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RELATIONAL DATABASE SYSTEM DESIGN FOR FMECA PROGRAM CREATION

Master’s thesis in Production Engineering

DEEPAK DODDAGOUDAR
VIKRAM SOORYANARAYANA SHETTY

Department of Industrial and Materials Science
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VIKRAM SOORYANARAYANA SHETTY

Examiner: Anders Skoogh , Department of Industrial and Materials Science
Supervisor: Jon Bokrantz, Department of Industrial and Materials Science

Department of Industrial and Materials Science
Division of Production Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 (0)31-772 1000

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Abstract

SKF has been continuously strengthening its commitment towards providing reliable solutions and continuously develop new technologies in manufacturing and maintenance by setting a strong footprint towards industry 4.0 and world class maintenance strategies. The SKF technology platform comprises of bearings and units, seals, motion technologies, services and lubrication systems.

Currently, majority of the factories at SKF are using their own maintenance programs without following a standard. But today, SKF, Goteborg has a standard maintenance program Excel sheet template that is being followed to increase the employee skill, competencies and awareness but this template is cumbersome and not efficient to use.

Within SKF most of the equipment types, its systems, subsystems and components are similar within the same machine family.

The purpose of this master thesis was to design and implement a database system to store and easily transport and reuse the existing or creation of new equipment data. The output file of the database system would then be integrated to the computerized maintenance management system API Pro.

The design and development of the database was carried out through the established scientific DMADV methodology. The relational database application MS Access was chosen as the Database for the project. The thesis has established a flexible and a user-friendly database system to add new information as and when they emerge thereby reducing the lost time in creating new equipment data. It will also reduce the equipment breakdowns by easy identification of failures and each SKF factory could easily build their own maintenance program thereby supporting them in increasing equipment reliability in a standardized way

Keywords: Relational Database, DMADV, Failure Mode Effect & Criticality Analysis, Maintenance Program, Reliability Centered Maintenance, Excel Sheet, MS Acces

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List of Abbreviations

DMAIC - Define, Measure, Analyze, Improve, Control.
FMEA - Failure Mode & Effect Analysis
FMECA - Failure Mode, Effect & Criticality Analysis
CMMS - Computerized Maintenance Management System.
FTA - Fault Tree Management
VOC - Voice of Customer
CTP - Critical to Process.
RCM - Reliability Centered Maintenance
RCFA - Root Cause & Failure Analysis
PM - Preventive Maintenance
RPN - Risk Priority Number
WSM - Weighted Score Matrix/Method
VBA - Visual Basic Application
SQL - Structured Query Language
CSV - Comma Separated Values
DMS – Database Management System
IT-Information Technology

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Introduction

This chapter provides an introduction on the basic concepts of Maintenance Planning & Reliability Centered maintenance and how it is used in today's industries to increase the reliability of the equipments. This would also encapsulate brief background of SKF's Maintenance Excellence, purpose and delimitations for the master thesis. The Context explains the reason behind the development of the Database System

1.1 General Introduction

Maintenance is an art of keeping an equipment or a machine in continuance and in an existing mode. Since the evolution of maintenance, its role within the organization has drastically evolved. In early days maintenance of equipment's was considered as a department that played a second fiddle to the production department. However, as technology advanced and industries began adopting automation as their foremost business strategy, the need for better maintenance practices, maintenance personnel and associated cost increased. For many asset-intensive industries the cost associated with maintenance when compared to production and operation accounts to 20-50% for the mining industry. Also, reducing the maintenance expenditure by $1 million would lead to gain as much profits as increase in sales by $3 million (Parida & Kumar, 2009). Nevertheless, the reliability of the machines began to decrease due to lighter and quicker machines. This forced the production system department to shift the focus on maintenance and its concepts (Khalid et al., 2015). Also, with the emerging paradigm, Industry 4.0, there was a need for digitization and automation of the manufacturing environment. This digitization process encompasses the entire production system focusing mainly on the maintenance of the systems and equipment's along with the related documents (Scuratia et al., 2018). The main purpose of these transformation was to increase the efficiency and productivity of the maintenance and production system to elevate the competitive power of the companies (Alp & Emre, 2018).

Maintenance Planning and Scheduling is the process of identifying and addressing any possible issues ahead of time enabling the maintenance workers to complete the work quickly and efficiently. Planning is one of the most time consuming yet one of the most important activity, if an organization needs anything done efficiently and effectively. Maintenance planning identifies the **WHAT, WHY** and the **HOW**. WHAT defines the work, tools, equipment, and documentation that will be required. WHY defines the reason for choosing a particular approach and HOW defines how the work should be completed. To improve the reliability of the assets it is of prime importance to promote uptime and availability. In addition to that the ever-increasing maintenance cost, Europe and Sweden accounting for 1500 billion euros and 20 billion euros respectively per year (Parida & Kumar, 2009), has forced the industries to adopt effective ways of maintaining production assets. Reliability Centered

Maintenance (RCM) was one such practice that was adopted. Evolved in 1960’s in the aircraft industry it was used as a substitute for Preventive Maintenance (PM). With experience many industries drew light on RCM due to its significant savings in maintenance cost and increase in availability of the production system (Khalid et al., 2015).

There are different methodologies utilized in Maintenance Planning involving all the stakeholders in the process using tools such as brainstorming and focused group meeting. On a high level the process consists of identifying the stakeholders, formulating the purpose for the existence of maintenance in the organization, setting the maintenance objectives to achieve, analyzing the current situation, strategizing options to achieve the objectives, developing quantitative measures to assess the performance of the objectives and finally implementing the plan to execute the selected strategy (Umar et al., 2014). There are several challenges to be addressed during the consideration of the above-mentioned strategies. The challenges concern financial obligations. reliability, ease of implementation, cost and time effectiveness (Parida & Kumar, 2006).

1.2 Project Background

Currently each factory at SKF develops their own maintenance program without following a certain standard, method, or template causing the need to reinvent the wheel over time. To counter this problem, SKF has developed a standard in the form of a Preventive Maintenance (PM) Program template, for its critical equipments, in an Excel spreadsheet. SKF regularly conducts workshops to ensure that the employees have the competence to follow this standard and are aware of the method that is to be followed. The Excel sheet PM program can be divided into two parts. First the hierarchical breakdown of the equipment data into four levels viz: Machine, Machine System, Machine Sub System and Components (with its functions). Then the second part comprises of the Failure Mode, Effect and Criticality Analysis (FMECA) along with the necessary preventive action for the lowest equipment data level i.e. Components. Hereafter the entire PM program shall be addressed as FMECA program. Currently different computerized maintenance management system (CMMS) tools like API Pro, SAP, FTM (Fault Tree Management) and other software’s are being used across different factories of SKF globally to manage the FMECA program.

The main problem with the Excel sheet is the performance issue as more machines are added. Adding new machine data in an Excel sheet is time consuming, fallible and the users find it highly tedious and are vulnerable of making mistakes. The inability to cope with customized machine data and redundancy makes it highly necessary to develop a new system and make the process more efficient. There is also a high risk of the users accidently deleting the data.

1.3 Project concept and purpose

The primary scope of the project was to conduct a research on the current Excel sheet template based on its drawbacks. To counter the drawbacks of the data in the Excel sheet a thorough evaluation was done to search for the most efficient database system. Different database systems were evaluated based on criterias like user friendly, cost, reliability and flexibility. Finally, after narrowing down on the Database system, a simple and effective user interface was developed in a way such that even an unskilled worker could use it with ease. The new system eliminated manual entry of data, thereby semi-automating and in some cases completely automating the entries. It promoted generation of transportable and reusable data for the creation of new machines.

The newly designed system can be accessed online by maintenance engineers across the SKF factories worldwide by sharing the database through an online platform. The database system will be user friendly for the operators to add new functions or new information as and when they emerge. The system developed will be deemed as a global standard across SKF factories globally in building their maintenance program. As a result, each SKF factory across the globe can easily build their maintenance program in a standardized way supporting in increased machine reliability and mean time to failure and reduction of buffer size, lost time, cost and uncertainties.

1.4 Delimitations

The limitations identified for this project are:

- The group shall assume that the data provided in the form of Excel sheet template is correct and no further verification and validation is required
- The development of a new database system shall be only for the machine’s data provided by SKF

1.5 Research Question:

How can the process of creating a FMECA maintenance program be improved?

1.6 Area of Investigation

The main area of interest is the system design, development and the meaningful division of FMECA data. With an efficient system design the FMECA data can be stored and displayed in a way that the user finds it easy enough to understand and interpret. The following section explains the context behind the need for developing a better system for developing the FMECA program at SKF in the master thesis.

1.6.1 Context

The Maintenance Excellence Team at SKF is responsible for the maintenance and servicing of the machines at SKF. The team's main job is to make sure that the potential failures are identified beforehand and take necessary steps to prevent it from happening in the future and this is done by developing a FMECA program for the machines by breaking the machine into 4 hierarchical levels namely Machine, Machine System, Machine Sub System and Components respectively in an generic Excel sheet template which is used by SKF factories across the world. While using the Excel sheet by the users there have been cases reported, where due to negligence some of the FMECA programs of the component is deleted or the data being switched across the rows and columns creating a mess of the entire Excel sheet. Also, when a new maintenance data is found out for a machine for which the FMECA program has been already developed, there is a mismatch during the creation of new rows resulting in errors and lot of time is consumed in correcting these errors. Based on the FMECA program developed, the workers service and maintain the machines and is also updated accordingly when a new failure data is found out.

At SKF, the physical machines are not standard. Meaning, the machine system, machine subsystems and the components are constantly removed from one machine and added to another to reduce the downtime and increase the uptime. So. there is no standardized way to track these parts to analyze their time for failure. Currently SKF develops the FMECA program for each machine component from scratch making it an extremely lengthy and cumbersome process.

1.6.2 FMECA Program Excel Sheet

The FMECA Program currently used in SKF is as shown in the Figure 1. The different criterias for the components of the machines are arranged in the columns. There is a total of 37 criteria for each Component which can be filled in by the user as required depending on the component. The data shown in the Excel Sheet below is just for one machine named SPC62. With SKF operating hundreds of machines worldwide, this data would run into thousands of rows making it extremely cumbersome for the user to narrow down on a specific piece of data for a component or to add new data for a specific component when new failure data is found out.

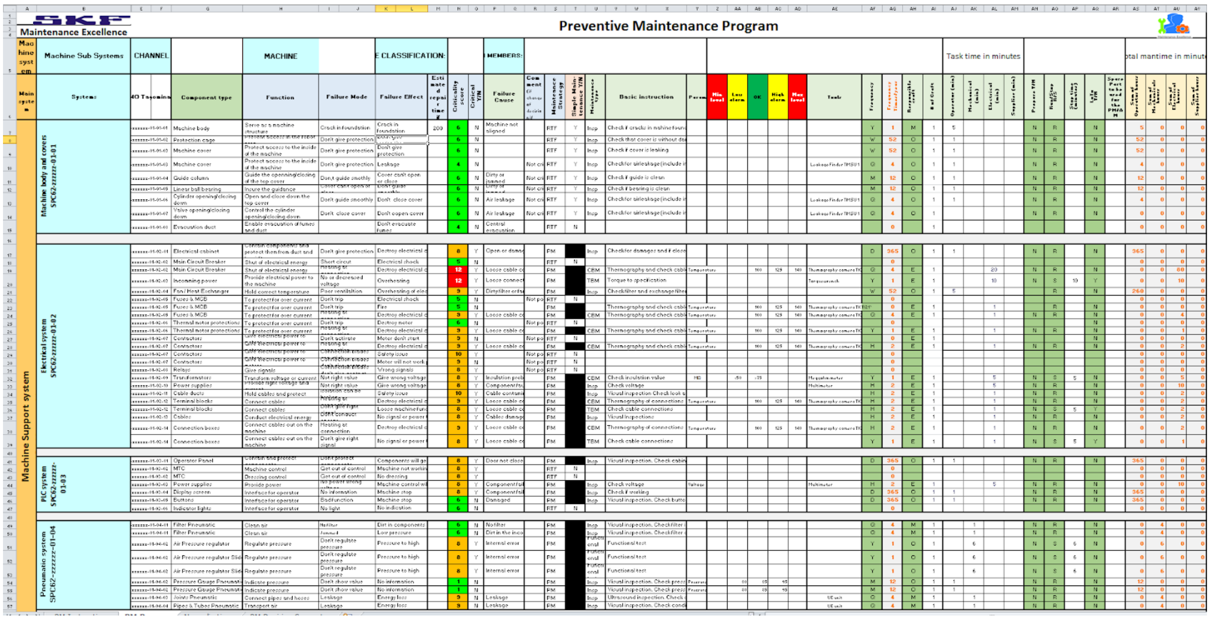

Fig.1 FMECA Program Excel sheet (SKF)

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Theory

The following chapter contains the established literature referred by the authors in the master thesis. In general, the concepts related to Reliability Centered Maintenance, Failure mode and Effect Analysis, Failure Mode, Effect and Criticality Analysis and the process of automating FMECA through Relational Database are explained

2.1 Reliability Centered Maintenance and its evolution

Reliability Centered Maintenance (RCM) is a process used to determine the most efficient approach that can be deployed towards maintenance. The process involves identifying the most cost-effective actions that will reduce the probability of failure. RCM is an amalgamation of reactive, preventive, predictive and proactive based maintenance methods. RCM is a continuous process which gathers data on the system performance which is analyzed to improve design and future maintenance. These maintenance strategies are integrated instead of being applied independently to optimize equipment facility, operability and efficiency while minimizing life-cycle costs. (Nasa, 2000). The evolution of RCM began in 1950's in the aircraft industries and it was a result of major reliability studies and a response to the ever-increasing maintenance costs and insufficient machine availability (Nowlan et al., 1978). The nonexistence of a relation between failures of equipment's and their age led to this development as the premise on which time-based maintenance did not hold good for most of the equipment's. Prior to RCM, Preventive Maintenance was the prevalent maintenance strategy that was used by the industries. The assumption that the failure probabilities can be determined statistically for components, machines in many cases to prevent failure proved to be ineffective. The studies on PM showed that there is a difference between the perceived and the intrinsic design life for most of the equipment and components. SKF, a bearing manufacturing company was a pioneer in establishing a change in method for evaluating bearing life from empirical method to one where bearings exhibit a minimum fatigue life. This process was known as Age Exploration (AE) and was used to extend the time between periodic overhauls and to replace time-based tasks with condition-based tasks. Development of new technologies to determine the actual condition of equipment and not relying on when the equipment might fail based on age has made RCM more prevalent. (Nasa, 2000). Time based maintenance should not be completely replaced with condition-based maintenance especially in instances where an abrasive, erosive, or corrosive wear takes place and if material properties changes due to fatigue, embrittlement then there exists a clear correlation between age and functional reliability.

2.2 The Reliability Centered Maintenance objectives and analysis

According to (Nowlan et al., 1978) and (Marvin, 1998) the objectives of RCM is to ensure the reliability and safety of the system or equipment, restoration of equipment after the occurrence of deterioration, improve the design if the reliability measures are inadequate, remove maintenance tasks that are not stringently necessary and accomplish the above goals at an economic cost. To accomplish these objectives, it is of utmost importance to derive a simple understanding and analysis of RCM. (NASA, 2000) suggests that the objectives can be met by answering and analyzing the following questions.

1. What is the function of the system or the equipment?

A function can be defined as the performance measures and expectation of a component and it can have several elements. For example, it is not just enough to define the function of a compressor to compress air. The function of the compressor must be defined how much air can be compressed per unit of time.

2. Which failures are likely to occur?

Defining failure depends upon the function of an item or a component or a system and the operating environment in which it is used. Failure can be simply considered as an unsatisfactory condition. A piece of equipment can be considered as operating (a compressor, for example) but if the output is less than desired then it has failed. On the other hand, if a small chip in the mouse has stopped working even though a mouse as a whole is still working then the system's function has not changed.

3. What are the modes and the consequence of the probable failures?

Failure modes is the various ways in which an equipment or a component can fail leading to the overall system functional failure. For example, a drilling machine can catastrophically fail due to the collective failure of bearing, windings, seals or controllers. Dominant failure modes must be identified as all failure modes will not result in consequential effect. The consequence of the failure will result in prioritization of maintenance activities. For example, if the consequence is not large enough maintenance activities will be at a minimum and on the other hand if the consequence is critical enough to cause a safety issue then utmost care and maximum activities will have to be assigned.

4. What is the action plan to mitigate the consequences of the probable failures?

The goal of RCM is to allocate the safest and the most cost-effective tasks to minimize the risks and impact of failure ensuring maintenance of equipment systems and functionality. According to (NASA, 2000) the development of action plans to reduce the consequences of the probable failures can be accomplished when the user understands the system boundaries, functional failure and failure modes all of which leading to the critical components of the RCM Program.

2.3 Reliability Centered Maintenance program components

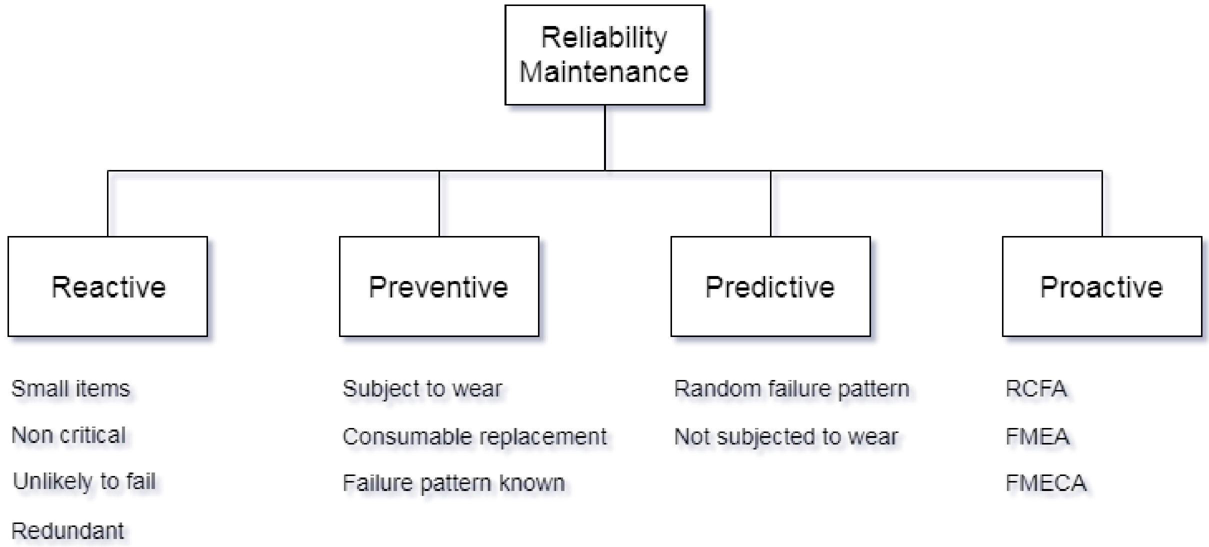


Fig 2: RCM Program Components (NASA, 2000)

According to (Mirka et al., 2007), (NASA, 2000) and (Islam, 2010), an RCM program includes reactive, preventive, predictive and proactive maintenance.

