were taken in March 2013 and the latter 20 were taken in March 2014. The calculation of the mean and standard deviation of the readings are shown in Table 6.1.

The process of performing the MSA was improved by reducing the human error while placing the sample on the measurement surface. During the initial

	March 2013	March 2014
Mean	348.3	347.93
SD	1.94	1.02

Table 6.1: Calculation of mean and standard deviation (SD) of interferometer readings

set of measurements (taken in March 2013), the sample was placed directly on the sample base shown in block 2 of Figure 6.2. The measurements were made by approximating the center point by the experimenter. The disadvantage of taking the readings at an approximate center point was the introduction of variations caused by measuring another point closer to the center due to non-homogeneity of the sample. It was necessary to devise a method to ensure that the sample thickness is measured accurately at an exact point in order to determine the true variation of the interferometer. A sample holder was used to align the samples on a fixed point of the measurement base. However, the position of the measurement head was not fixed. Hence, the source of variation caused due to measuring a different point still existed. To overcome this variation, a fixed point was marked on the measurement surface. The light from the measurement head was focused on to the marked point prior to the measurements to ensure that the position of the measurement head with respect to the base was fixed. The sample holder was then aligned with respect to the base and the positioning error was eliminated. The measurements made with the correction, made in March 2014 showed lesser variations and had a lower SD as given in Table 6.1. The maximum deviation shown by the interferometer was less than 2% from the mean value. A deviation of less than 10% is considered acceptable [66] [68] and so, the interferometer as a measurement system for measuring thin films was acceptable.

6.3 Designing a process flow

The guideline for performing a process is explained in this section. The components of the QMS are used for providing the guideline. A schematic is shown in Figure 6.4 that shows the process guideline.

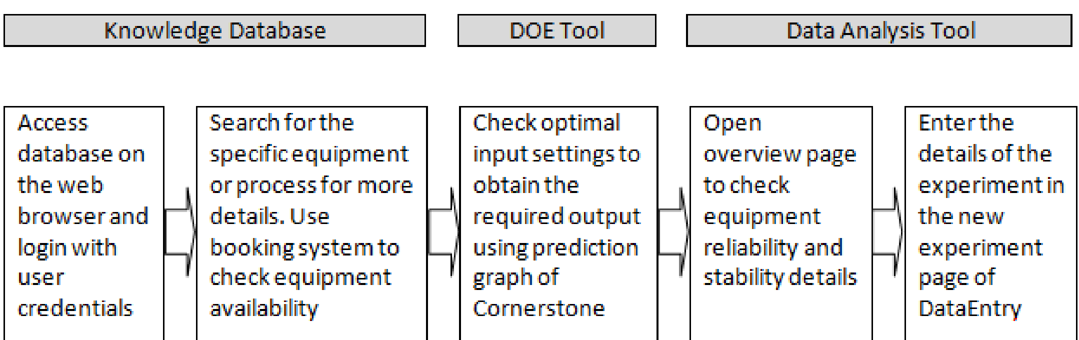


Figure 6.4: Process flow using the components of QMS

Each of the equipment in the institute is assigned to one or more key users. They are responsible for ensuring that the equipment is operating as per the requirements, the maintenance activities are planned and performed when necessary and to provide the necessary training to new users to work with the equipment. The process guideline explained here is to complement the training for using the equipment. It provides an overview for performing the necessary experiments as per the requirements of the internal quality specifications in EIT2.

A plasma etcher from *Technics* is used for the study. A plasma etcher produces plasma from a process gas, using a high frequency electric field to deposit an oxide layer with the help of oxygen or to remove a substrate with a fluorine-bearing gas [113].

6.3.1 Using the knowledge database

The knowledge database is the starting point in order to understand the details of the equipment and the process. The user is first required to login to the database with the user credentials and navigate to the corresponding folder of the required equipment. In the equipment folder, the user manual of the equipment is available. The equipment operating instructions and other details specific to the process that needs to be performed with the equipment are also available. The database provides a link to the internal equipment booking system, which can be used to check the availability of the equipment. The booking system shown in Figure 6.5 can be used to book the required equipment for the desired duration after receiving permission from one of the key users of the equipment.