1. **Reactive Maintenance**: Reactive maintenance is also termed as run-to-failure, breakdown and repair maintenance. This type of maintenance assumes that failure is likely to occur in any part of component and that failure is not critical to the operation of the system. When this is the lone maintenance practice followed then there is a high expectation of failure rates with high inventories.
2. **Preventive Maintenance**: Preventive maintenance is also coined as time-based maintenance. It consists of scheduled maintenance program that includes inspection, machine parts adjustments, tightening of parts, replacement of worn out parts etc. It is performed regardless of the machine condition.
3. **Predictive Maintenance**: Predictive Maintenance is also called as Conditioning Based Monitoring (CBM). In this type of maintenance non-intrusive testing methods are used to monitor the current performance of the equipment. The data or the trend collected from the testing methods gives information about the current condition of the equipment. Depending upon the condition the personnel can decide whether to schedule any maintenance activity before failure occurs.
4. **Proactive Maintenance**: Proactive Maintenance is more diligent and systematic when compared to other maintenance types. According to (NASA, 2000) proactive maintenance improves maintenance program through better design and installation procedures.

The project is based on the FMECA that is derived from Failure Mode and Effect Analysis (FMEA), which is an important analysis tool under Proactive Maintenance (as seen in the Fig: 2). Henceforth majority of the discussion will be based on FMEA and FMECA and only small parts of the rest of the program will be discussed if need be.

2.4 Failure Mode Effects Analysis-FMEA

FMEA is a “systematic process for identifying potential design and process failures before they occur, with the intent to eliminate them or minimize the risk associated with them”. FMEA is built on standard procedures used in reliability engineering industries. (Krzysztof, 2002). According to (Mobley, 2014) FMEA is one of the first systematic approach towards risk analysis. FMEA requires extensive use of tables for the components, assemblies and subassemblies that make up a complex system. It is a deductive technique that comprises of identifying all the types of component functions, all possible functional failures, the causes for failures and the effects of failures and steps to prevent the failures. According to (Vanderley et al., 2009) FMEA is also needed to perform brainstorming with the operators to collect more information for the type of failures that can occur at a component level**.** In general, the FMEA requires the identification of the information for Components, Component functions, Failure modes, Failure effects, Risk priority number (RPN), Failure causes, Recommended action plan, Personnel or department carrying out the action plan. To assess the risk associated with the problems recognized during the analysis and the action plans prioritization, two methods using Risk Prioritization Number (RPN) and Criticality Analysis are used.

2.5 Failure Mode, Effect and Criticality Analysis-FMECA

FMECA is similar to FMEA with a few exceptions: it uses a different risk evaluation method and standard. To carry out FMECA it is imperative that the analyst performs FMEA first and then carry out Criticality Analysis. According to (Carlson, 2012) there are two reasons for an organization to use FMECA over FMEA. One is when the customer mandates and when mandated a certain standard like Military Standard (MIL-STD) 1629A or Society of Automobile Engineers (SAE) ARP5580 is followed. The second reason is the organization may wish to gather more information from the criticality analysis provided the organization has enough time and information to carry out the same. (MIL-STD-1629A, 1980) indicates that there are two types of FMECA, one is the qualitative FMECA and the other is the quantitative FMECA. According to (Carlson, 2012), the two FMECA types are similar in terms of functionalities with the exception that quantitative FMECA follows the quantitative criticality analysis whereas the qualitative FMECA follows the qualitative criticality analysis. According to (Carlson, 2012), the graphical depiction of comparing the failure modes based on severity and occurrence is termed as the criticality matrix. The severity rating indicates the horizontal axis and the probability of occurrence rating indicates the vertical axis. Sometimes color coding to visually depict the severity is also used.

2.5.1 FMECA Tree Structure

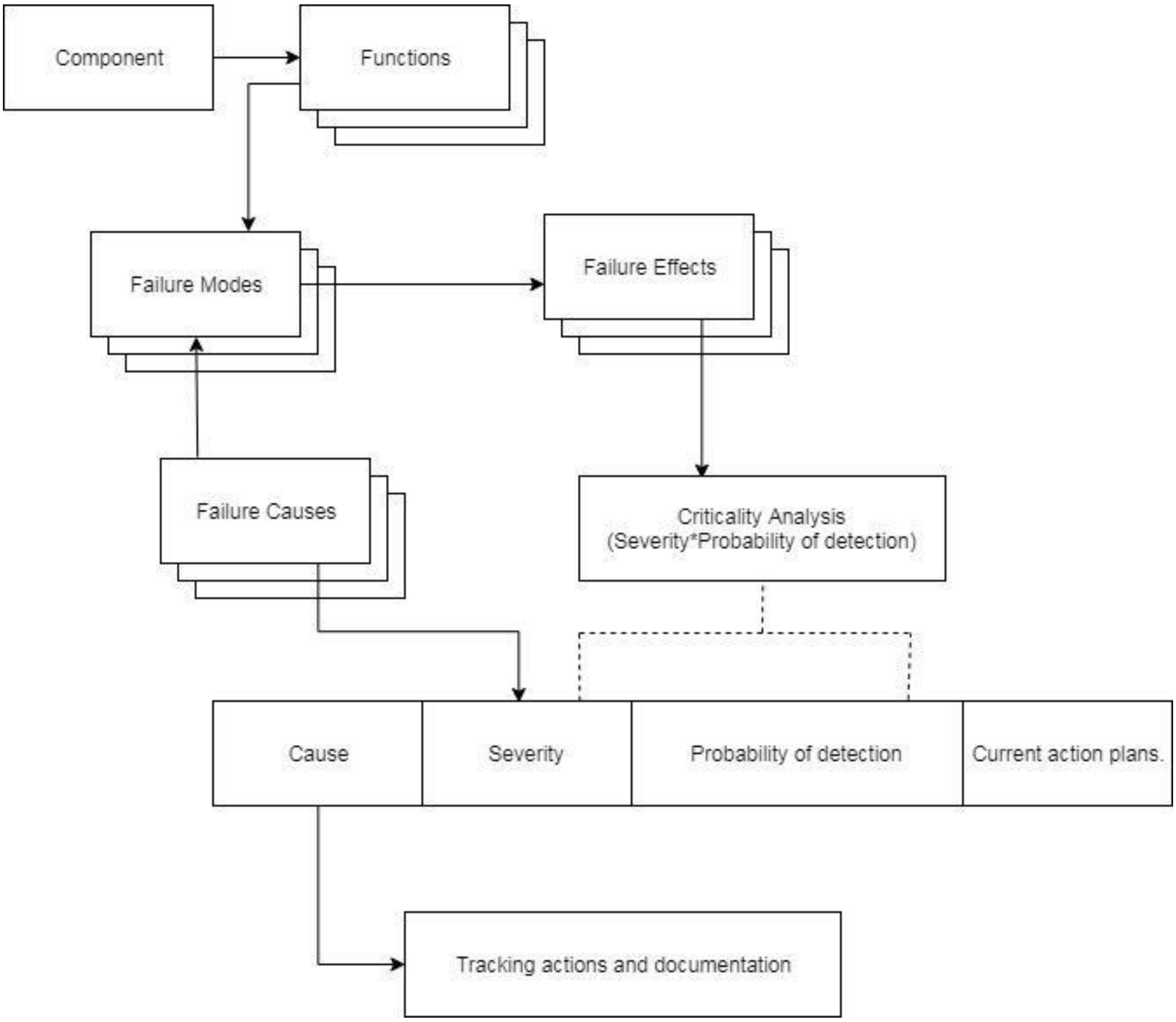


Fig 3: FMECA Tree Structure

2.5.2 Problems of using FMECA in a spreadsheet

Most of the FMECA's used today in the manufacturing industry are either manual or Excel based spreadsheet. This kind of format is suitable when maintaining simple calculated set of data. Data sorting and filtering is easy and simple. But Excel is not built for maintaining complex data containing hundreds of interrelated records because it is prone to errors and duplication leading to tedious data analysis. The FMECA is a complex data analysis process and can be easily analyzed if its information is presented in a tree structure (Fig: 3). A single component can have many functions and it can fail in many ways. Also, a single failure mode can have one or multiple effects. And that failure mode can occur because of many failure causes. Hence, FMECA does not follow a cause and effect relationship. FMECA represented in a spreadsheet is not a living document. It has unattractive user interface, limited security control, less support for teamwork with extensive scrolling and non-user friendly (Khairul et al., 2014). It can be sometimes misleading due to its arrangement in a row-column format. Imagine personnel, with limited knowledge in Excel, who is told to create an FMECA program for a new machine with components that are similar to the components of the machine whose FMECA is already existing. Since it is a new machine, its components' failure modes, effect and causes might not be exactly same as the existing one. Hence the personnel must click on selected rows and paste it. This process is error prone leading to mistakes in the new program thereby leading to wrong analysis and incorrect output. This process is also not user friendly and consumes more time. Another problem with the Excel sheet is data replication. Data replication can lead to errors and inconsistent values. To overcome such issues, it is important that all the FMECA related data is stored in a database in a well-organized fashion to efficiently access and manipulate the data (Kukkal et al., 2002).

2.6 Database Management Systems

Database management systems are a collection of programs that enable the user to store, modify and extract information from a database. These systems can run on personal computers to huge mainframe systems. There are several types of database that the authors initially researched on to implement the FMECA program. Several of them are discussed below: -

- **Flat File Based Database Management Systems**

  Flat File based database management systems are probably the simplest of them all. These are sometimes called Flat models. These come in human readable text formats as well as in binary formats. These are ideal for standalone applications, holding software configuration and native format storage models. Flat files in a formatted row and column model rely on assumptions that every item in a particular model consists of the same data. One common example of this type of database is the CSV (Comma Separated Values) and another is a spreadsheet such as MS Excel.

- **Hierarchical Database Management Systems**

  Hierarchical database management systems operate on the parent-child tree-like model. These normally have a 1: many relationships and are good for storing data with items describing attributes, features and so on. These could store a book with information on chapters and verses. They can also be used to store a database of songs, recipes, models of phones and anything that can be stored in a nested format. Hierarchical database management systems are not quite efficient for various real-world operations. One such example of a Hierarchical database management system is an XML document.

- **Network Database Management Systems**

  A Network database management system uses a data model like Hierarchical database management systems. The major difference here is that the tree structure in the Network models can have a many parent to many child relational model. The Network model structure is based on records and sets and most of these databases use SQL for manipulation of their data. Network database management systems tend to be very flexible but are rarely used and were common in the 1960s and 1970s. Searching for an item in this model requires the program to traverse the entire data set which is quite cumbersome. These have mainly been replaced by Relational database management systems in today's modern computing.

- ### Relational Database Management Systems

  Relational database management systems are the most widely used database management systems today. They are relatively easy to use. Relational database management systems are named so because of the characteristic of normalizing the data which is usually stored in tables. The relational model relies on normalizing data within rows and columns in tables. The data can be related to other data in the same table or other tables which have to be correctly managed by joining one or more tables. Relational models may be somewhat less efficient than other models; however, this may not be a problem with the processing power and memory found in modern computers. Data in this type of model is stored in fixed predefined structures and are usually manipulated using Structured Query Language (SQL). Relational database management systems include Oracle, MS SQL Server, IBM DB2, MySQL, SQLite and PostgreSQL among others.

- ### Object- Oriented Database Management Systems

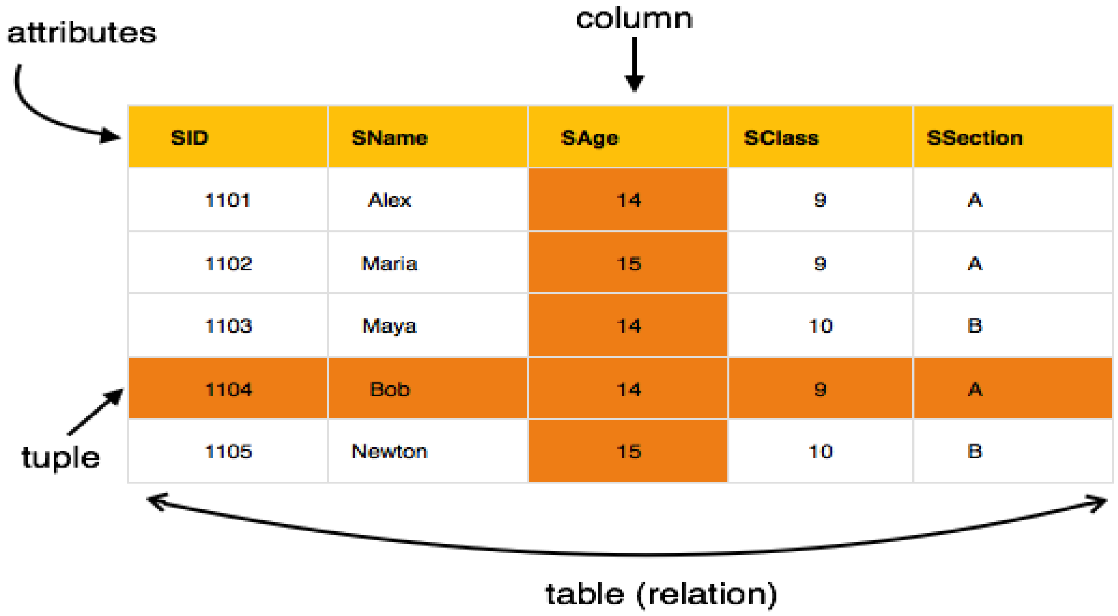
  Object-oriented database management systems borrow from the model of the Object-oriented programming paradigm. In this database model, the Object and its data or attributes are seen as one ad accessed through pointers rather than stored in relational table models. Object-oriented database models consist of diverse structures and is quite extensible. This data model was designed to work closely with programs built with Object-oriented programming languages thereby almost making the data and the program operate as one. With this model, applications can treat the data as native code. There is little commercial implementation of this database model as it is still developing.

2.7 Relational Database

A relational database is a logical set of collection of data structured in the form of relations. The data is stored in what is called as tables. The tables can be considered as a small set of spreadsheets whose data is arranged in rows (also called as records) and columns (also called as fields). There can be multiple tables and each table has a primary key which is unique and identifies the set of information. The relation between the tables can be established with the help of a foreign key. The **Objects** which have been used in designing the database have been briefly explained below and the reason for using them. Objects are used in database to help the user identify and organize information. Relational database provides many objects but the most commonly used and the ones that have been used in this thesis are Tables, Queries, Forms and Reports.

2.7.1 Tables

Table is an object that is used to define and store data. Each column in a table must have unique name and data type. An entity is generally used to represent a table and the columns of that table are its attributes. Similarly, different entities can be presented in different tables and they are represented through entity relationship model. The tables in the database are generally designed to only those entities whose attributes have a large number of data and the possibility of addition of data in the future. The other attributes which have a limited number of functions have been placed in a master table to which all the other tables are related through a entity relationship model (Mark et al, 2007).



SID	SName	SAge	SClass	SSection
1101	Alex	14	9	A
1102	Maria	15	9	A
1103	Maya	14	10	B
1104	Bob	14	9	A
1105	Newton	15	10	B

Fig 4: Generic Table

The database is designed using the entity relationship model which consists of Entities which is used to represent a person, place, object, event or idea. The entity in a database has its own table. Within the table of this entity are the attributes. Attributes are used to describe the characteristics of the entity. The instances of the entity class which share some common properties are categorized under the same entity and relationships, which is used to define the association and the cardinality among the different entities. It is a connection between the entities. The cardinality shows how much of one side of the relationship belongs to how much of the other side of the relationship. Cardinality exists in four forms namely. As said earlier there are three different types of relationships namely **One to one** which refers to the relationship between two tables where each record appears once or each record in the first table can have only one matching record in the second table and each record in the second table can have only one matching record in the first table. The relationship is created by linking the primary key to another primary key in another table which shares some value. **One to many**, a type of relationship that refers to the relationship between two tables where each record in the first table can have many matching records in the second table but each record in the second table can have only one matching record in the first table. The entire database has been established using this relationship model and **Many to many** relationships that refers to the relationship between two tables where many records in the first table can have many matching records in the second table and many records in the second table can have many matching records in the first table. Generally, many to many relationships are established with the help of a junction table which is a table used to map tables together by referencing the primary keys of each data table. As a result, the junction table will consist of several foreign keys each in a many-to-one relationship from the junction table to the individual data tables. The use of junction table essentially makes the relationship into a one to many relationship model (Harrington, 2016).

Primary Key is a specific choice of a minimal set of attributes that is designated to uniquely identify all the table records. It is basically a key which uniquely identifies a specific record in the table. As the primary key contains unique data, they are frequently defined on an identity column. The primary key cannot contain null values and must contain a unique value for each row of data and **Foreign Key** is a column or combination of columns that is used to establish and enforce a link between the data in two tables to control the data that can be stored in the foreign key table. In a foreign key reference, a link is created between two tables when the column or columns that hold the primary key value for one table are referenced by the column or columns in another table. As a result, this column becomes a foreign key in the second table. In this database majority of the primary keys of the different tables have been placed in the master data table and the rest have a link to the master table from another table through the one to many relationships (Jeffrey et al., 2004).

2.7.2 Join Types

The extent of the overlap between the records from two different tables determines the join types. Depending on the subset that is to be selected from the two tables the different join can be conceived. If there are two sets of data in a database namely Table A and Table B with a relation between them specified by the primary and foreign key. The result of the tables when joined would be one of the three join types namely Inner Join, which is used to obtain all the records from Table A and Table B, where the join condition is met. Left Join which is used to obtain all records from Table A, along with records from Table B for which the join condition is met if there a match if at all and Right Join, which is used to obtain all the records from Table B, along with records from Table A for which the join condition is met if at all.

Since all the tables relate to the master data and it is important to obtain all the records from the master data regardless of the match between the keys, only the left join has been used throughout the design of the database. **Derived Data** is the data that is derived from the other data that is already saved. Suppose there are two columns and the third column obtain the data from the relation between the two columns, then it is known as derived data. A change in data in one of the columns of the two columns will result in a change in the derived data column as well. Some of the fields in the master data use the concept of derived data where a change in one field results in a change in another field automatically based on the expression that has been written for the change.

2.7.3 Normalization

It is the process of organizing attributes in the columns and the relationship between the different tables of a relational database to minimize data redundancy and maintain data integrity. The data is split into multiple tables to improve overall performance, longevity and ensuring that the data dependencies make sense. The Excel sheet obtained from SKF Maintenance Excellence was used for the normalization process. There are three types of normalization forms upon which the database can be designed such as **First Normal Form** where each attribute can contain only one atomic value and the value of each attribute contains only a single value from that domain. This form ensures elimination of duplicate columns from the same table, separation of table for each set of related data and identification of each set of data with a primary key, **Second Normal Form** where apart from meeting the requirements of the first normal form, all the non-key columns must be functionally dependent on the table's primary key. The Excel sheet is converted into the second normal form from the first normal form and **Third normal Form** where apart from meeting the requirements of the second normal form, there must be no transitive functional dependency that is all the non-key columns must be functionally dependent only to the table's primary key. Suppose, if there is a following relationship in the table: A is functionally dependent on B, and B is functionally dependent on C. In this case, C is transitively dependent on A via B. Then the database is not in third normal form. The tables that have been designed in the database are based on the guidelines for obtaining the third normal form. The data obtained from SKF was established in First Normal Form. (Harrington, 2016)

2.7.4 Queries

Queries are used to extract data from the database and format the same in a readable form. A query is generally written in the language the database understands known as structured query languages (SQL). If used wisely the query can be utilized to obtain complex trends and activities from the database. Since the database consists of multiple tables storing a myriad of data, query can be used to filter it into a single table so that the data can be analyzed easily. (Mark et al., 2007)

2.7.5 SQl

The data stored in the database can be retrieved by using the Structured Query Language, or SQL. SQL is a computer language that closely resembles English. Every query that is used in the database runs the SQL behind the scenes. It is required to follow the correct syntax when using SQL, which is a set of rules by which the elements of a language are correctly combined. The SQL statement has clauses and each one of the them performs a specific function. Some of the clauses that have been used in the database design are SELECT, FROM, WHERE, ORDER BY, GROUP BY HAVING (Harrington, 2016).

2.7.6 Visual Basic for Applications

It is a language embedded within the database. It enables building user defined functions, automating the database processes, control aspects of the host application, manipulating user interface features used in customer user forms. In short, every operation that can be performed with a mouse, keyboard, or a dialog box can also be done by using VBA, the repetitive tasks can be automated, and the user interface can be designed in a way specific to the business needs. VBA includes a Module which is container of code that helps organize the code which can be assigned to a form or a report. The module consists of a **Function** which is a bunch of code grouped together so that they can be easily managed, and they return a value. The code is reusable and be called repeated and a **Subroutine** which is also a group of code grouped together so that they can be managed easily and can be called repeatedly, and it does not return a value. It is the code performed when a form or a report triggers an event.

VBA also includes other items such as variables which is used hold a space in the memory to store data and assign and recall the values. The values can be changed and recalled repeatedly. The VBA code can be placed behind an event procedure such as the "On Click" event of a command button and Executed in the Run Code action in a macro. In this Database design, significant amount of VBA code has been written to different event actions such as before, after and on close to perform specific function in forms and reports (Harrington, 2016).

2.7.7 Referential Integrity

It is a feature in relational database management system which ensures that the relationships between the different tables in a database remain accurate by providing constraints to prevent the users from entering the data in one table and linking to it another table where the data does not exist. Suppose Table B has a foreign key that points to a field in Table A, then referential integrity would prevent the user adding a record to Table B that cannot be linked to Table A. The referential integrity has been used in this database design to avoid the above said errors (Mark et al., 2007).

2.7.8 Forms

A Form in Access is a database object that is used to create a user interface for a database application. It is a more user-friendly way of entering the data into the fields of the tables instead of directly entering the data in the tables. There are two kinds of forms namely **Bound Form** which is directly connected to a data source such as a table or query and is used enter, edit, or display data from that data source and **Unbound Form** which is not directly linked to a data source, however the command buttons, labels and other controls can be used to operate the application. The forms designed in the database are mainly based on the bound form where the data entered in the form results in a change in the master data table. Also, an unbound form has been designed to open other forms through command buttons and not to enter data into the tables (Mark et al., 2007).

2.7.9 Reports

A report is a formatted result used for analysis. The results are obtained from tables and queries. They provide a way to achieve or distribute the snapshots of data, either by printed out or by converting into different file formats like PDF or XPS. Reports provide details about individual rows or many rows. All the reports designed in the database are dependent on the forms and it has been designed in such a way that the user has to first select a criteria in the form and entire data for that particular criteria can be obtained in the report associated with that form (Mark et al., 2007).

2.8 Ways of sharing an Access Desktop Database

There are several ways in which you can share the Access database depending upon the customer requirements and system availability. Several of them are discussed below:

- **Network Folder**

  This is the most simplistic method and has the least requirements but at the same time has the least functionality. In the system, the database is stored in a network drive and is shared with many users who can use it simultaneously. Reliability and availability are the major concerns in this type of sharing if multiple users start editing the data at the same time. Since the database network is sent across the network performance can also be an issue. This system might work if there are few users and there is no customization of data design.

- **Split database**
  This system works if there is no SharePoint sharing. In this type of sharing the database sharing is split into two parts. One part is the backend database that contains the data tables and the front-end database containing all other objects like forms, queries and reports. The users interact with the data with the local copy of the front-end database.

- **SharePoint lists**
  This type of sharing is similar to split type database and the users can use their own copy. This is possible since it is shared on the SharePoint site. It is possible to access the centrally located data. Using the SharePoint features the database can be made separately available.

- **Database Server**
  This type of sharing is the most beneficial but at the same time requires additional software- a database server. This method is similar to split database where in the user have their own copy of the database.

2.9 Advantages of using FMECA in a Relational Database Tool.

To negate the problems associated with the Excel sheet, a relational database can be a suitable tool. Apart from the problems associated with the Excel sheet the flexibility and extensibility of FMECA should also be taken into consideration. As the FMECA comprises of different forms a high degree of flexibility must be taken into consideration (Huang et al., 1997). A relational database functionality provides this flexibility by storing all the related information in one single location and allows the user to connect the different parameters together (Kukkal et al., 2002). It minimizes the potential of creating duplicate and inconsistent values. The data integrity is the biggest advantage of a database where in the user needs to change only one set of record and all other information related to it will automatically link to the change. Database can provide better control and security thereby providing better productivity. It can also be controlled with an encrypted password and a username.

2.10 Automating the process of FMECA through Relational Database

According to (Kukkal et al., 2002) automation of FMECA can be obtained in two stages by first automating the clerical component (data collection) and then automating the analysis component. To attain stage one, the FMECA process data must be stored in a structured database (not necessarily relational) that can be accessed efficiently. Accomplishing stage two requires additional knowledge and reasoning skills that can be acquired by using the database. Automating FMECA through relational database has the potential to provide immense benefits. An analyst can concentrate more on the analyzing the data rather than collecting and formatting the same. Automating FMECA can also eliminate redundant data making it more efficient and consistent. Filtered data can be obtained making the process faster and accurate. According to (Kukkal et al., 2002) to help the analyst in the FMECA process, the FMECA database system must satisfy number of requirements. The failure modes and the likelihood of the occurrence must be stored for each component and its function. It must exactly relate the failure effects and failure causes to the failure modes as entered by the analyst. (Kukkal et al., 2002) also says that the system designed must be accessed in a multi user environment and the filtered data is tailor made for a specific user. This report answers the questions on how best to automate the FMECA process by organizing the data in a database to reap the benefits of automation.

3

Methodology

This chapter depicts the methods and tools used in the master thesis. It is organized by describing a short theory behind the established methodologies and required tools for realizing it. Moreover, common methods adopted for both the methodologies and research quality are also presented in this chapter

3.1 DMADV [Define, Measure, Analyze, Design, Validate]

DMADV is a methodology for analyzing and improve business needs and processes. It is an integral part of the Six Sigma but can be used as a standalone analytical tool for process improvement (Selv et al., 2014). This methodology focuses on the development of a new service, product or process as opposed to improving a previously existing one with the help of several tools and techniques to develop the solution. The method allows the organization to determine the customer's most important needs and design a system based on it. DMADV is generally used when a non-existent product or a process is to be developed at a company or when an existing product or process exists and still needs to meet the customer specification and expectations (Peter, 2007). Since the project involved the development of a new database system which had to be a better tool than the Excel template used before, this methodology was preferred over the others. The methodology was modified in accordance with the needs of the master thesis. It consists of five phases viz: Define, Measure, Analyze, Design and Validate. Each phase has a set of tools and they are as shown below: -

Fig 5: Tools of DMADV

3.2 Define

The define phase involves understanding the current problem in the system as told by the customer. This phase also involves defining the project objectives, scope and the deliverables which will be delivered at the end of the project. A Project charter tool outlining the different stages of the project with its timeline for completion and start date was designed and used for this purpose. However, as the project progresses the different phases during the development is updated throughout the lifecycle of the project due to new findings and changes in design strategies.

3.3 Measure

The measure phase ensures better understanding on the current state of the problem by gathering comprehensive information about the problem. This phase is generally carried out by conducting detailed data collection through various tools (Bishu et al., 2009). The methodologies used in this project was first conducting interviews and researching on the problems through literature survey. Then a Voice Of Customer methodology was initiated to capture the expectations and preferences from a stakeholders point of view based on which the objectives to be delivered was determined.

3.3.1 Data collection

Data works as the foundation for any research, thus the outcome of a research is heavily dependent on the quality of the collected data (Yin, 2003). Following subchapters cover the data collection activities of the thesis.

- **Interviews**

  One part of the data collection process was to interview people associated with the maintenance program creation. The purpose of the interview was to acquire information about the problems faced by the users and the software's that can be used to develop maintenance program. The interviewees chosen were employees who are related to the maintenance Excellence team and the software developers at SKF. These included **(a) Maintenance Program Developer (b) Maintenance Methods engineer (c) IT Engineer and (d) PLM Professor at Chalmers.**

- **Interview type, Structure & Guide**

  Before going ahead with the interview, the interview type needs to be determined. In theory there are three types of interviews (Qu et al., 2011) namely **Structured,** where the interview type is characterized by using a set of prepared questions with a limited amount of answers. Open-ended questions are avoided, **Semi-structured** where the interview is formal, and the interviewer uses a guide of topics to be covered. Usually these topics follow a specific order and when appropriate allows for more in-depth discussion. In this type of interview the interviewee is normally only interviewed once and finally **Unstructured,** where the approach is formal and uses strictly open-ended questions, trying to get the respondents to open up.

  The interviews were carried out in a semi structured way and the reason for going ahead with this approach was due to time limit of the research and since the interview was only one part of the data collection process. The interviewees to be interviewed were decided after the identification of the main stakeholder for the project, the Maintenance Excellence team. Therefore, the people interviewed involved maintenance managers, maintenance engineers and maintenance operators. However, since the project involved the development of a database, experts from Information Technology, Academia were consulted and interviewed as well. The development process of the interview guide was to first prepare a draft based on the questions developed by the authors. The questions developed were based on the objectives to be delivered and the topics which the authors had very little knowledge about.

- **Literature Study**
  Literature study was mainly conducted on the evolution of RCM, FMEA, FMECA and finally on the different types of database management systems in use and the process of automating the FMECA program creation. The information was obtained from technical papers, scientific studies and online websites. The focus was on the use of RCM and FMEA followed in industries.

3.4 Analyze

The analyze phase aids brainstorming the potential root causes of the problems faced, develop hypotheses as to why problems exist and then work to prove or disprove their hypothesis and come up with several promising solutions which can be implemented. This phase is initiated by analyzing the data obtained from the measure phase, followed by further data collection of process after pilot changes and then finally analyze the data obtained after making the changes (Breyfogle, 2003). This leads to finding insights to various improvement solution for the process. The authors used a Voice of Customer analysis as tool towards analyzing the problems faced by the users and laying out the objectives which needed be to be achieved in the new product.

3.4.1 Voice of Customer & Critical to Process

In a layman's language, the Voice of Customer (VOC) is what the customer requires for a specific project/product/process. It is used to capture the expectations and preferences from a stakeholder's point of view. It is also concerned with the end to end alignment of requirements in an industry. A successful project outcome depends a lot on analyzing the stated 'voice' more than merely doing what the customer wants. The VOC can be captured by interviews, surveys, observations and suggestions and it forms a solid basis. Critical to process (CTP) are the measurable parameters related to VOC and is an output to the customers requirement to improve performance (Abbie et al., 1993).

VOC provides key input on capturing the business requirements. It is very important to translate the subjective requirements of the customer into objective requirements. The VOC was classified into four different categories viz. Process, Technical, User and General. The preliminary VOC was to design the FMECA program in a Database System. The designed database system shall be user friendly unlike the Excel sheet that would bring with it various forms of complexity due to redundancy, duplication and growth in complex data. These issues would be amplified especially if the operators are novice users. It was also required to build new machine data from existing machine data by simplistic selection without having to create new data. Another important voice of the customer was that the new system shall be accessed online by users to edit the data. Above all the new system must be up and running within 20 weeks. All these critical inputs from SKF prompted the group to investigate database that is first and foremost easy to implement within the prescribed time limit, user friendly and simple to use.

3.4.2 Weighted Score Method/Matrix (WSM)

The weighted criteria matrix is a valuable decision-making tool that is used to evaluate program alternatives based on specific evaluation criteria weighted by importance. By evaluating alternatives based on their performance with respect to individual criteria, a value for the alternative can be identified. The values for each alternative can then be compared to create a rank order of their performance related to the criteria as a whole. The tool is important because it treats the criteria independently, helping to avoid the over-influence or emphasis on specific individual criteria (Aristidis et al., 2011).

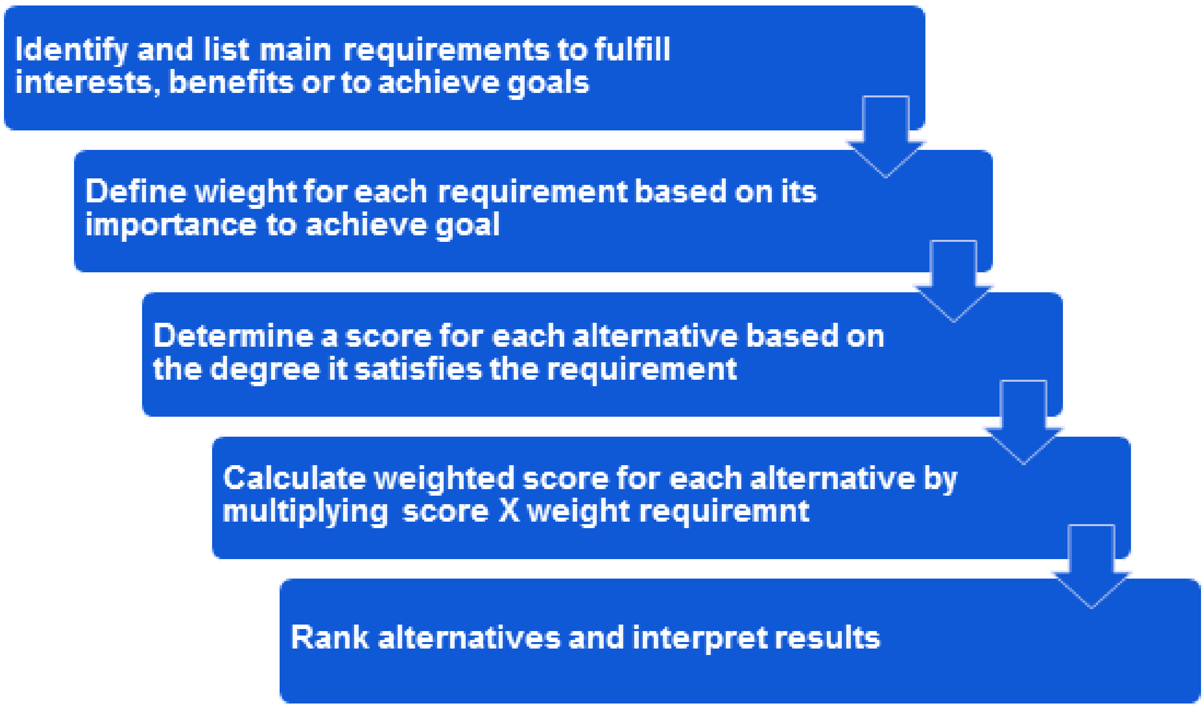


Fig 6: WSM Methodology

The alternatives that have been used in the method have been scored based on their importance. Criteria score of 5 is given for High importance, 3 for Medium Importance, 1 for Low Importance. These ratings are based on the author's convenience and ease to motivate the decision of using a database system.

Evaluation Criteria	Criteria Scores	Access		Microsoft SQL		Mysql		ORACLE	
		Score	WS	Score	WS	Score	WS	Score	WS
Cost	A	B	A*B						
Usability									
Reliability									
Time									

Authorisation									
Total									

Table 1: Weighted Score Matrix

3.5 Design

This phase is the most critical of the DMADV process as it is imperative to the success of the project. This phase represents the detailed and complete design of the Relational database. The design developed is based on the criterias derived from the previous phases (Chowdhury, 2002). Since the project involves the design of FMECA program in the relational database tool containing a myriad of functions to develop the database as per the user requirements, the design has been developed using most of the available functions and objects described in the Theory section.

3.5.1 Relational Database design

A relational database is a type of database that organizes data in the form of tables and these tables consists of rows and fields that represents the data. The rows are called as records and columns are called as fields. Apart from the tables there are three other main parts of a relational database. These are called as forms, queries and reports. To relate the tables, it is imperative that a relationship is first established between them and these relationships define the entire database and are vital for the output. A relationship can be established when the value in one field (called the primary key) in one table compares successfully with a value in the field in another field (called as secondary key) according to the criteria specified in the relationship. Keys usually are the holder of the unique values called as ID's (Harrington, 2016). A relationship between two tables can be established in one of three different ways: one to one, one to many or many to many. The output obtained after establishing any one type of relationships described above depends upon what are called as joins. A join can be considered as a set of instruction given as input to extract data from the related tables. There are three types of joins, they are inner join, left join and outer join. The main aim of relational database is to reduce redundancy and improve data integrity and to achieve this a process called as normalization is done to restructure the relational database and make it simple. The data simplicity and restructuring are done on three different levels: first normalization form, second normalization form and third normalization.