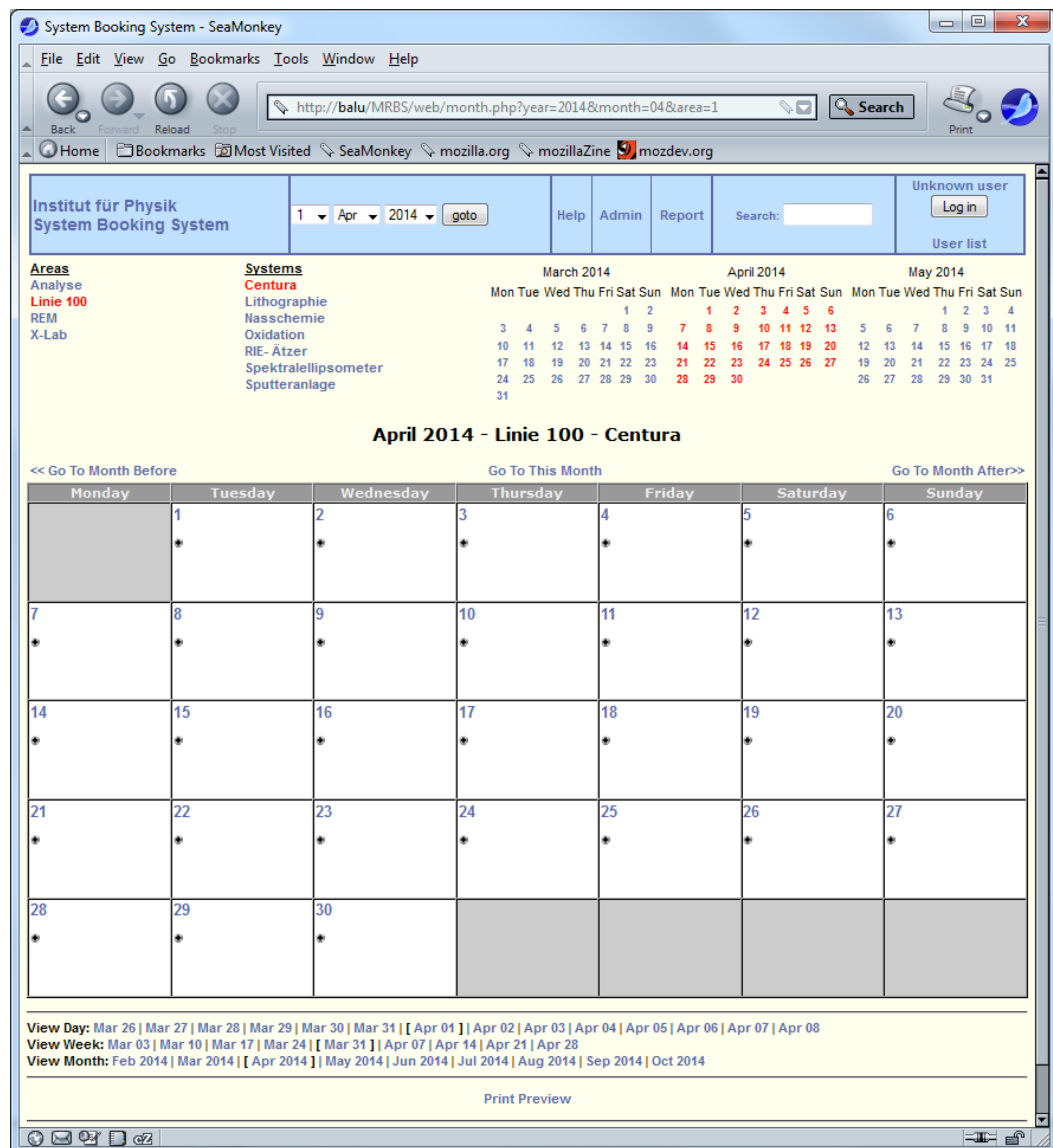


Figure 6.5: Equipment booking system of the institute

The booking system with the Centura tool from cleanroom 100 is selected and a monthly view is chosen in the example shown in Figure 6.5. Users are able to login to the system using the “Log In” link provided at the top right of this page. The lab and the equipment (from systems) can be selected from the links provided. On clicking the required date in the calendar, the user is redirected to a page where the booking details have be entered along with the desired duration for the equipment usage. The changes would then be reflected in the calendar and the user can then use the equipment.

6.3.2 Using DOE tool

The next stage is to use *Cornerstone* in order to determine the input settings for performing the process, if the process is different from the standard processes that are listed for the equipment. The prerequisite for using the predictor graph for *Cornerstone* is that DOE data must be available for the equipment.

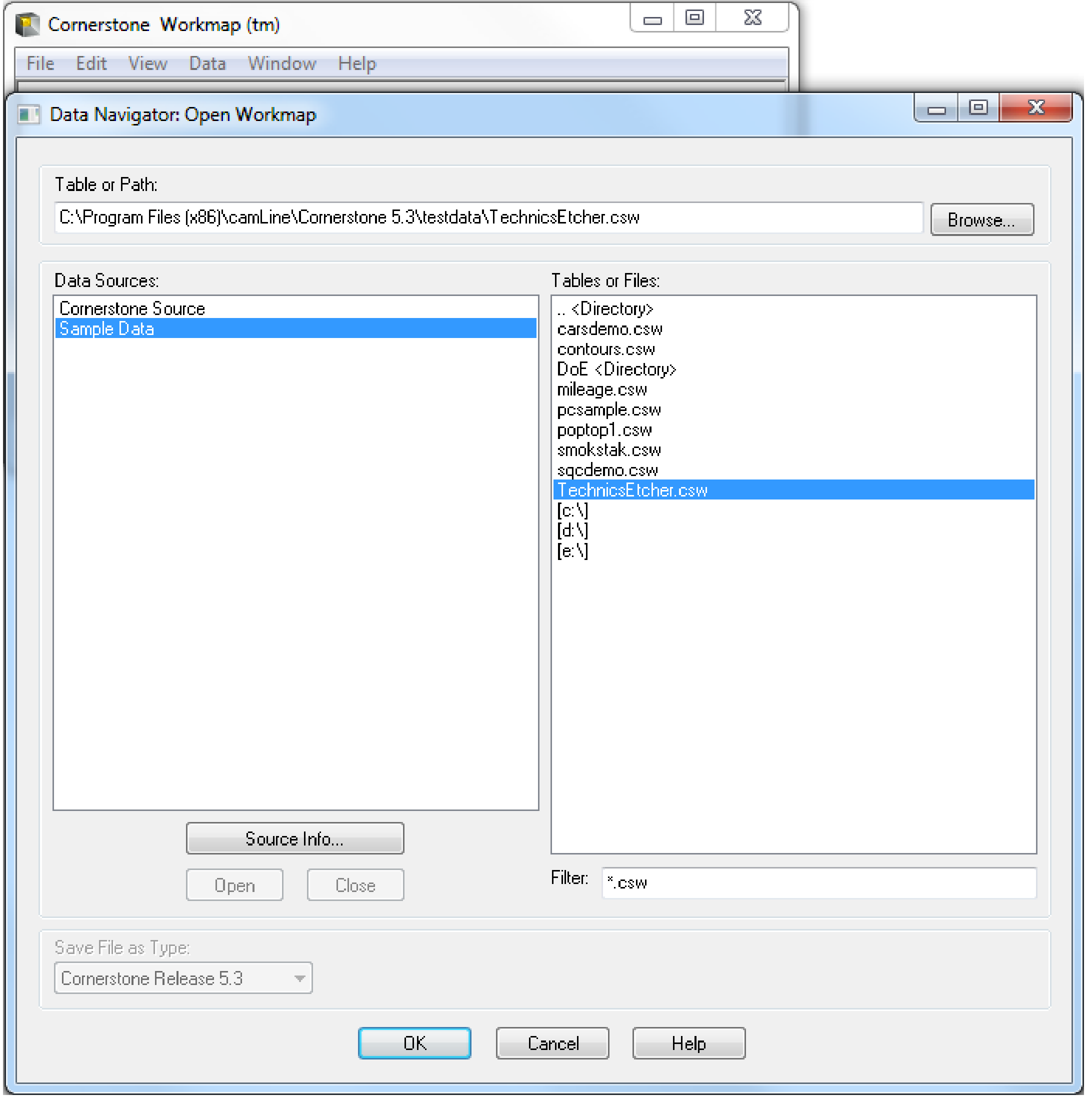


Figure 6.6: Opening a saved workmap

DataEntry tool needs to be opened from the internal server "Balu" or by using the shortcut icon provided at the desktop of all laboratory PCs. In the "New experiment" page of the *DataEntry* tool shown in Figure 5.8, "DOE Run" option needs to be selected. This loads the "Experimental design Overview" page

where some basic ideas on using the experimental design module of *Cornerstone* are provided. *Cornerstone* can be accessed using the link provided on this page. Section 4.4 provides the instructions to open the experimental design module of *Cornerstone*. The experimental design data needs to be present for the selected equipment to obtain the optimized settings for performing the experiment. The saved workmap with the experimental design data is opened by accessing "File" -≫"Open Workmap" from *Cornerstone* interface screen. The resulting page that appears is shown in Figure 6.6.

The experimental design data corresponding to the equipment will be saved as a workmap and the user can navigate to the location where the file is saved and open it. In Figure 6.6, the default folder of *Cornerstone* is shown and the data for *Technics plasma etcher*, saved as *Cornerstone workmap (.csw)* format in the folder can be accessed. Opening the *csw* file loads the experimental design data for the equipment. The equipment data is loaded into the *Cornerstone workmap* and each object of the file is depicted as shown in Figure 6.7.

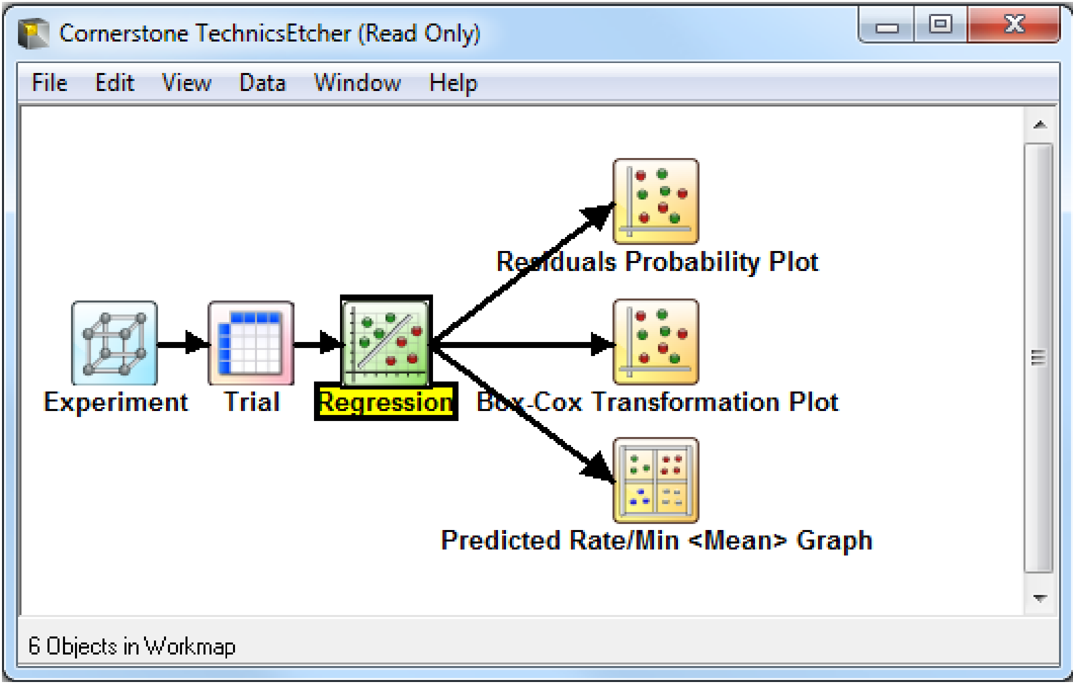


Figure 6.7: Experimental design data of *Technics plasma etcher*

The starting module is the "Experiment" module where the factors and responses are listed. This module also contains the model type and the constraints specified for the experiment. "Trial" module contains details of the trial runs

for the experimentation. The generated model with the required input settings and the actual outcome of the run are listed in the "Trial" module.