3.5.2 Working of Access relational database

As discussed earlier in the project there are many relational database tools but since Microsoft Access is the tool used for the project the generic working will be referred to it. So far, the main parts of Access viz: tables, forms, queries and reports have been described in isolation. When they are used together they display a wonderful synergy. Query is a storable question that is asked to extract specific data that is extracted via tables. Forms are based on the tables and hence they can be based on the query. Reports are based on tables and hence they can be based on queries. Hence forms and reports are based on queries (Mark et al., 2007). Suppose we have a table that contains information about production data of machines. If a query is created to extract the production data of a particular machine whose output is less than say 50%, a form can be based on that query. When we tell the system to use the form, it will run the query automatically and extract the relevant data and display it in the form. In general Access database there can be one or many queries, forms, tables and reports depending upon the intricacy of the stored data. Forms are the media through which the user interacts with the data. With the provision of button one form can be constructed to interact with several other forms. In usual practice the database is best built on multiple tables. Database built on a single table are suitable for simple data but not for complex data, which is a data that most users wants to store and manipulate (Mark et al., 2007).

3.5.3 User Interface

User interface is the front-end application with which the user interacts to use the software. With this the users can manipulate and control the software. User interface is part of the software and is designed in such a way that it is expected to provide the user an easy insight of the software. The User Interface in this case which has been focused on is the Graphical User Interface. The main intention behind the development of the software was to make it easier for the maintenance engineers to develop the FMECA program for the Maintenance Engineers easily eliminating the current Excel sheet with the help of a well-developed easy to use User Interface.

3.6 Validation, testing & implementation

This is the final phase and it verifies if the design suits the requirements of the user and customer (Thieleman, 2002). Also, before implementing the product into actual use, it is imperative to check if the products works appropriately in normal working condition.

3.6.1 Validation & testing

The testing phase involves the execution of the software to determine if the software meets the requirements that guided its design and development, responds correctly to all kinds of inputs, performs its functions within an acceptable time and finally achieves the general result the stakeholders desire. Since the number of possible testing for a simple software is infinite, a strategy was laid out to test the database software developed based on the time and resources available. The intent of such testing is for finding software bugs which in this case is finding defects and errors. The job of testing is an iterative process as when one bug is fixed, it can give rise to another bug, or can even create new ones. The strategy that was laid out for executing the testing of the software and for finding the errors was to have constant communication with the stakeholders or the end users on the development of the software. Getting the end users involved at this point is a good way to get them excited about the system, as it also acts as a way of training them. Once the developed function is agreed on, the software is tested for errors by inputting various possible combination that would be used by the users once they start to work.

3.6.2 Training & User Manual Creation

Training of the end users is one of the most important keys to a successful implementation of any software. Getting the end user involved in this phase is pertinent. The assistance of end users in parallel testing will help them prepare for when the system goes live. Since end users are good at using the system in more of a "real world" situation they can judge when process flows are not working. Even though the system may have been tested for functionality and all customizations are working accurately, if the end users do not know how to use it or feel uncomfortable with it, then the launch of the new system will be viewed as unsuccessful. Therefore, the timing of the end user training is critical. Also, equally important is the design of a User Manual which forms an important part of the formal training program to improve the quality of a performed task. The intention of preparing the User manual is that it is supposed to be used as a general reference document or an outline of the standard procedures that is to be followed during training. The User Manual involves a step by step instruction on how to use the software with pictures developed by real examples.

3.6.3 Implementation

After the development of the Database software, the final step is the implementation which is the realization of the application across all the SKF factories globally and making sure that all the users have the access to the Database software through an online sharing platform.

4

Results

This chapter depicts the empirical results established, obtained by the application of the methodologies and tools used by the authors

4.1 Interview Summary

The interviews and the literature study enabled the authors to understand the overall dynamics involved with the problem of creating maintenance programs for the machines and the user's problem in developing the programs at SKF. Also, the authors were able to understand the importance of developing a software to ease the process of Maintenance Program creation by using one of the economically efficient database software's available commercially. The interviews conducted have been summarized below.

Maintenance Excellence PM Developer, SKF

The interview was with the Maintenance Excellence PM Developer who is the architect of the PM Excel template. The discussion revolved around the difficulties faced by engineers in using the current template. The expert shared that the main problem with the Excel sheet is the change in format when new data is being entered or modified which results in confusion and increases the possibility of entering data in the wrong columns or rows. Also, since the PM has been created for only 2 machines systems as of now and in future when new machines are being added which mainly consists of repetitive data it would take a lot of time entering them manually.

Maintenance Methods Engineer, SKF

The interview with the maintenance methods engineer focused on the importance of developing a web-based application for developing the maintenance program and the different relational database software's which can be used to develop one. The expert stressed on developing an application on devices such as iPad or a mobile phone which the operator would find easy to use and download the required maintenance program. He also suggested the use of a relational database system such as MS Access for demonstration purpose as the development of a full-scale application in software's such **Microsoft Azure Cloud, MySQL** would require licenses and be time consuming.

IT Engineer, SKF

The interview was with the IT head at SKF, responsible for development of SKFs software Mobile Operator Support Tool (MOST). The interview covered topics on the working of relational databases and the principles related to it such as normalization. The expert shared his views on the practical implementation of such a software at SKF and the technicalities behind relational databases. He briefly gave an overview about reducing the complexity between the different tables in the relational database system during normalization procedure by trying to establish a one to one or one to many relationships between the different tables instead of using many to many relationship.

PLM Professor at Chalmers

The interview was with the Product Lifecycle Management (PLM) course Examiner at Chalmers. The discussion was mainly on the use of different relational database management systems. He was of the opinion that creating an online database which can be accessed all the over globe across SKF factories can lead to security issues such as confidential data being misused, altered or deleted leading to bigger problems. He also gave an option of using current Excel sheet and developing macros to ease the use of it.

Manufacturing Reliability Engineer, SKF, Luton (UK)

A telephonic interview with the manufacturing reliability engineer from Luton, UK revolved mainly around the difficulties operators face using the current PM Excel sheet. The consensus among all the workers was that their knowledge on the use of computer is very limited which makes it tough for them to work with Excel. Also, since Excel sheet contains a lot of data, they sometime end up modifying or entering the data in wrong columns or rows.

SKF Factory visits, SKF Bangalore - 10/12/2017

A visit to SKF factory provided an insight as to how the Fault Tree Maintenance (FTM), a CMMS software similar to API Pro at Gothenburg, is used. The authors met with Maintenance Experts who explained as to how the system works in Bangalore, India. As told by the experts the FMEA for current machine system is not completely broken down to component level in FTM and a further analysis must be done so that a detailed work breakdown is achieved. The problem with the current software was that whenever a new work order is created at a machine level there is no option of selecting the components, therefore, the work order automatically selects the entire machine causing problem of automatic selection of all components creating multiple work orders which in turn resulted in wasting time in identifying the components to which the maintenance work has to be carried out.

Company Data Excel PM Sheet

The Maintenance Excellence FMECA program is an Excel sheet which is developed by the maintenance Excellence team of SKF, Goteborg. The sheet consists of the Machine System broken down to its sub components. Each component is then associated with its functions and the failures modes, effects and causes which might arise from it, the frequency of the remedial tasks which must be carried out to prevent failures, the time for each task and the responsible craft for the specific failure.

Technical Support

The database design was carried out based on the fact that the lowest level of the hierarchy i.e. components could fail in multiple modes and these can lead to multiple effects. Also, the causes for the failure could be multiple. The database design gives the output information in the form of a tree structure which enables the users to identify the failures and assign proper failure action and plans. A lot of YouTube videos were referred to gain knowledge about the working of Microsoft Access, right from creation of tables to forms and reports.

The basic requirement of the database design was to enter the new records, prevent duplicates and add existing data to existing or new records. For this VBA programming was required and the Information on VBA codes for specific requirement was gathered through expert websites and developing codes by the authors. The authors took technical assistance from Anders DL Larsson, an expert in Microsoft Access at SKF, who helped in building and understanding the VBA codes to meet the specific functional requirement of the project.

4.2 Analyze

The Voice of the customer or the requirements was broken down into four drivers namely User, Technical, Process and General. Drivers are the parameters that drive the specific requirements of the customers. Based on the specific requirements identified for each driver, the criteria to achieve those specific requirements are developed.

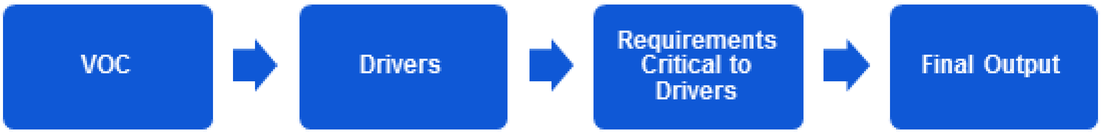


Fig 7: VOC: Process Flow

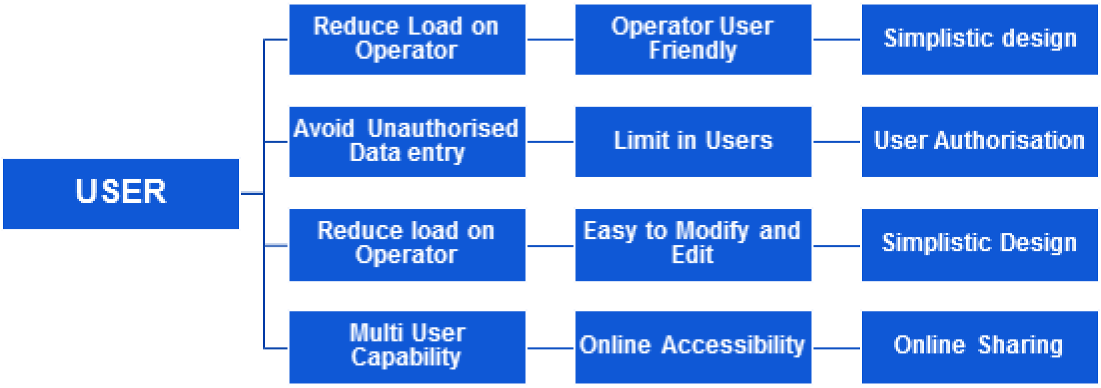


Fig 8: VOC: User

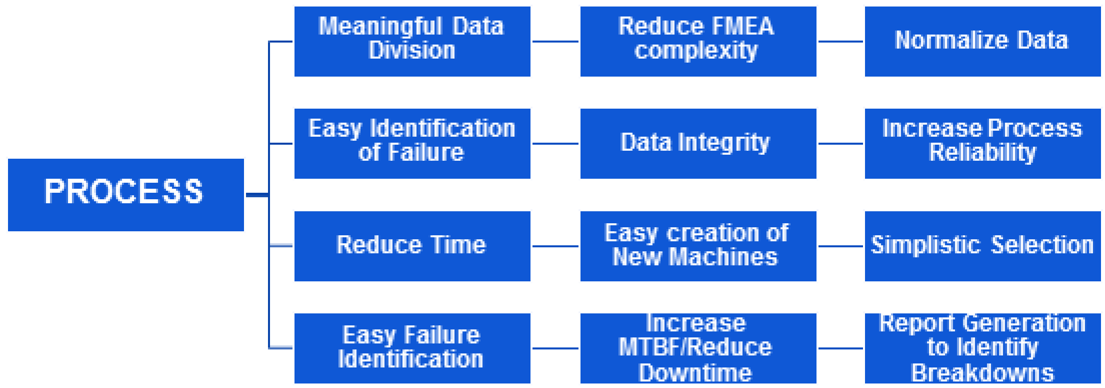


Fig 9: VOC: Process

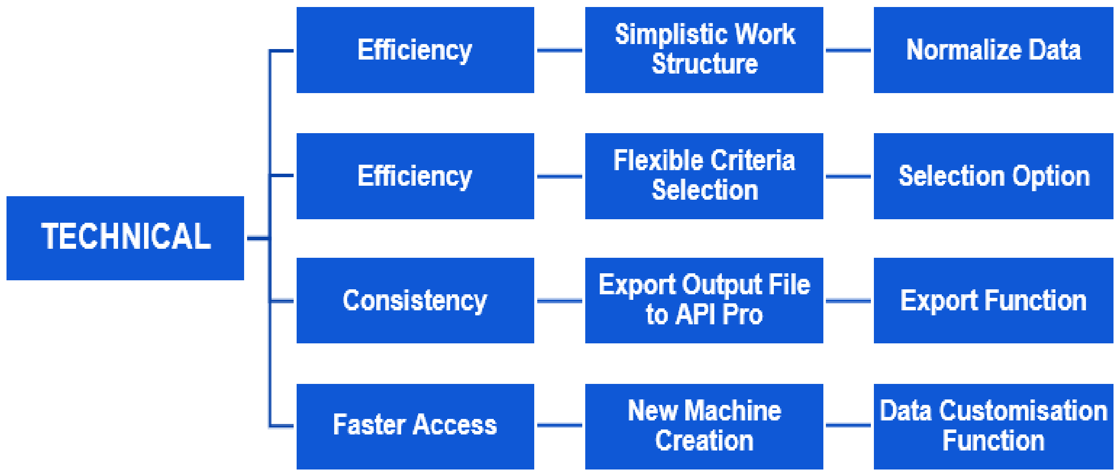


Fig 10: VOC: Technical

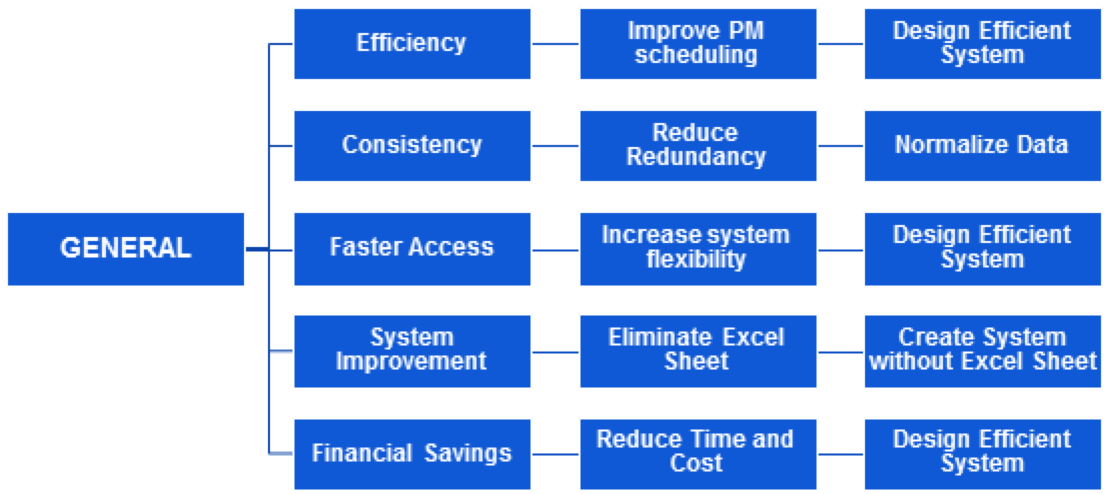


Fig 11: VOC: General

After carrying out the VOC analysis, criterias such as critical to user, critical to process, critical to technical, critical to general were identified. The outputs obtained from the four drivers are as follows

1. **Design an efficient and user-friendly system**
2. **Create simplistic system design**
3. **Create user authorization**
4. **Provide online sharing of the database file**
5. **Normalize data**
6. **Provide option for selection or deselection**
7. **Develop easy to use user interface**
8. **Create system without Excel sheet**
9. **Provide data customization function**
10. **Provide report generation option to identify breakdown pattern**
11. **Increase process reliability**

After analyzing the VOC and inputs from personnel who worked on databases, the authors decided to compare the types of databases available in the market. Below are the five structural types of database management systems selected for the comparison

- **Hierarchical databases**
- **Network databases**
- **Relational databases**
- **Object-oriented databases**
- **Flat File Based Database**

4.2.1 Comparison Matrix for comparing different types of database

Comparison matrix is a decision-making tool used to prioritize between different choices or decisions depending upon pre-selected criterias that are related to the decisions. The decision matrix is the best tool to argue on defending a decision that is already taken. The alternative decisions are arranged in rows and the different criteria are arranged in columns. Scores are added in the last column to weigh each choice and conclude. The scores used were derived based on the user's convenience

Database Type	Physical Structure	Programming Language	Flexibility	Advantages	Examples	Scores (1 - 10)
Flat File	Flat File 1-D	Assembler, COBOL. Fortran	NO	Old method of converting raw data	MS. Excel, Lotus 1,2,3	2
Hierarchical	Tree, Parent child relations	Assembler, COBOL. Fortran	NO	More efficient than flat file, less redundancy	Info. Management Sys by IMB	2

Network	**Network of interrelated lists**	**Assembler, COBOL. Fortran**	**NO**	**Less redundancy simplifies complex data, fast, efficient than Hierarchical**	**Satellite communications**	**2**
Relational	**Relational tables**	**SQL**	**YES**	**Easy visualization, ease of design, user friendly, ease of data entry, good security features,**	**Oracle, SQL, MS. Access, MySQL**	**8**
Object Oriented	**Modelled as objects**	**JAVA, C++, Pascal**	**YES**	**Ability to model and store complex data, support for special operations, faster performance**	**Objectstore, Gemstone**	**6**

Table 2: Comparison matrix for different database, Results

After analyzing the result from the comparison matrix, the authors decided to go with Relational Database mainly due to the existing relation between the various parameters in the Excel sheet template. The other reasons were its ease of visualization, implementation, user friendly characteristics and available time frame for implementation. After narrowing down the choice to relational database, its four most popular software's were identified, and these software's were evaluated against certain criterias through the means of a weighted score matrix. The criteria selected for the evaluation are as described in the following section

4.2.2 Evaluation Criterias for the choice of Relational Database

The criterias that were chosen for evaluating the choice for the relational database were Cost and Scalability, as the developed system should be economically viable to be implemented across all SKF factories and it should be able to handle huge amount of maintenance data that is going to be added in the future. Usability, as the system will be designed for those who predominantly work in the maintenance team and since the project is going to be taken ahead after the completion of the thesis, it is imperative that the developed system is simple enough for the maintenance team to modify it accordingly. Reliability-As the current Excel sheet is not reliable due to the chance of data being deleted or misrepresented and the new system should be able to protect the data. Time to Implement-As the time frame is one of the vital parameters for the selection of the database system and the new system must be up and running by the end of 20 weeks. Finally, User Authorization, as the developed system must have control in terms of user access and should not be able to access by a random user without proper authorization. The choice for the different database system is filtered and frozen to Relational Database. Further the choice for different relational database software's is narrowed down using the weighted score method

Requirement Criteria	Criteria Scores	Access		Microsoft SQL		Mysql		ORACLE	
		Score	WS	Score	WS	Score	WS	Score	WS
Cost & scalability	3	5	15	3	9	3	9	1	3
Usability	5	5	25	3	15	3	15	3	15
Reliability	3	3	15	5	15	5	15	5	15
Time to implement	5	5	.25	3	15	3	15	1	5
User Authorization	3	5	15	5	15	5	15	5	15
Total			95		69		69		53

Table 3: Weighted Score Matrix, Results

One important thing that the users would like to point out is it was decided to go with MS Access from the beginning based on the user's knowledge and experience and its similar interface and toolbars with MS Excel, but the option was kept open on exploring the different relational database softwares. The scores were solely decided depending on the user's comfort and ease of implementation of the project within the stipulated period of 20 weeks. Apart from the above motive on the decision to stick with MS Access there was also an external motivation. Many Information Technology (IT) experts at SKF were familiar with MS Access and would come in handy during difficult project stages.