Details of the data analysis mentioned in Section 4.4.6 are available in the "Regression" module. The module opens the "Term significance table" that lists the significance of each of the input factors towards the output. The user may check the distribution of the error terms in the "Residuals probability plot" and identify the outlier in the data as explained in Section 4.4.6. The plot is shown in Figure 6.8

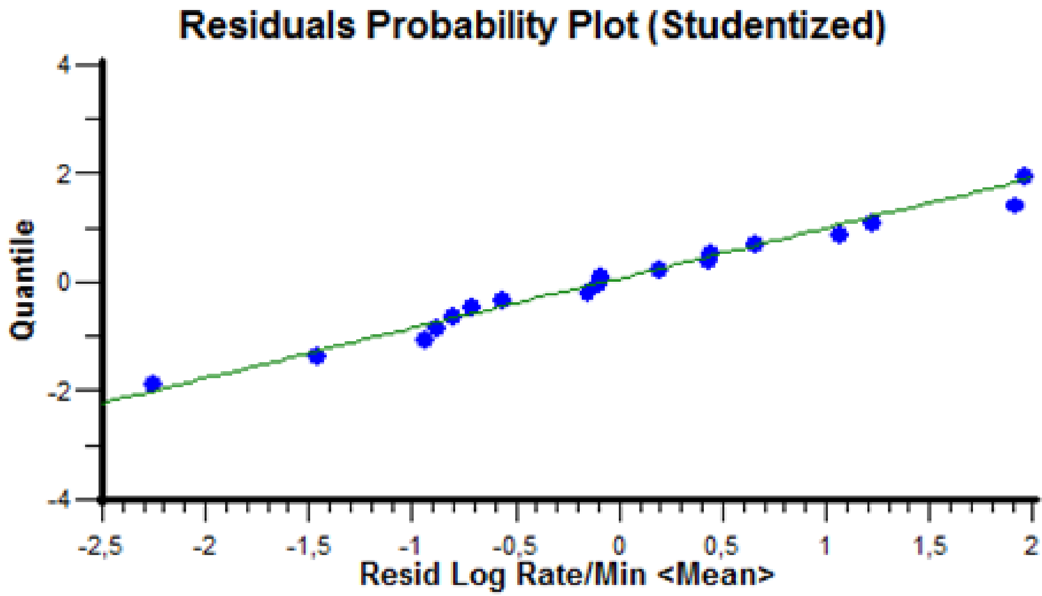


Figure 6.8: Residuals probability plot of *Technics plasma etcher*

In the case of the Plasma etcher, it can be seen from Figure 6.8 that the error is normally distributed and there are no outliers from the line drawn. "Box cox transformation plot" is used to identify if a different type of transformation would result in a better fitting model [65]. The selection of the transformation must be based on the process knowledge and the RMS error value as described in section 4.4.6. In the case of the *Technics plasma etcher*, the untransformed model had only a slightly higher RMS error value over the log-normal transformation. The untransformed model was found to be a better fit in this case, considering the process output. The "Predicted etch rate graph" module shown in Figure 6.9 is the output predictor graph. This graph is used to estimate the values of the input settings that are required to get the output response. To ob-

tain the necessary input settings corresponding to the response, the user must specify the required target value in the “Define” segment of the Experiment module given in section 4.4.3. The input settings corresponding to the required output should be provided along with the confidence intervals for the predicted output value. The predicted output graph for the *Technics plasma etcher* is shown in Figure 6.9.

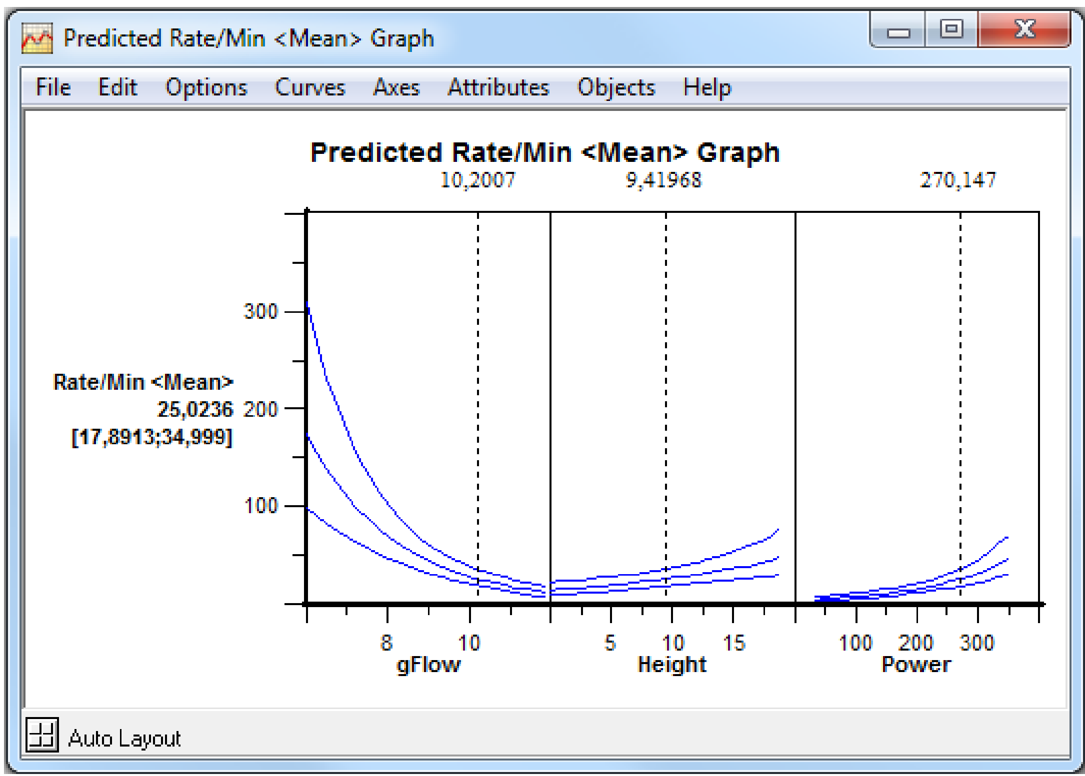


Figure 6.9: Predicted output graph for an etch rate of 25nm per minute

The experimenter is also able to manually adjust the required input settings to obtain the required output with minimal amount of variations. In Figure 6.9, the required output value of 25nm is given on the left hand-side and the upper and lower limits of the predicted value are provided below the output response value. The input settings for the gas flow (O_2 flow, given as gFlow) in *SCCM*, height of the sample from the base in *mm* and the input power in *watts* are available, that are needed to perform the experiment. The experimenter is required to take a note of the factor settings prior to performing the experiment to obtain the desired response.

6.3.3 Using Data Analysis tool

The next step is to reopen the *DataEntry* tool and select the lab and the equipment on which the experiment would be performed in the "New experiment" page. Segment 2 in the "New experiment" page displayed in Figure 5.8, provides information that is specific to the equipment. The past usage details of the equipment is provided as well as precautionary measures that have to be taken into consideration to use the equipment. The experimenter is required to make sure that there are no stability issues with the equipment that would be used for his/her experimental run. If the equipment output depends on the past processes, then it is necessary to click on the "More information" link available in the "New experiment" page to understand the corrective actions that are needed to obtain the required output. To check the equipment reliability, "Reliability Test" option needs to be selected. "Reliability check" button will be displayed as shown in Figure 5.10. Clicking the "Overview" button in the resulting sheet opens an overview page shown in Figure 5.10. The "Overview sheet" provides the instructions for performing the reliability test processes and displays the corresponding stability charts. The experimenter is able to understand the stability issues with the equipment depending on the type of processes performed on it. The experimenter may then take necessary measures to ensure that the equipment output would be stable prior to performing the actual experiment.

The reliability test page is loaded on clicking the "Next" button on the Overview page. The experimenter is able to select the process type. The charts and process details are loaded on clicking the "Plot on chart" button shown in Figure 5.12. The process capability, mean, control limits and the actual process mean are loaded. A chart that shows the output distribution curve is also loaded along with the stability chart for the selected process. The information in the "Reliability check" segment aids the experimenter in understanding equipment specific issues that exists in research institutes where the equipment operating conditions are often varied. A feedback from an experienced staff is required when the experimenter is unsure about interpreting the information given in the guideline. The "Actual run" may then be performed. Once the actual experimental run is completed, the input and output parameter values need to be logged in the "New experiment" form. The data analysis tool would append the data into the equipment logbook after a verification of the entered values.

6.4 Checking the results of plasma etcher

The output response value for the first experimental run performed with the plasma etcher showed higher amount of variations and is seen from the overview page shown in Figure 5.10. The output value is seen to stabilize only after one trial run is performed on the equipment. A set of five tests were performed on the plasma etcher over six days with the same input factor settings. The input factors are provided along with their standard settings in Table 6.2.

	Parameter name	Standard value
Input factors	Power (in Watts)	300
	O_2/Gas flow (in SCCM)	12
	Height of sample from base (in mm)	0
Output response	Etch rate (in nm per minute)	7 (predicted output)

Table 6.2: Input factor values and output response for *Technics plasma etcher*

The values provided in Table 6.2 are the standard process settings used for performing statistical process control with the *Technics plasma etcher*. The *control chart* made using the experimental results is shown in Figure 6.10.

The first run in every block is indicated with the vertical block separation line as shown in Figure 6.10. It can be seen that the output response of the first trial run in every block has a higher level of deviation when compared to other runs. The comparison of the process parameters with the first run included and the run excluded are summarized in Table 6.3.

	Experiment with dummy run	Experiment without dummy run
Mean	6.95	6.88
Standard Deviation (σ)	0.74	0.46
Process Capability (C_{pk})	0.78	1.20