After narrowing the choice of relational database software to MS Access it was necessary to find out a way to share it online with different users at SKF across the world. For this an analysis was done using a Comparison Matrix for after narrowing down 4 different types of Sharing methods. Below are the four structural types of Sharing methods:

- **Split Database**
- **Network Folder**
- **SharePoint Portal**
- **Database Server**

Scores: 1 being the lowest and 10 highest.
The scores are finalized by taking into consideration the competency, time frame, ease of implementation and level of complexity.

4.2.3 Comparison matrix for Sharing Access File

	Server Software requirement	SharePoint requirement	Access running on SharePoint server	Data availability	Security	Flexibility
Split Database	**No**	**No**	**No**	**Good**	**Requires additional measures**	**Flexible**
Network Folder	**No**	**No**	**No**	**Small scale editing**	**Least secure**	**Flexible**
SharePoint Portal	**No**	**Yes**	**Linking and saving does not whereas publishing as web database requires SharePoint server**	**Best! Allows for offline scenarios.**	**Best**	**Flexible**
Database Server	**Yes**	**No**	**No**	**Best**	**Best**	**Flexible**

Table 4: Comparison matrix for sharing Access File

After carrying out the comparison and analyzing the result, it was decided to go with the SharePoint Portal. Also, the Maintenance Excellence team was already using SharePoint portal to upload documents related to maintenance and it would be an easy task to share the Access file with anyone who has the authority to download and have their own local file. Also, this type of sharing would be more secure since it would require a permission from the portal owners to edit the master Access file.

4.3 Design

After deciding on Relational Database software MS Access as the Database for the development of the FMECA Maintenance Program, the authors worked on first establishing the different objects of MS Access imperative for laying the foundation of the Database. The normalization of the data was then carried out to reduce data redundancy and improve data integrity after organizing the columns (attributes) and tables (relations) of the database to ensure that their dependencies are properly enforced by database integrity constraints. The authors were successfully able to attain the second normal form and did not find it necessary to attain the third normal form of normalization.

4.3.1 Entities (Tables)

Entities are nothing but tables with a title. The tables in the database have been designed for the attributes or fields (discussed below) having a large number of data and with the possibility of addition of new data in the future. A table can be viewed in two ways, one is the datasheet view and the other is the design view. In datasheet view a user can view and edit the data but change in the format of the database is not permitted. In design view the user is permitted to alter the structure of the database and configure the fields. An example of the different views of Machine Sub System table (tblMachineSubSystem) can be seen below in Figure 12 and 13 and couple more tables in Appendix C. The different entities used in the database are as follows:

- Machine
- Machine System
- Machine Subsystem
- Components
- Functions
- Failure Mode
- Failure Effect
- Failure Cause
- Basic instruction
- Tools
- Master Data

tblMachineSubSystem

Machine Subsystem ID	MachineSubsystem	Machine Sytem ID	MO_TAG	MachineSubSystem_Details	Click to Add
1	MACHINE BODY AND COVER	1	SPC62-zzzzzz-01-01	NEWLY MADE COVER	
2	ELECTRICAL SYSTEM	1	SPC62-zzzzzz-01-02	NEWLY MADE COVER	
3	PLC SYSTEM	1	SPC62-zzzzzz-01-03	NEWLY MADE COVER	
4	PNEUMATIC SYSTEM	1	SPC62-zzzzzz-01-04	NEWLY MADE COVER	
5	SAFETY SYSTEM	1	SPC62-zzzzzz-01-06	NEWLY MADE COVER	
6	LUBRICATION SYSTEM	1	SPC62-zzzzzz-01-07	NEWLY MADE COVER	
7	LOADING UNLOADING	2	SPC62-zzzzzz-02-01	NEWLY MADE COVER	
8	GRINDING WHEEL LEFT	2	SPC62-zzzzzz-02-02	NEWLY MADE COVER	
9	FEEDING-SLIDE LEFT	2	SPC62-zzzzzz-02-03	NEWLY MADE COVER	
10	GRINDING WHEEL RIGHT	2	SPC62-zzzzzz-02-04	NEWLY MADE COVER	
11	GRINDING SLIDE RIGHT	2	SPC62-zzzzzz-02-05	NEWLY MADE COVER	
12	COOLANT	2	SPC62-zzzzzz-02-06	NEWLY MADE COVER	
13	DRESSING UNIT	2	SPC62-zzzzzz-02-07	NEWLY MADE COVER	
14	GRINDING UNIT	2	SPC62-zzzzzz-02-08	NEWLY MADE COVER	

Fig 12: Datasheet view
(Image adapted from the current project)

tblMachineSubSystem

Field Name	Data Type
Machine Subsystem ID	AutoNumber
MachineSubsystem	Text
Machine Sytem ID	Number
MO_TAG	Text
MachineSubSystem_Details	Text

Fig 13: Design view
(Image adapted from the current project)

4.3.2 Data Type

The different data types common to tables are auto number, text, number and calculated fields. Calculated data type is used to automatically generate the record dependent on the value of another record eliminating the need for the user to ensure that the record is updated. For example, in the database “Sum of Operating hours” is dependent on two fields i.e. “Frequency times/year “and “Operator(min)” based on the formula

Sum of operating hours = [Frequency Times/Year] *[Operator (min)]/60

It is enough for the user to enter the values of “Frequency times/year” and “ Operator(min)”

4.3.3 Attributes (Fields)

After deciding the tables, the attributes that go into the specific tables were decided. The fields for the different entities above are as shown below. Majority of the fields were added to the table tblMasterData. This was done since there was no proper relationship with the other tables and fields. The fields that are placed in the specific tables are shown below.

- Machine - Machine ID, Machine, MO Tag, Machine Detail
- Machine System - Machine System ID, Machine System, MO Tag, Machine Detail
- Machine Subsystem - Machine Sub System ID, Machine Subsystem, MO Tag, Machine Subsystem Details
- Components - Components ID, Components, MO Tag, Component Details
- Functions - Functions ID, Functions
- Failure Mode - Failure Mode ID, Failure Mode
- Failure Effect - Failure Effect ID, Failure Effect
- Failure Cause - Failure Cause ID, Failure Cause
- Basic instruction - Basic instruction ID, Basic instruction
- Tools - Tools ID, Tools
- Master Data - Maintenance Strategy, Comment Simple, Criticality score, Critical Y/N, Simple Maintenance Y/N, Maintenance type, Parameter, Operator (min), Mechanical (min),Electrical (min) ,Supplier (min), Sum of Operator hours, Sum of Mechanical hours, Sum of Electrical hours, Sum of Supplier hours, Estimated repair time if failure, Frequency, Frequency Times/year, Responsible craft, # of Craft, Prepare Y/N, Run/Stop R/S, Stop time (minutes), LoTo Y/N, Spare Part to be used for the PM/AM

4.3.4 Relationships

After creating the tables and its fields, the primary key of the tables were related to the primary key of the other table depending on the hierarchy of the machine creation and out of the three types of relationship possible, One to Many relationship was used in the database since most of the attributes in the FMECA program generally have a one to many relationship and the specifics of it are as described below

One to Many relationship

- Machine System - Machine Subsystem: 1 to Many
- Machine Subsystem - Master Data: 1 to Many
- Components- Master Data: 1 to Many
- Functions - Master Data: 1 to Many
- Failure Modes - Master Data :1 to Many
- Failure Effects - Master Data :1 to Many
- Failure Cause - Master Data :1 to Many
- Basic instruction - Master Data :1 to Many
- Tools - Master Data :1 to Many

4.3.5 Joins

From the data integrity point of view, it was important to view all the records from the Master Data table for the user's easy identification of failure modes, causes and effects. Some of the components would have multiple failure modes but only one failure cause and effect. From the user's point of view, it was imperative that all the failure modes, effects and causes were displayed irrespective of any matches. To get this kind of information, the right join was used.

4.3.6 Referential Integrity

The purpose of using the referential integrity in the database is to prevent orphan records and to keep the references synchronized to avoid any records that references other records that no longer exist. The referential integrity in the database has been specifically used between the tables Machine, Machine System, Machine Subsystem and Master Data and not the other tables as these are the only tables in which the data is entered when a new machine is created. So, it is necessary for the data that is linked to data in another table to be deleted when any one of the data related to the machine creation is deleted by the user. The Figure 14 shows the one to many relationships, the right join and the referential integrity established between the tables.

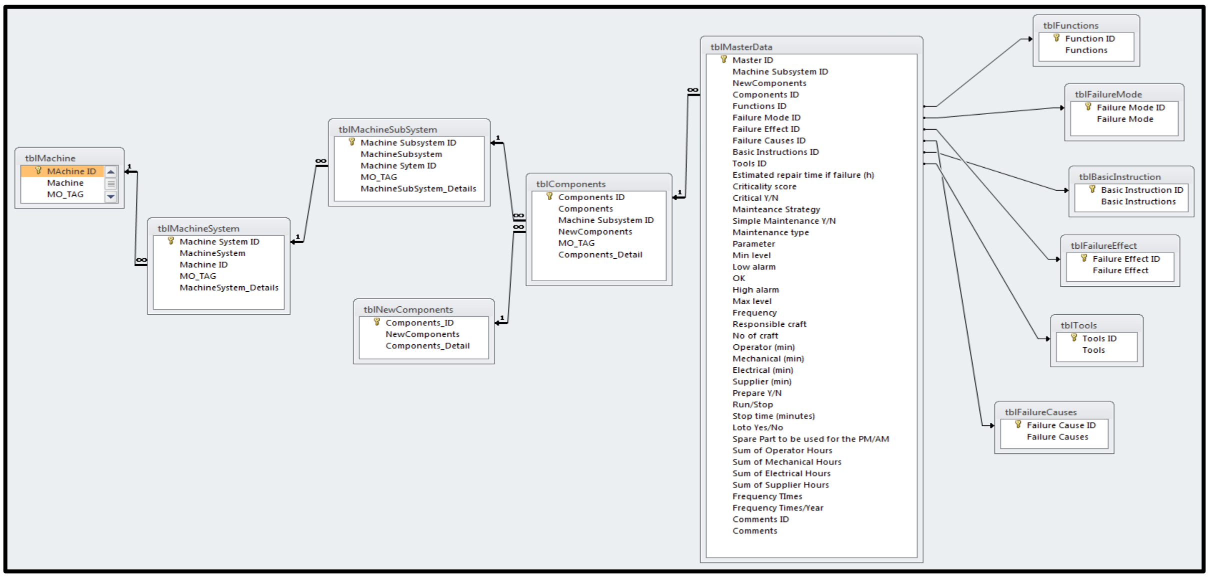


Fig 14: Relationship Diagram
(Image adapted from the current project)

4.4 Database Development

After the creation of the tables, fields and the relationships between them, the main task was to decide the way to enter the data in the different tables. It is not a good practice for the user to go to the tables to enter or edit data and this would not serve the purpose of the database and it would be like entering data in the Excel sheet template leading to errors and duplication of data in the tables. Therefore, manually entering the data in the tables was ruled out. Hence, it was decided to design data entry forms to act as an interface between the user and the tables.

4.4.1 Forms

First a Complete Form was created to fill the Master data table as it is the table to which all the other tables are related to. After the creation of the complete form, a lot of changes were made to it over the course of the project as per the input of the stakeholder. Finally, the form was designed in a way to allow the user to select the Machine, Machine System, Machine Sub System and finally the Component through the means of dropdown combo boxes and then enter or edit maintenance data for that specific component. As this form had data entry boxes which would not be necessary for the Maintenance Planner or the Maintenance Engineer, two separate forms with the fields only necessary for those users were created.

4.4.2 Lookup Function

Some of the attributes in the master data table had limited amount of data such as Maintenance Type that consisted of Inspection, CBM, TBM and Functional Test. So, for these attributes Lookup function was used to create the data once that the user can select while filling the Form using the dropdown function. For the attributes with a possibility of data addition such as Functions, Failure Modes and others, a separate form called New Table Data was created to allow the user to enter the data if it is not found in the dropdown of its respective combo box.

4.4.3 VBA and Structured Query Language (SQL)

VBA and SQL played an important role in automating the database functions. Majority of the buttons and functions developed in the Access database were done by first creating a Structured Query to retrieve the right data and then the query developed was integrated into the VBA code which was developed based on the function. This VBA code was then placed behind an event procedure such as ‘On Click’ Event for a specific button to run the command when the user clicks the button. The VBA codes written for couple of Form functions can be seen in the Appendix C

4.4.4 Types of Forms

Depending upon the user’s requirement different forms have been designed. In this database a total of eight forms were created:

1. **Create New Machine Form**: This form is used to create a new machine using the parts from an already created machine stored in the database or by creating new parts. The form can also be used to add new parts, Machine identification tags (MO Tags) and details for the new parts.
2. **New Table Data Form**: This form is used to add new function, failure mode, failure effect, failure cause, tool and basic instruction.

3. **Machine Summary Form**: This form is used to view all the parts of the machine created.
4. **Data Entry for Machine Form**: This form is used to view all the data entered for a particular machine in one place.
5. **Complete Form**: A generic form that contains all the fields regardless of the user's choice. The information is gathered on a component level depending upon the user's previous selection of "machine", "machine system" and "machine sub system".
6. **Maintenance Planner Form**: This type of form is created for the specific field choice of a Maintenance Planner and the information can be gathered on a component level depending upon the user's previous selection of "machine", "machine system" and "machine sub system".
7. **Maintenance Engineer Form**: This type of form is created for the specific field choice of a Maintenance Engineer and the information can be gathered on a component level depending upon the user's previous selection of "machine", "machine system" and "machine sub system".
8. **Complete Machine Info Form, Maintenance planner Form, Maintenance Engineer Form** These three forms are used to export the details of a machine only to an Excel sheet.

Create New Machine Form

This form is the foundation for the entire database designed in a way that the user can choose the required Machine system, Machine subsystem and the components from an already created machine stored in the database to create a new machine without having to manually create the parts again. When the user adds a component to a Machine, the maintenance program associated with it also gets added eliminating the need to create the maintenance program again. Also, when a New Machine is created, the Machine Identification Tags is automatically updated for the Machine System, Machine Sub System and to all the Components added. The form can also be used to add a new Machine System, Machine SubSystem and Component to an existing machine. The Create New Machine Form is shown in the Figure 15.