Table 6.3: Comparison of process parameters

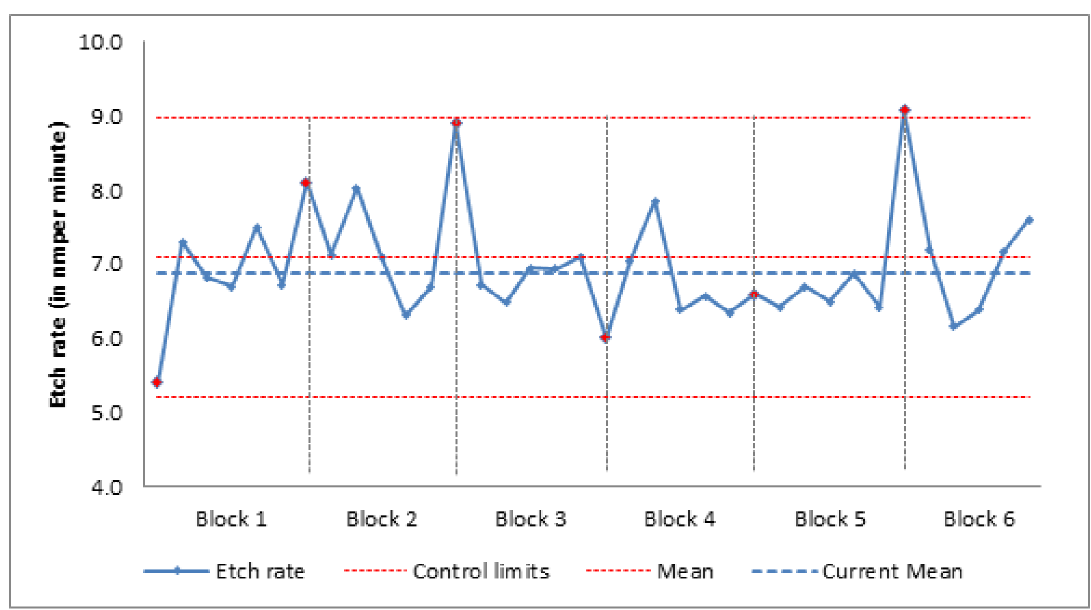


Figure 6.10: Etch rate graph at standard process conditions

The input and output values in Figure 6.10 are given in Appendix. All the runs in the block are considered for the calculations in "Experiment with dummy run". The first trial run in every block is excluded and considered as a dummy run for the calculations in "Experiment without dummy run". A higher process capability index indicates that the process is stable when the values of the first trial run is not considered. From the equipment stability charts given in Figure 5.10 and the *control charts* given in Figure 6.10, it can be concluded that the *Technics plasma etcher* output stabilizes only after the first run. The information was provided to the users through the data analysis tool that it is necessary to perform a dummy test without their test sample on the plasma etcher before the actual test is performed.

6.5 Process flow on the oxidation furnace

The process flow described in Section 5.2 was used with the Oxidation furnace from *Carbolite* in the X-Lab. Oxidation furnace is used to grow oxide over the silicon substrate layer [114]. Thermal oxidation process can be classified into dry and wet oxidation process. In dry oxidation, pure oxygen reacts with silicon at high temperatures from 800 °C to about 1200 °C [114]. In wet thermal oxidation, the oxygen is led through a bubbler vessel filled with heated water

into the oxidation chamber [115]. The rate of oxide growth for a wet oxidation process is higher than that of a dry oxidation process [115].

It was observed for the *Carbolite oxidation furnace* that the oxidation rate was higher for the dry oxidation process whenever a dry process follows a wet oxidation process. A theoretical explanation was the presence of water vapor in the oxidation chamber which aids in higher oxide growth rate. A possible solution was to perform a dummy dry oxidation experiment prior to performing the actual experiment. However, dry oxidation process is performed in the range of 900 °C. Heating up the oven and the subsequent cooling takes almost a day and also requires gases like oxygen and nitrogen in addition to the operational resources. Therefore, performing a dummy experiment was not a viable option due to the wastage of time and resources.

To investigate the issue further, it was decided to repeat the experiments with changes in the process conditions. The instruction manual for the oxidation furnace available in EIT2 database was followed. The precautionary measures and the necessary steps to reduce the variability due to process variation were taken prior to performing the experiments. However, while taking the measurements, it was found that the dry oxidation process when followed by a wet oxidation process did not have the high amounts of variations that were initially noticed.

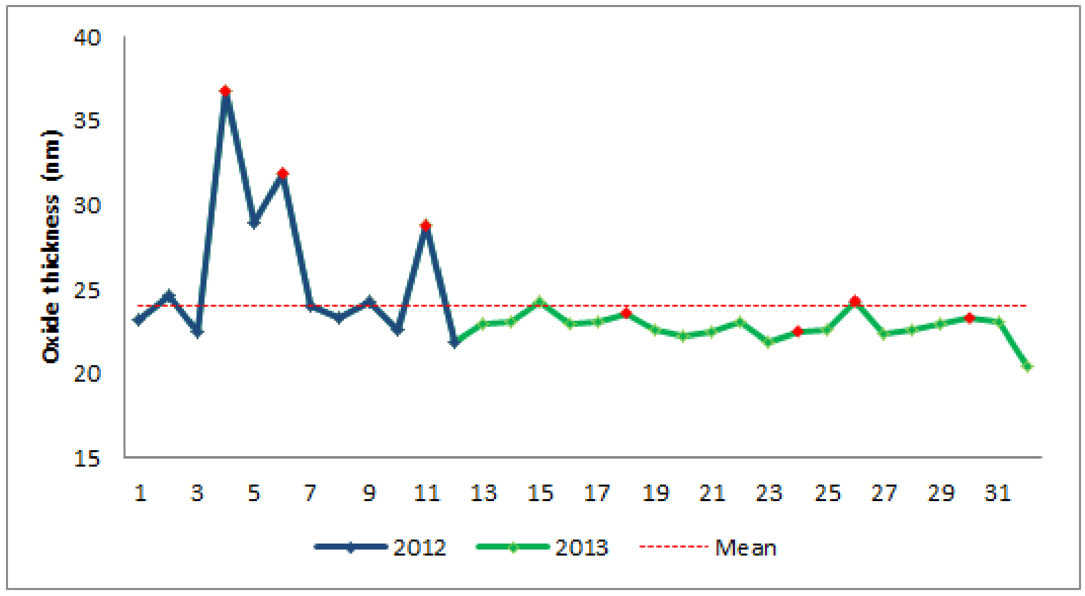


Figure 6.11: Comparison of measured oxide thickness with changes in process conditions

A comparison of the oxidation thickness taken in 2012 and 2013 are shown in Figure 6.11. The data points for the measurements taken for the dry oxidation process following a wet process are marked in *red* in Figure 6.11. It can be seen that the process outputs taken in 2013 following the instruction manual improved considerably from 2012. The improvement is also brought about by increasing the accuracy of measurements with the interferometer. The standard deviation improved from 4.6 to less than 1.0.

An explanation for the larger deviation in 2012 was that the process requires passing nitrogen for 30 minutes before the samples are placed in the chamber of the furnace. Passing nitrogen at a specified steady rate during the heating stage is also necessary to ensure that oxidation process does not take place during the heating process. The influence of water and therefore a higher oxidation rate was seen only when the nitrogen level was below the specified rate. Failing to maintain the required rate of nitrogen was identified as the reason for the higher oxidation rate. Additional tests were performed to verify the theory. The *DataEntry* tool was updated to highlight the process issues and inform the users to ensure that the process instructions are duly followed.

6.6 Discussion

The data from the plasma etcher and the oxidation furnace were collected before and after following the process guidelines provided in the QMS. The comparison of the results showed that the variability in the output reduced after using the QMS. It was achieved using all the components of the QMS. The most significant factor that needs to be taken into consideration is that the equipment must be operated under specified conditions. Also, the MSA of the measurement equipment must be carried out prior to performing the actual experiment. This chapter also states that the QMS must only be used in conjunction with the information from the key equipment users. Users are expected to consult with the key equipment users in case of any confusion while performing a new process using the DOE tool.

Chapter 7

Conclusion

The thesis provided an insight into semiconductor fabrication and how semiconductor fabrication in a research institute is different from the industry. The issues concerning research institutes where multiple processes are performed on the equipment and inexperienced users operating the equipment are discussed. The thesis presented a QMS which caters to these issues in research institutes. The need for a QMS and its essential components to be used in a research institute are also discussed in this thesis.

Quality management involves quality planning, control, improvement and assurance. The DOE tool helped in quality planning by setting a target depending on the requirements and to ascertain the process parameters to run the process. DataEntry tool helped in quality control by ensuring that the process does not deviate from the requirements. All the components of the QMS helped in quality improvement. The simulated output from the DOE tool and the actual outputs were compared. The comparison data was used to improve the output prediction of the DOE tool. DataEntry tool served to inform users about issues which can cause higher variability in the output. The process related data in the CMS was also updated to reflect the common causes and special causes that affect a process. A standard process was defined for some of the equipment in EIT2. Measuring the output of the standard process at regular intervals helped in quality assurance to ensure that the equipment and process are stable. Each of the components of the QMS were thus helpful in ensuring that the manufacturing process is improved over time. The QMS thus developed following the standards of ISO 9000 aided to organize the documents effectively, control and

reduce the variability of the process.

The thesis also states that the effectiveness of the QMS is dependent on the users who use the system. Hence, the users need to ensure that the process is performed as per the guidelines provided in the CMS. The data verification performed by the developed DataEntry tool is only at a basic level to check if the data is within a range or if numbers are entered correctly. A basic level verification is not adequate and the users are also required to ensure that the process data entered in the DataEntry tool is accurate. When the users use the system effectively, the variability in the process reduces over time due to the reduction in the confidence intervals of the predicted output. A reduction in the output variability translates to an improvement of quality. Studies on the etching equipment and oxidation equipment, that are discussed in the thesis confirms that the process quality improved at EIT2 after using the QMS.

Appendix

This chapter is used to provide the data that are used for plotting the graphs in this thesis. The usage statistics of the Plone CMS by the members in EIT2 was taken from March 2013 to March 2014. A major chunk of the data were added from January 2013 to March 2013 (more than 1000 new documents were added). Data from the majority of the equipment and regarding the processes were available by end of March 2013. After this period, the CMS was used to update only data regarding new processes or issues related to infrastructure. Table 7.1 below shows the usage statistics from March 2013 until March 2014.

Month	No: of Updates	No: of updates (cumulative)
March 2013	551	551
April 2013	31	582
May 2013	1	583
June 2013	100	683
July 2013	33	716
August 2013	11	727
September 2013	7	734
October 2013	8	742
November 2013	9	751
December 2013	0	751
January 2014	23	774
February 2014	24	798
March 2014	6	804

Table 7.1: Usage statistics of the CMS

The table shows that the CMS was used in a satisfactory manner with data

being entered at regular intervals. The cumulative chart for Table 7.1 is shown in Figure 3.8.

The results of the oxide thickness measured after performing the oxidation process with the oxidation furnace is tabulated in Table 7.2. A standard dry oxidation process is performed with oxygen gas at a flow rate of 5 SCCM. The results are used to plot the graph shown in Figure 6.11.

Date	Gas	Temperature (deg C)	Process Time (minutes)	Ramp (deg C/min)	Wet/ Dry Ox	Gas flow (SCCM)	Oxide Thickness (nm)
13.12. 2011	Oxygen	900	90	10	Dry Ox	5	23.2
14.12. 2011	Oxygen	900	90	10	Dry Ox	5	24.6
15.12. 2011	Oxygen	900	90	10	Dry Ox	5	22.5
12.01. 2012	Oxygen	900	90	10	Dry Ox	5	36.8
17.01. 2012	Oxygen	900	90	10	Dry Ox	5	29
19.01. 2012	Oxygen	900	90	10	Dry Ox	5	31.9
15.02. 2012	Oxygen	900	90	10	Dry Ox	5	24
23.02. 2012	Oxygen	900	90	10	Dry Ox	5	23.3
13.08. 2012	Oxygen	900	90	10	Dry Ox	5	24.3
14.08. 2012	Oxygen	900	90	10	Dry Ox	5	22.6
16.08. 2012	Oxygen	900	90	10	Dry Ox	5	28.8

17.08. 2012	Oxygen	900	90	10	Dry Ox	5	21.8
02.10. 2013	Oxygen	900	90	10	Dry Ox	5	22.9
03.10. 2013	Oxygen	900	90	10	Dry Ox	5	23.1
04.10. 2013	Oxygen	900	90	10	Dry Ox	5	24.3
07.10. 2013	Oxygen	900	90	10	Dry Ox	5	23
08.10. 2013	Oxygen	900	90	10	Dry Ox	5	23.1
09.10. 2013	Oxygen	900	90	10	Dry Ox	5	23.6
10.10. 2013	Oxygen	900	90	10	Dry Ox	5	22.6
11.10. 2013	Oxygen	900	90	10	Dry Ox	5	22.2
21.10. 2013	Oxygen	900	90	10	Dry Ox	5	22.5
28.10. 2013	Oxygen	900	90	10	Dry Ox	5	23.1
29.10. 2013	Oxygen	900	90	10	Dry Ox	5	22.8
31.10. 2013	Oxygen	900	90	10	Dry Ox	5	22.5
19.11. 2013	Oxygen	900	90	10	Dry Ox	5	22.6
22.11. 2013	Oxygen	900	90	10	Dry Ox	5	24.3
27.11. 2013	Oxygen	900	90	10	Dry Ox	5	22.4