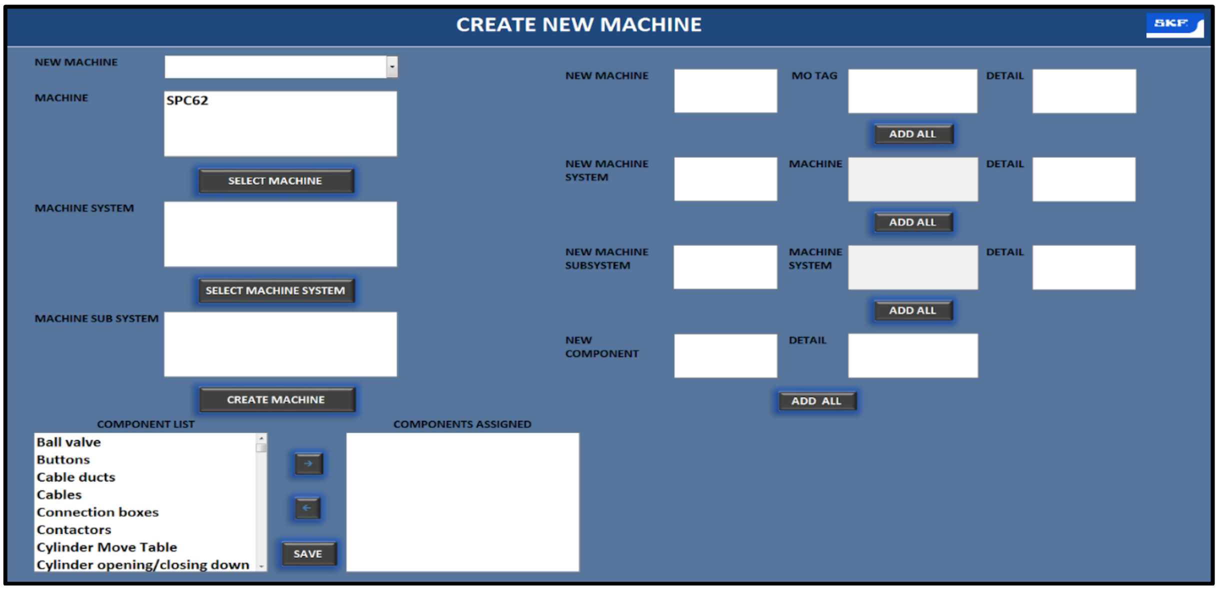


Fig 15: Create Machine Form
(Image adapted from the current project)

New Table Data

When creating the maintenance program, if the required data does not exist then the user can use this form. New data for fields like function, failure mode, failure effect, failure cause, tool, and basic instruction can be added and then the maintenance program can be updated in the respective forms. The **New Table Data** Form is shown in the Figure 16

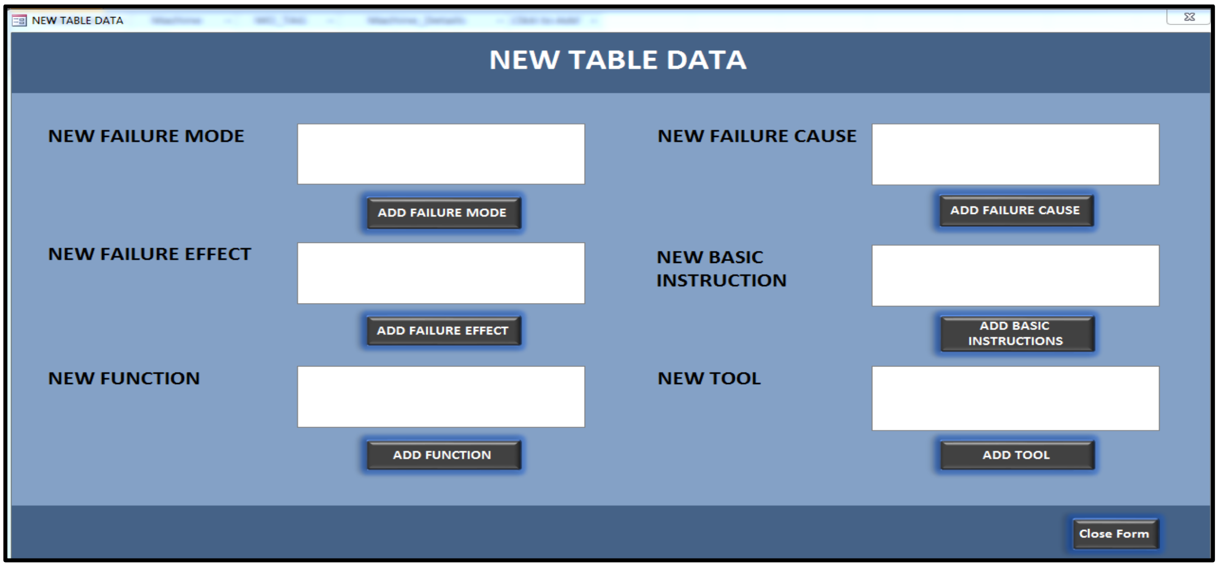
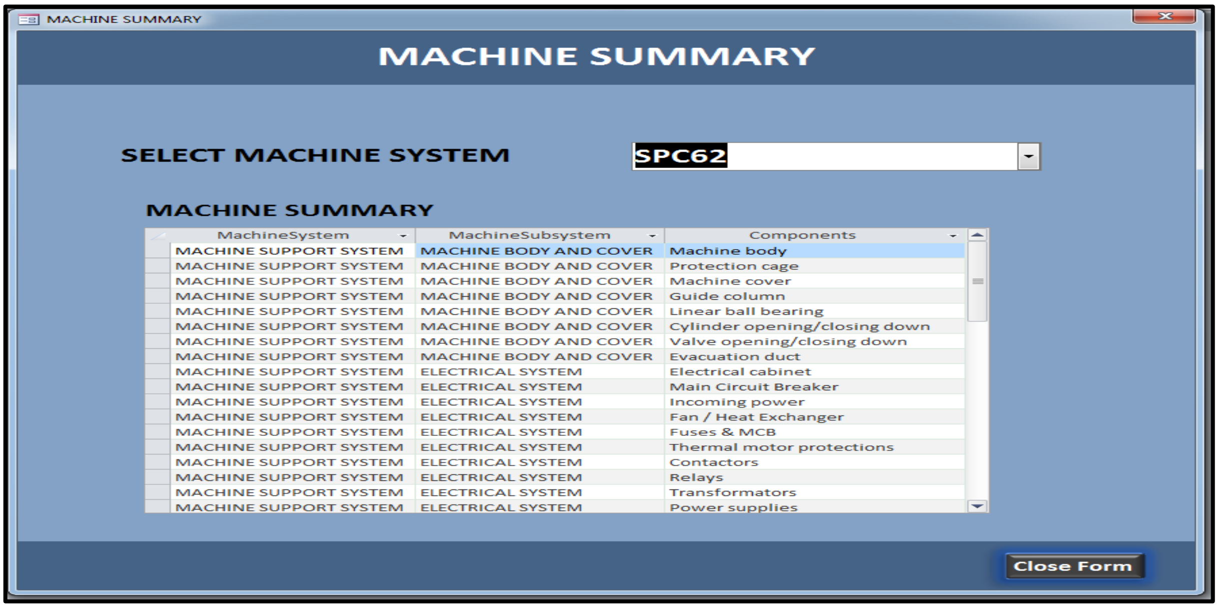


Fig 16: New Table Data Form
(Image adapted from the current project)

Machine Summary

The Machine Summary form allows the user to check if the newly created machine has all the parts that was intended to be added as there is a chance of missing out a part during the machine creation. The user can verify it by viewing all the parts of the newly created machine in this form and if any part is found missing, it can be added via this form. The **Machine Summary** Form is shown in the Figure 17



MachineSystem	MachineSubsystem	Components
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Machine body
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Protection cage
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Machine cover
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Guide column
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Linear ball bearing
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Cylinder opening/closing down
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Valve opening/closing down
MACHINE SUPPORT SYSTEM	MACHINE BODY AND COVER	Evacuation duct
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Electrical cabinet
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Main Circuit Breaker
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Incoming power
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Fan / Heat Exchanger
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Fuses & MCB
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Thermal motor protections
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Contactors
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Relays
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Transformators
MACHINE SUPPORT SYSTEM	ELECTRICAL SYSTEM	Power supplies

Fig 17: Machine Summary Form
(Image adapted from the current project)

Data Entry for Machine

The Data Entry for Machine form is used to view the information entered for all the machine parts after they have been created. Since there are a lot of columns with data, the user can select specific fields which he would like to see. The **Data Entry for Machine** Form is shown in the Figure 18

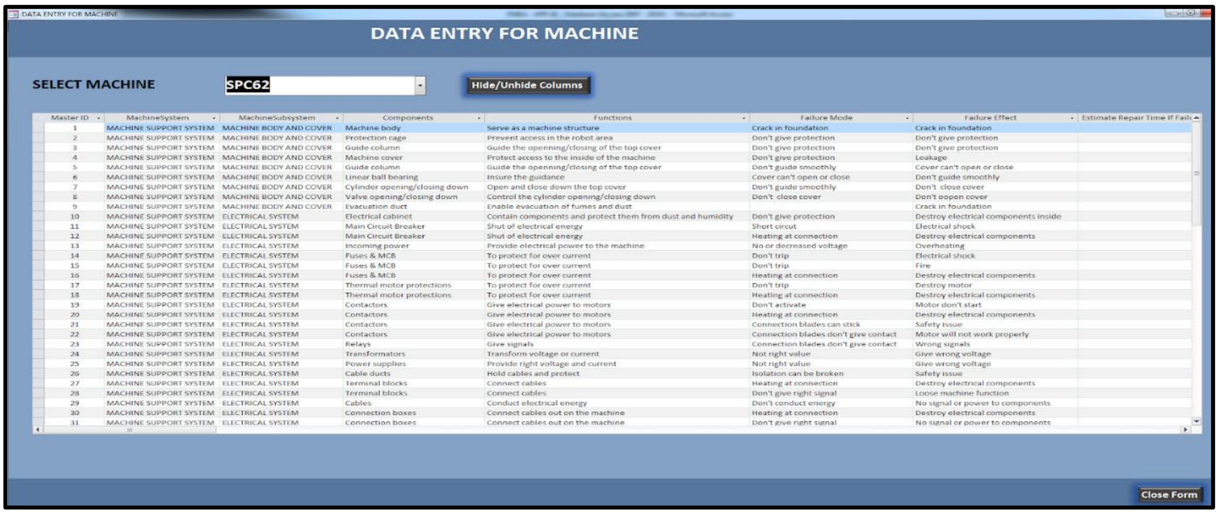


Fig 18: Data Entry Form
(Image adapted from the current project)

Complete Form, Maintenance Engineer Form & Maintenance Planner Forms

The Complete form is the form containing all the fields related to the machine where data can be entered or modified. This Form is used to create the maintenance program for a new machine, update or add to an existing maintenance program. The Maintenance Engineer and Maintenance Planner forms are similar to Complete form, but the difference is that they contain only the fields necessary for a maintenance engineer and maintenance planner respectively. In all the forms the user can select the specific component of the machine and then modify the required data. The data entered is stored in the database and can be modified any time using the forms. The **Complete Form** is shown in the Figure 19. The **Maintenance Engineer** & **Maintenance Planner Form**s can be seen in the Appendix B

Fig 19: Complete Form
(Image adapted from the current project)

Complete Machine Info, Maintenance planner, Maintenance Engineer forms

These three forms are linked to the Complete Form, Maintenance Planner Form & Maintenance Engineer Form respectively. These forms are used to select a machine and then either open a report to view the maintenance program data related to that machine or export the entire data into an Excel sheet from where the data can be exported into the Computerized Maintenance Management Software used at SKF called API- Pro. However, the user can make no edits in these forms. The advantage of this functionality is that the user will not have to go through the tedious task of viewing data and gathering information for specific machine. The **Complete Machine Info Form** is as shown in the Figure 20. The **Maintenance planner** and the **Maintenance Engineer forms** can be seen in the Appendix B

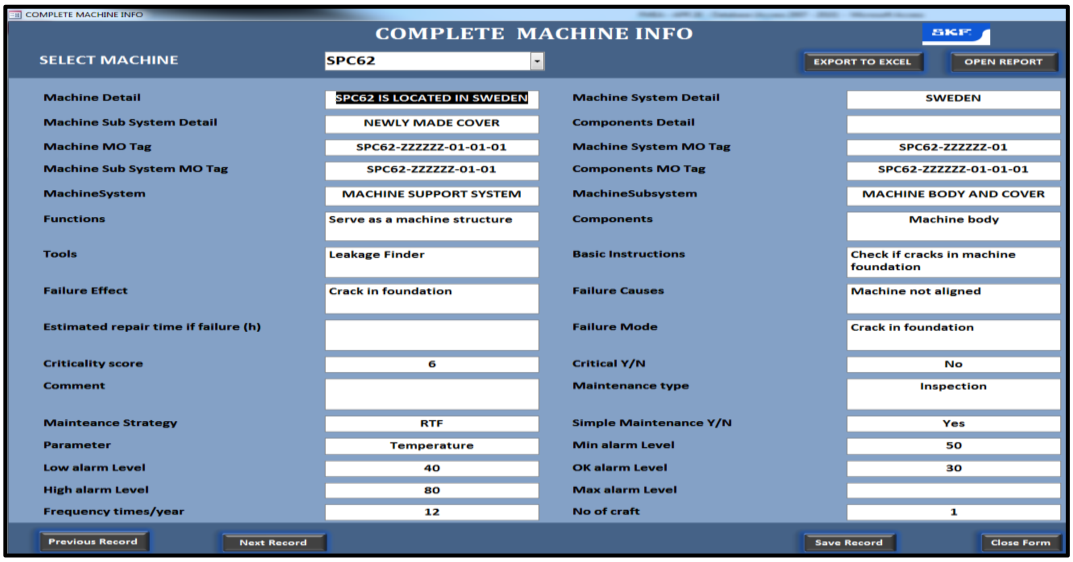


Fig 20: Complete Machine Info Form
(Image adapted from the current project)

4.4.5 Reports

Three reports associated with the Complete Machine Info, Maintenance planner, Maintenance Engineer forms are Complete Machine Info, Maintenance planner, Maintenance Engineer Reports respectively. The purpose of creation of the reports is to allow the users to see through the entire maintenance program data for one entire machine before exporting it in the form of an Excel sheet. The report is provided with a button for the user to export the data to an Excel sheet. Refer Appendix B

4.4.6 User Interface

The User Interface played an important role in developing and designing the software. The primary goal during the development of the database software was to make it as simple as possible with very less manual entry for the user and reduce the time and steps taken during the creation of a Maintenance Program. So, to accomplish this, buttons and dropdowns were provided in the forms to choose from the available list rather than write it manually every time. The Login and Menu Forms which consists several buttons can be seen in Appendix B

4.4.7 Exporting to API - Pro

The created FMECA maintenance program can be exported from MS Access in to an Excel Sheet and can then be exported to Computerized maintenance management software (CMMS) used by SKF which is API- Pro.

4.5 Testing and Validation

The testing strategy of collaborating with the end users by taking their input after every functional change proved to be a good technique. This technique of making changes to the software on the go resulted in a lot of revisions to the software developed over the course of the project.

Once the functional changes were agreed upon by the end user, the changes were tested with different inputs of the FMEA program which would be used by the end user for errors. The errors found during the testing phase were either eliminated if possible and in some cases the entire design was changed to obtain the required functionality. During the development, certain errors made it impossible to make any modifications to the code and go ahead with the same design and in such cases new codes were tried until the required solution was obtained. This problem was mainly encountered while developing the Create New Machine Form.

4.5.1 Training and User Manual Creation

The user manual and training is important for successful use of the software by the maintenance engineers. So, the User Manual was developed with detailed description for every Form in the Database with the use of pictures. Based on constant inputs by the users the User Manual was updated. The training for getting acquainted with the overall use of the database and the ways in which the database could be exploited to get the best result was carried out parallelly during the development of the software. The reason for carrying out the training parallel with the development of the database was to make the user interface better as per the inputs given by the users and to find out any errors which might have been overlooked.

4.6 Database Implementation

The database is uploaded to the Maintenance Excellence SharePoint Portal of SKF managed by the Maintenance Manager's to which the maintenance engineers working at SKF have access. Only the admins of the SharePoint portal have the authority to alter the master file thus providing a better control over the master file by protecting it from mishandling by the users and acting as a backup file in case something goes wrong when the users download and use the database file in their local systems. The SharePoint portal of SKF can be seen in Appendix A

5

Discussion

This chapter depicts the discussion relative to theory, the arrival of solution, scientific methodologies used, discussion on relating the results obtained to the theoretical concepts of RCM and databases by the authors and addresses the social sustainability considered during the master thesis

5.1 General Discussion -Theory

The objective of the master thesis was to design a relational database that would encompass the FMECA program maintained in the Excel sheet. For an effective database design that would meet all the requirements of SKF it was very important for the authors to first do a research on the working of RCM since FMECA was its derivative (NASA, 2000). The authors conducted research on the analysis of RCM like the functions, failures modes, the failure effects and the causes. The relationship between these four parts became the backbone of the database design.

The process of FMECA is an elaborate method of finding root cause to different types of failures and formulating action plans to counter failures. This process is commonly followed my maintaining the data in an Excel spreadsheet. This Excel sheet can be adapted accordingly to meet the various customer needs. But following FMECA process in an Excel sheet poses a lot of problems and is also time consuming (Khairul et al., 2014). Apart from finding the root cause to a specific failure it is a non-fool proof method to build or create new machine data to the existing machines. Also, if similar machine data exists, it would be difficult to browse through the Excel worksheet for finding specific information thereby increasing the workload on the user (Kukkal et al., 2002). The usual practice at SKF is to install the components used in one machine into other machines as well. The failure mode of the component will be the same regardless of the machine. However, the dominate failure mode, its effects and causes will differ from machine to machine (NASA, 2000). Due to this complexity the user will have to rewrite every time a new FMECA program is created leading to extra time consumption.

The main decision to design and implement FMECA in a relational database tool MS Access was to counter the problems of the Excel sheet and provide a standalone solution to the problem of maintaining multiple FMECA Excel sheet programs for multiple machines. This standalone solution or common database would also define, identify and integrate all kinds of data to implement and improve maintenance (Mirka et al., 2007). Having an FMECA in a database allows it to be sorted according to different severity levels and equipment categories providing an effective means of information distribution (Krzysztof, 2002). The other reasons that motivated the authors were the MS Access's ease of availability, implementation, flexibility and zero investment. As FMECA is a team tool many users from different departments might interact with it simultaneously at the different stages of the product life cycle. For example, a design engineer might use it to establish the structure of the design and create the functional requirements. Quality control engineers may use it to update a new failure they have identified for the component.

Process and maintenance engineers may use it to track the cause and effect of a specific failure (Huang et al., 1997). Also, different companies follow different standards of FMECA (Krzysztof, 2002), hence a certain degree of flexibility and extensibility was taken into consideration during the design structure of the database (Huang et al., 1997). A relational database tool like MS Access satisfies all these requirements.

Also, with the help of relational database it is not only possible to build a new combination of data with the existing machines, but it is also possible to create new set of machine/s and associate it with new data. Relational database also replaces the cumbersome tasks of searching through numerous spreadsheets used in Excel sheet FMECA process (Kukkal et al., 2002). To gain knowledge on Microsoft Access, various objects like tables, forms, reports and queries were studied. The design of forms to display data for the user was something the authors spent a lot of time on.

The process of normalization was carried out to simplify and restructure the contents of the tables, eliminate the duplicates and improve data integrity (Harrington, 2016). To automate the process of FMECA, a basic knowledge on the computer languages VBA and SQL was gained through online videos, web articles and online tutorials. The knowledge from RCM, FMECA, Microsoft Access and its parts paved way for an efficient database design that met all the project requirements.