28.11. 2013	Oxygen	900	90	10	Dry Ox	5	22.6
29.11. 2013	Oxygen	900	90	10	Dry Ox	5	22.9
03.12. 2013	Oxygen	900	90	10	Dry Ox	5	23.3
04.12. 2013	Oxygen	900	90	10	Dry Ox	5	23.1
05.12. 2013	Oxygen	900	90	10	Dry Ox	5	23.4

Table 7.2: Results of standard dry oxidation process

Table 7.3 shows the interferometer readings which was used to perform MSA. The PMMA layer was coated on a silicon sample using the equipment called the spin coater. The readings were taken using an interferometer at the centre point of the sample. The values were taken during March 2013 and March 2014. The values are plotted in Figure 6.3.

Experiment Number	Interferometer reading
Exp. 1	348.4
Exp. 2	346.8
Exp. 3	348.5
Exp. 4	345.1
Exp. 5	346.5
Exp. 6	350.8
Exp. 7	350.9
Exp. 8	350
Exp. 9	350.6
Exp. 10	347.1
Exp. 11	346.1
Exp. 12	351.8

Exp. 13	348.2
Exp. 14	348.5
Exp. 15	345.8
Exp. 16	350
Exp. 17	349.8
Exp. 18	346.8
Exp. 19	348.7
Exp. 20	346.9
Exp. 21	347.5
Exp. 22	347.1
Exp. 23	347.2
Exp. 24	348.7
Exp. 25	346.3
Exp. 26	347.1
Exp. 27	346.9
Exp. 28	349.1
Exp. 29	348.7
Exp. 30	348.9
Exp. 31	346.1
Exp. 32	347.9
Exp. 33	346.9
Exp. 34	349.5
Exp. 35	348.6

Table 7.3: MSA readings of Interferometer

The experimental results for the processes performed with the Technics plasma etcher using the input settings provided in Table 6.2 is provided in Table 7.4. A total of 35 experiments were performed with the plasma etcher from 19.08.2012 to 25.09.2012.

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Date	Power (Watts)	O_2 level (SCCM)	Height (mm)	Work pressure (mbar)	Material	Etch rate (nm/min)
19.08. 2012	300	12	0	5.8e-1	PMMA	5.4
19.08. 2012	300	12	0	5.8e-1	PMMA	7.3
20.08. 2012	300	12	0	5.8e-1	PMMA	6.82
21.08. 2012	300	12	0	5.8e-1	PMMA	6.7
22.08. 2012	300	12	0	5.8e-1	PMMA	7.5
23.08. 2012	300	12	0	5.8e-1	PMMA	6.72
24.08. 2012	300	12	0	5.8e-1	PMMA	8.1
24.08. 2012	300	12	0	5.8e-1	PMMA	7.13
25.08. 2012	300	12	0	5.8e-1	PMMA	8.03
26.08. 2012	300	12	0	5.8e-1	PMMA	7.1
27.08. 2012	300	12	0	5.8e-1	PMMA	6.3
28.08. 2012	300	12	0	5.8e-1	PMMA	6.7
29.08. 2012	300	12	0	5.8e-1	PMMA	8.9
29.08. 2012	300	12	0	5.8e-1	PMMA	6.72
30.08. 2012	300	12	0	5.8e-1	PMMA	6.48

31.08. 2012	300	12	0	5.8e-1	PMMA	6.95
01.09. 2012	300	12	0	5.8e-1	PMMA	6.93
02.09. 2012	300	12	0	5.8e-1	PMMA	7.1
03.09. 2012	300	12	0	5.8e-1	PMMA	6
03.09. 2012	300	12	0	5.8e-1	PMMA	7.05
04.09. 2012	300	12	0	5.8e-1	PMMA	7.85
05.09. 2012	300	12	0	5.8e-1	PMMA	6.38
06.09. 2012	300	12	0	5.8e-1	PMMA	6.58
07.09. 2012	300	12	0	5.8e-1	PMMA	6.35
08.09. 2012	300	12	0	5.8e-1	PMMA	6.6
08.09. 2012	300	12	0	5.8e-1	PMMA	6.43
09.09. 2012	300	12	0	5.8e-1	PMMA	6.7
10.09. 2012	300	12	0	5.8e-1	PMMA	6.5
11.09. 2012	300	12	0	5.8e-1	PMMA	6.88
12.09. 2012	300	12	0	5.8e-1	PMMA	6.43
13.09. 2012	300	12	0	5.8e-1	PMMA	9.07

13.09. 2012	300	12	0	5.8e-1	PMMA	7.2
14.09. 2012	300	12	0	5.8e-1	PMMA	6.15
15.09. 2012	300	12	0	5.8e-1	PMMA	6.38
16.09. 2012	300	12	0	5.8e-1	PMMA	7.17
25.09. 2012	300	12	0	5.8e-1	PMMA	7.6

Table 7.4: Etch rate of Technics plasma etcher at standard settings

As given in Table 7.4, the experiments were performed at the standard settings and after ensuring that the operating conditions did not vary during the experimentation.

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