5.2 Application of DMADV in this Master Thesis

DMADV is a framework that focuses primarily on the development of a new service, product or process as opposed to improving an existing one and is the most sought out method for realizing new products in industries to stay competitive in the market. The DMADV methodology has been used in this master thesis to develop a radically new database system

The DMADV methodology used in the thesis by the authors is a modified version of the DMAIC methodology which provides a framework to optimize and improve the operational process in in question (Tushar et al., 2008). The measure phase determines the current problems associated with the process and as to how the process performs currently (Bishu et al., 2009) and this phase proved to be an important aspect to clearly understand the problem from a user's perspective by interviewing several members of the maintenance team. However, since the authors had absolutely no experience in developing database systems and very little knowledge in the development of the maintenance programs, this phase proved to be a challenge as to where to start when it came to collecting the data. So, the authors decided to counter this problem by dividing the entire project into data required from a software point of view and the information required from the FMEA maintenance process point of view and the interviews with the interviewees were conducted accordingly. The interviews with the maintenance personnel provided the authors with not only the problems related to the use of the Excel sheet but also the possible ways in which the authors could provide a solution in the form of a database system and the interviewees related to IT background suggested relational database as an optimistic solution. The analyze phase deals with analyzing the data collected in the measure phase, giving enough attention to the details of the problems before jumping to conclusions and finally determining the best course of action for reaching the goal (Breyfogle, 2003). So, the authors brainstormed on the different methods that could be used to analyze the data collected and the one that would address the problems covering all aspects such as the user who will work with the FMECA program, the technical problems with the current tool and the overall general problem with the Excel sheet. The voice of customer proved to be the one method which could be used to answer all the problems by categorizing into different aspects. After conducting the VOC analysis, the authors were able to narrow down the specific criteria's to be achieved in the new database. Based on these criteria's the authors were able to determine the database management system and the software to be used for the database development by using the weighted score method. This phase provided a structured direction to follow and carry out a thorough analysis of the problems before deciding if a database system was indeed necessary and if it would be a viable option.

Once it was concluded that a database system was indeed necessary to ease the process of FMECA program creation, the design stage which deals with the technical development of the product, carrying out pilot runs and the stage which determines the success or failure of the project and generally takes the longest time was started (Chowdhury, 2002). In this phase the authors faced a lot of challenges when it came to designing the application using VBA coding since the authors were not proficient in coding with VBA. However, this main challenge was overcome by learning basic VBA online, taking help from the experts at SKF and learning to debug the mistakes made in coding and thereby writing a better version of the code to obtain the intended functionality. However, as the definition of the phase suggests that the success of the entire project depends heavily on this phase, there were times when certain functions in the database software was not able to be developed which put the entire project at the risk of being scraped, but these problems were overcome by either modifying the design of the database functions by making sure that the customer objectives were still met. After the completion of the Design phase, the final phase, Validation which involves the verification of the design to adapt to the real – world environment (Thieleman, 2002) was carried out. This phase actually acts as a litmus test to see if the design works against the real world data and be able to withstand the amount of work done in the database. This phase in our case was carried out simultaneously with the design phase itself that is the users were working with real data when they were testing the functions developed in the design phase. However, the database was once completed was fully tested by creating an entire machine from scratch by utilizing all the functions that were developed in the database software. During the test small errors found were rectified. Overall, the authors followed the DMADV methodology guide to conduct a proper research-oriented approach to the thesis rather than just focusing blindly on developing the database system without verifying the problems that were caused in the current tool and if a tool was necessary in the first place. As for the results which the authors got in each stage of the methodology was pretty much what the definition and the possible outcomes of the methodology described.

5.3 Discussion on the suggested improvements and the use of MS Access in this Master Thesis

The current Excel sheet used by the maintenance department at SKF is unstructured, cumbersome, error prone and not easy to create new maintenance programs given its complexity. The operators were vulnerable of making mistakes during the creation of new maintenance program and associate the failure modes, effects and causes. So, a change was required to move to a user-friendly system. The suggestion by the authors was to first research on the problems faced by the users using the current Excel sheet template. The research proved that the bad user interface, tedious data keeping, limited skills of the operators and difficulty in associating the failure modes for the similar components in new machines for the creation of maintenance programs in Excel sheet was the main reason for the errors. So, it was suggested to use a database system (Kukkal et al., 2002), (Khairul et al., 2014). After arriving at the conclusion that there is a requirement for developing a relational database software, the authors researched on the possible options of zeroing in on the right database software by weighing in on the positives and negatives of different database software's available commercially. MS ACCESS was adopted in the master thesis to achieve the stakeholder's requirement. The most important factors which made the software favorable among the other software's were that it was a freely available software which could be uploaded on SKF's SharePoint Portal and used by multiple users on their desktops locally with good security control. Also, the time frame to carry out the project was very short and within the given time limit the authors had to learn to use the software and simultaneously develop a fully functional database by the end of 20 weeks.

5.4 Social Sustainability & Effects of Database

This master thesis with the development of a FMECA Database management system in MS Access through the approach of DMADV has considered various aspects of improvements mainly with respect to user interface and ease of use. In the aspects of DMADV by developing a new system, the master thesis has enabled the engineers to easily create and manage new FMECA maintenance programs for new and old machines. Particularly, the creation of new machines has been made easier. Since, SKF operates hundreds of different types of machines around the world, the maintenance team consistently invested a lot of time in creating each machine from scratch even though many of the machines had similar components being used among them. The creation of the database has enabled the engineers to easily create a new machine by just copying a machine system, machine subsystem, component and the maintenance program along with it to new machines which significantly reduces the time in creating new machine programs and eliminates the need to create the maintenance program for the components again for the new machines

Prior to development of the database, the machines components at SKF were randomly moved across and installed in different machines which made tracking the failure time of the components impossible to know. But now in this database the components are identified by a 13-digit Maintenance Object Unique name code also known as the Machine Tag where the first three letters correspond to the machine initial name, next 3 digits describe the machine range and version and the last seven numbers correspond to the machine inventory number. This process of identifying the machine components using Machine Tag makes it easier to determine the component failure time and to enter that data in the database for future maintenance planning

The development of the database application in MS Access makes it an economically viable option compared to different available database software's unlike other software's where a significant amount of price must be paid to license the software, MS Access is freely available with the MS Office Suite and even though there is a size limit of 1GB for the application, it serves the purpose as the application is planned to be used separately in different factories of SKF across the globe and not as one application for the entire company.

As the database file can uploaded into the SKF's SharePoint portal as a generic maintenance program, local maintenance engineers in SKF factories around the world can download the file on their local desktops and either change the existing program according to their needs or create new ones as per their own requirements from scratch increasing the efficiency and accuracy of the process thus making the process socially sustainable, meeting the needs of the current users and carrying out the maintenance program creation in a systematic way.

5.5 Suggestions for Future Work

As part of the thesis, further work that can be carried out to take this work forward which SKF should consider exploring are:

- The possibility of using the current database to carry out the maintenance work automatically by using machine learning techniques can be researched.
- The use of database in the long term for the maintenance managers can be evaluated and a better version can be developed using the inputs given by the users of the software.
- A more efficient relational database tool can be utilized to build the maintenance data to counter the drawbacks of Microsoft Access.
- All in all, for making the process of maintenance program creation more reliable and efficient, a process other than FMECA can be developed.

6

Conclusion

The master thesis study focused on the design and implementation of a Relational Database for Failure Mode, Effect and Criticality analysis maintenance program. This chapter depicts the main highlights of the master thesis study

The Master Thesis involved the design and development of the Database application in MS Access, a Relational Database management system using the DMADV methodology, a methodology which is used to develop a new product or improve an existing one to satisfy customer specifications to enable users to create the FMECA program efficiently.

It can be concluded that the authors successfully achieved the purpose of the thesis to help SKF develop their FMECA Maintenance Program for the existing machines and for the creation of new machines easily and efficiently eliminating the previous use of an Excel Sheet template. As an end note the bulleted points below gives the main highlights of the master thesis

- Eliminated the use of Excel sheet template for creating FMECA Maintenance Programs by developing a Database in MS Access which was realized by following the DMADV methodology.
- Reduced the time and energy required for creating the Maintenance Program for machines having the same components from scratch by automatically updating the Maintenance Program for the component when used in another machine.
- Significantly automated majority of the work and the rest was semi-automated by the means of providing drop downs in the database to eliminate manual entry.
- Database created is flexible, simple and has an easy to use “User Interface” to eliminate the possibilities of making mistakes.
- The database can be shared online through the SKF’s SharePoint Portal and can be accessed by maintenance engineers at SKF factories across the world.
- If the recommended solutions are implemented, SKF can have a common Maintenance Program template across all their plants. It can be concluded in such a case that the maintenance program creation standard can be controlled and monitored on a global scale.

7

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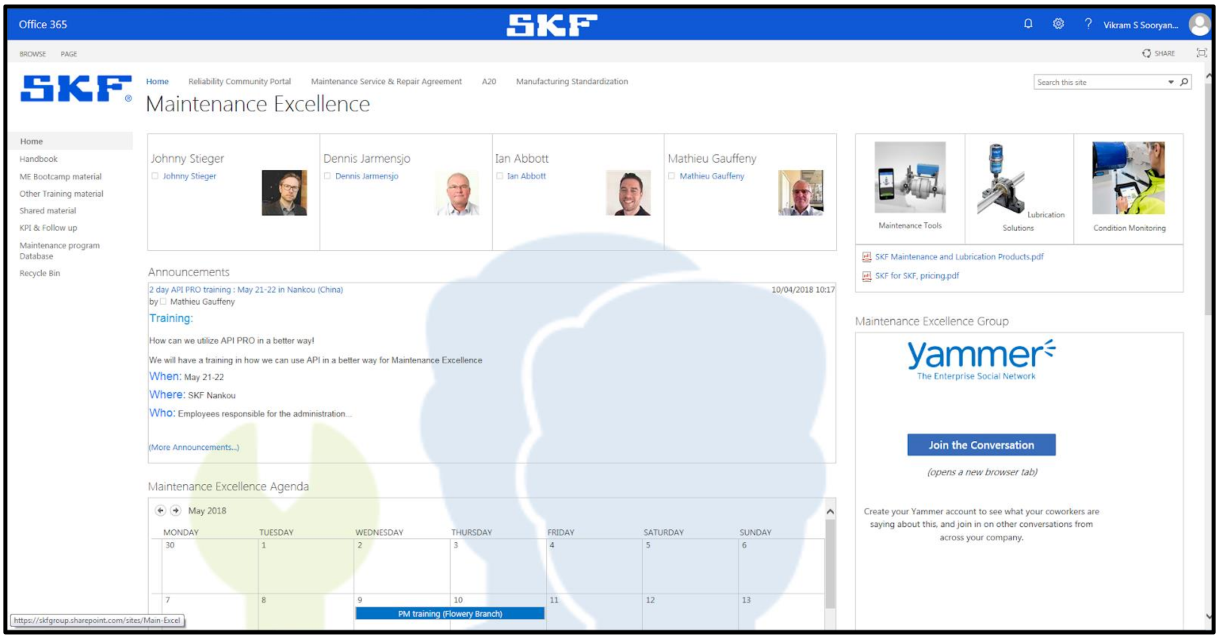
Appendices

APPENDIX A - SharePoint Portal

This Appendix shows SharePoint Point Portal Pictures

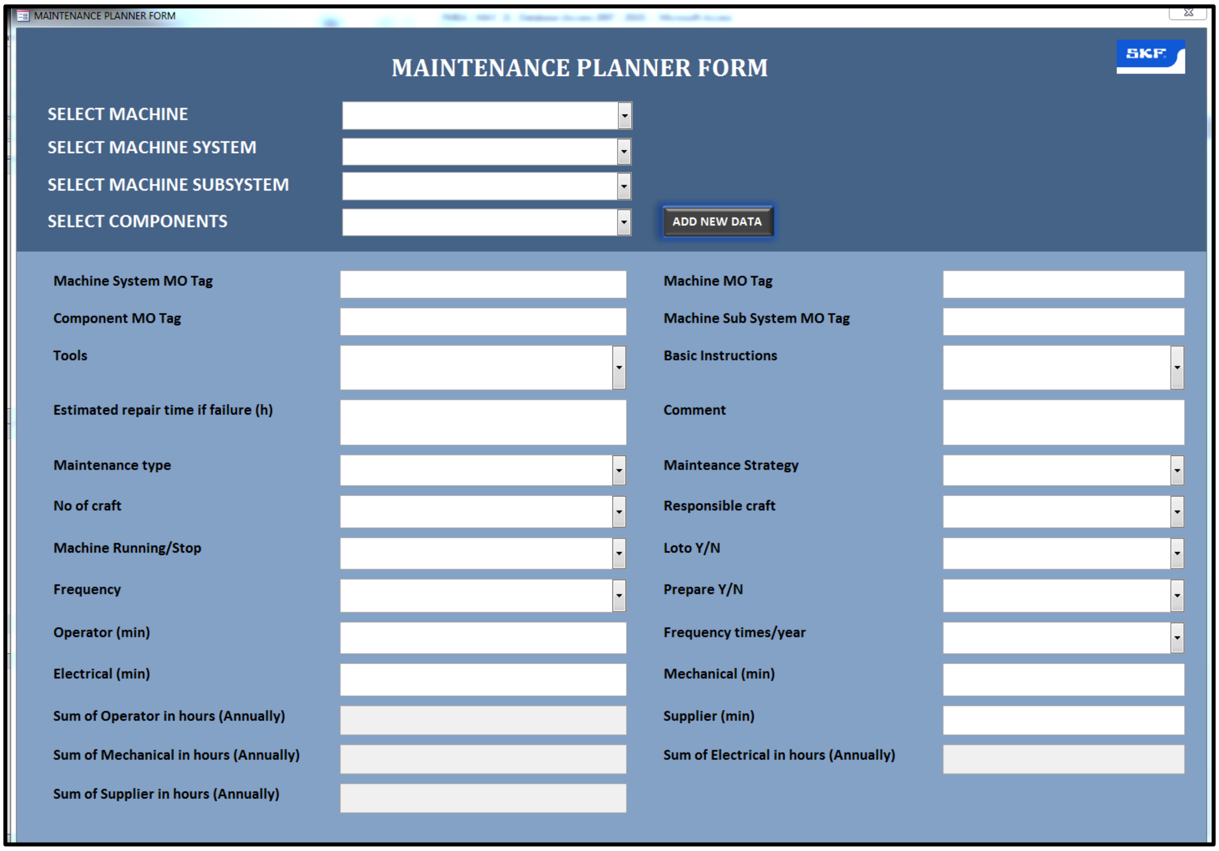


SharePoint Portal

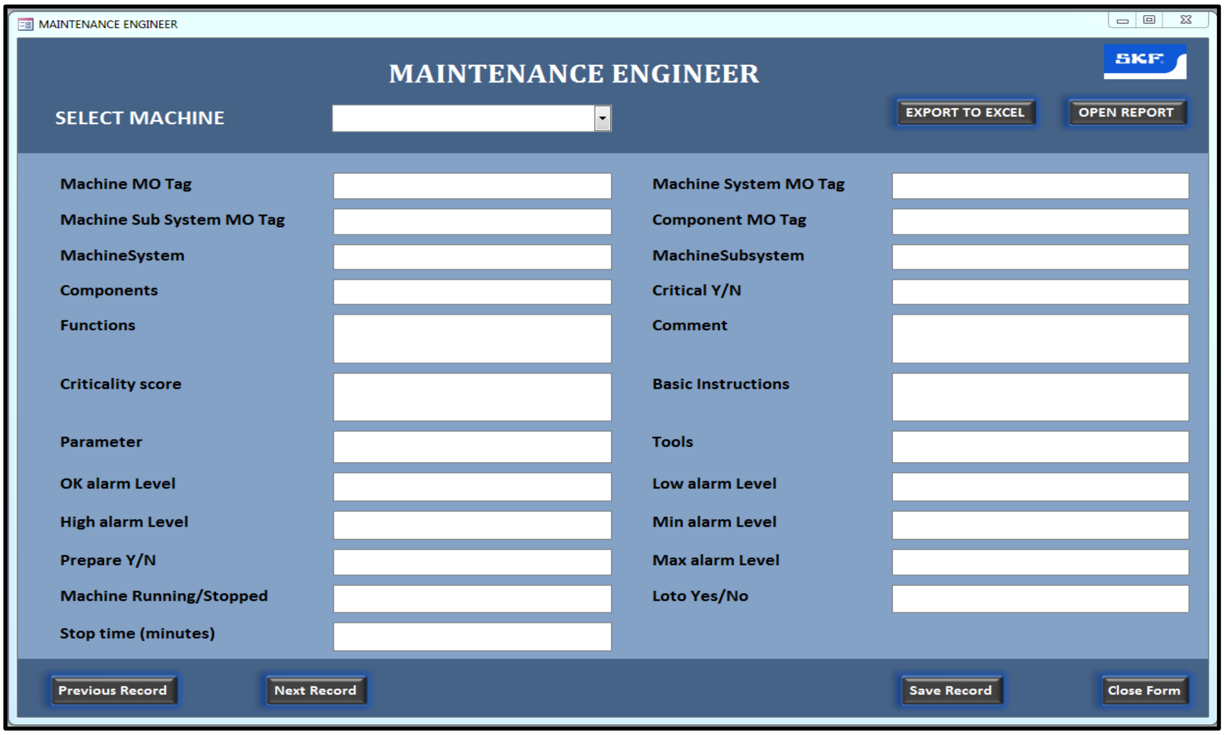
SharePoint Portal with Access Database

APPENDIX B - Forms, Tables & Reports

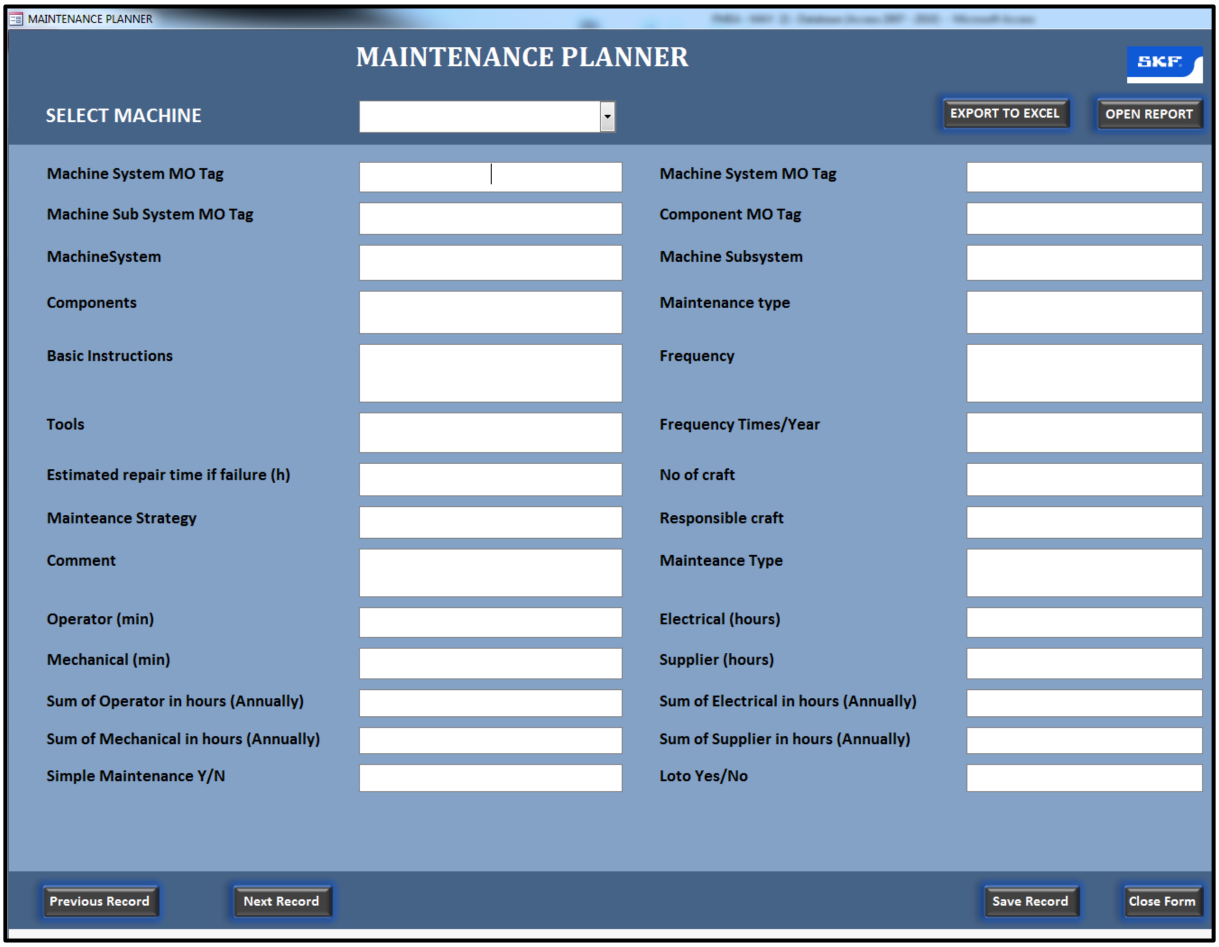
This appendix depicts the different Forms, Tables and Reports created in MS Access



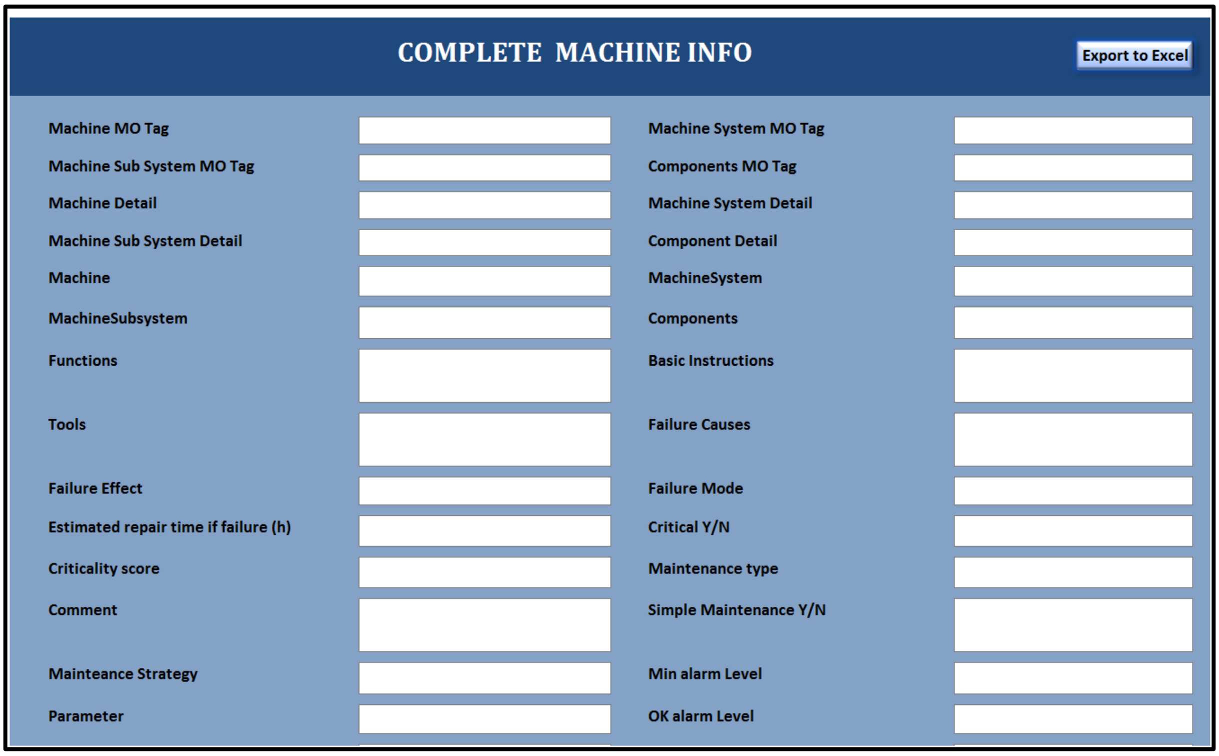
Maintenance Planner Form



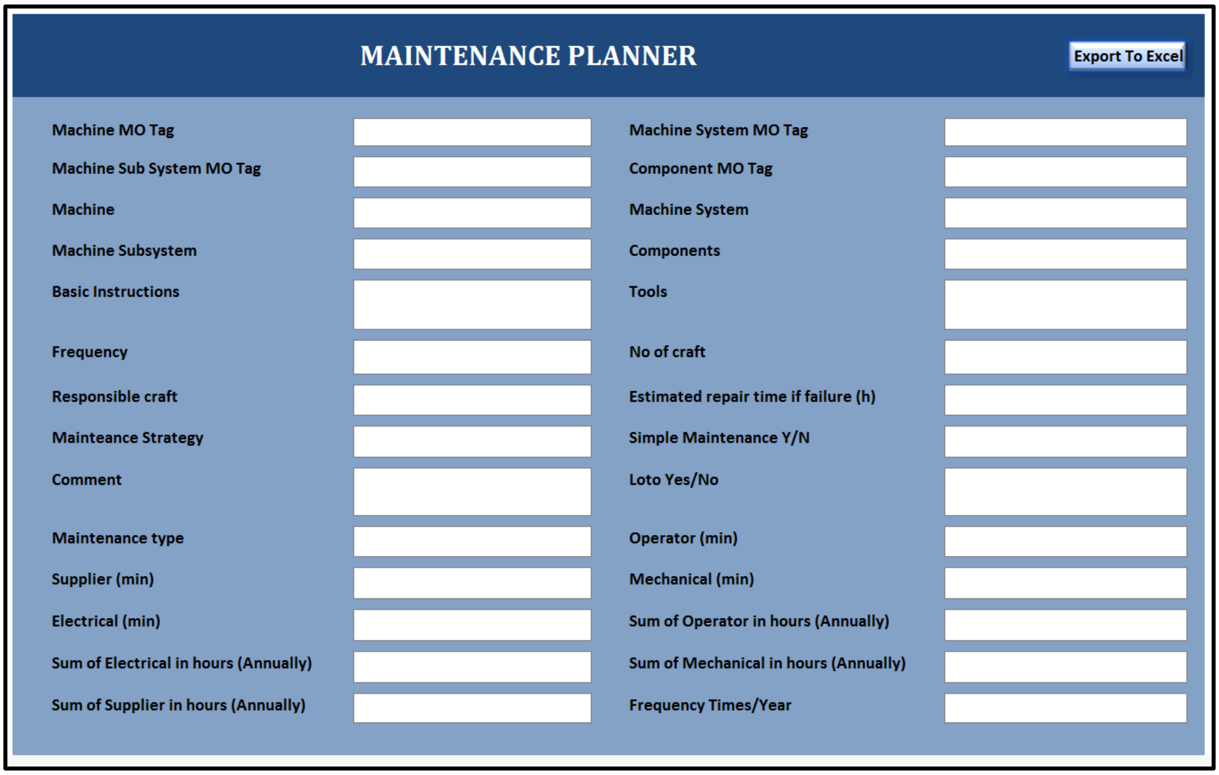
Maintenance Engineer Info Form



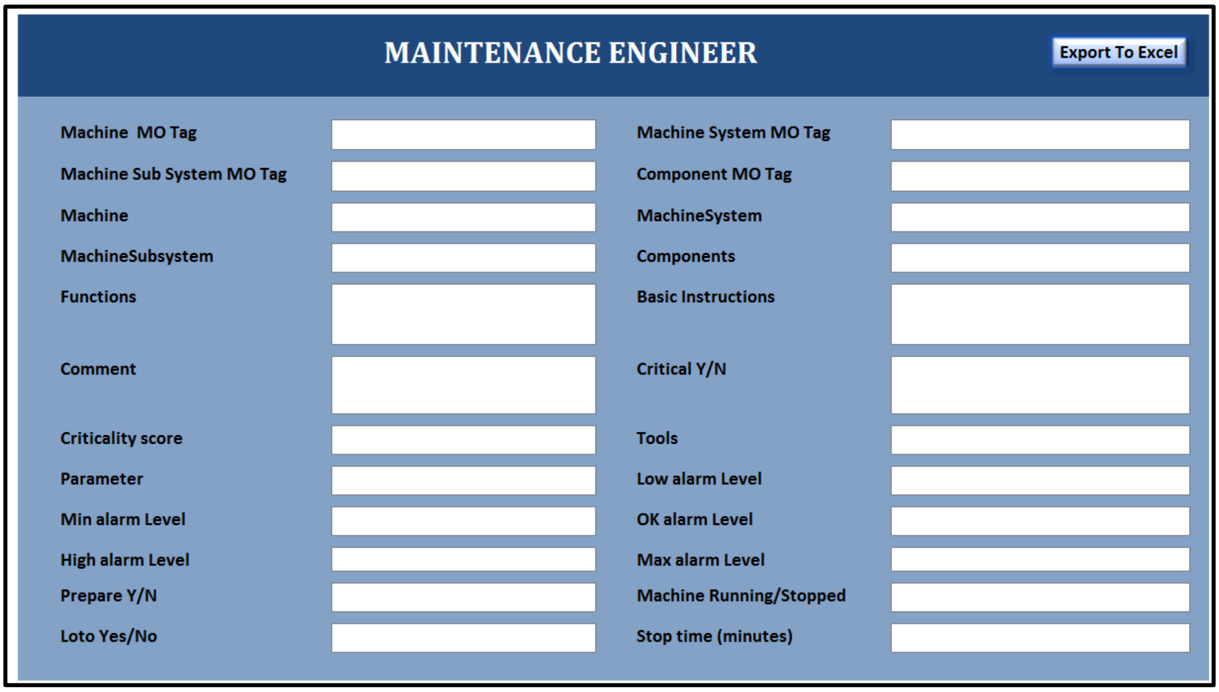
Maintenance Planner Info Form



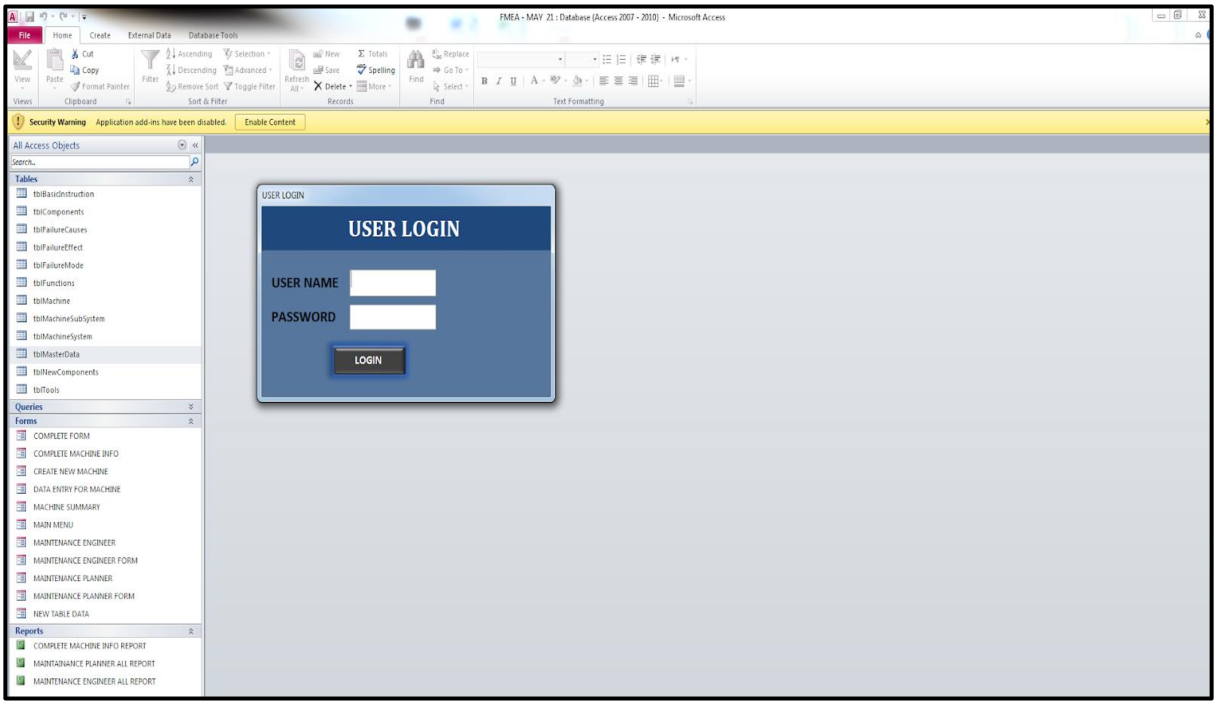
Complete Machine Info Form



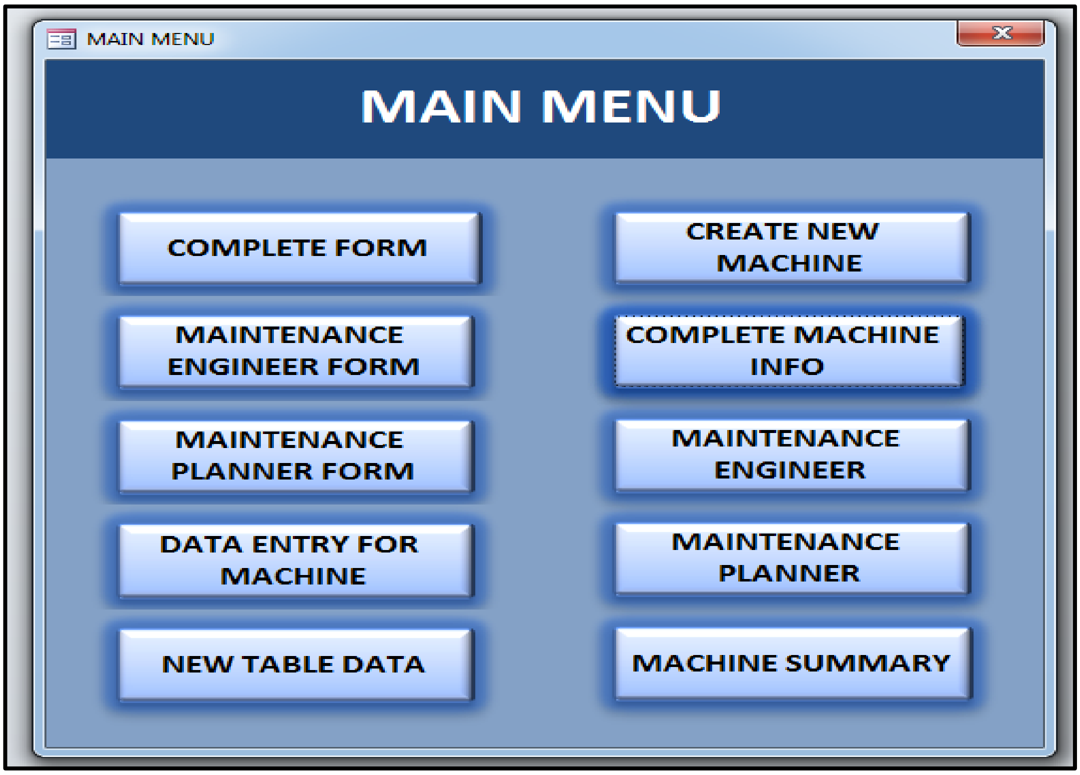
Maintenance Planner Report



Maintenance Engineer Report



User Login



Menu Form

	Machine Sys	MachineSystem	Machine ID	MO_TAG	MachineSystem_Detail:	Click to Add
+	1	MACHINE SUPPORT SYSTEM	1	SPC62-zzzzzz-01	SWEDEN	
+	2	GRINDING SYSTEM	1	SPC62-zzzzzz-02		
+	3	MACHINE SUPPORT SYSTEM	2	NEW123-	SWEDEN	
+	4	MACHINE SUPPORT SYSTEM	1	SPC62-zzzzzz-	SWEDEN	
*	(New)					

Machine System Table

tblMasterData

Master ID	Components ID	NewComponents	Functions ID	Failure Mode ID	Failure Effect ID	Failure Causes ID	Basic Instructio
1	1		1 Serve as a machine structure	Crack in foundation	Crack in foundation	Machine not aligned	Check if cracks in machine fou
2	2		2 Prevent access in the robot area	Don't give protection	Don't give protection		Check that cover is without da
3	4		4 Guide the openning/closing of the top cover	Don't give protection	Don't give protection		Check if cover is leaking
4	3		3 Protect access to the inside of the machine	Don't give protection	Leakage		Check for airleakage (include
5	4		4 Guide the openning/closing of the top cover	Don't guide smoothly	Cover can't open or close	Dirty or jammed	Check if guide is clean
6	5		5 Insure the guidance	Cover can't open or close	Don't guide smoothly	Dirty or jammed	Check if bearing is clean
7	6		6 Open and close down the top cover	Don't guide smoothly	Don't close cover	Air leakage	Check for airleakage (include
8	7		7 Control the cylinder opening/closing down	Don't close cover	Don't oopen cover	Air leakage	Check for airleakage (include
9	8		8 Enable evacuation of fumes and dust		Crack in foundation	Central evacuation out of order	
10	9		9 Contain components and protect them from dust and humidity	Don't give protection	Destroy electrical components inside	Open or damaged	Check for damages and if clos
11	10		10 Shut of electrical energy	Short circut	Electrical shock		
12	10		10 Shut of electrical energy	Heating at connection	Destroy electrical components	Loose cable connection	Thermography and check cabl
13	11		11 Provide electrical power to the machine	No or decreased voltage	Overheating	Loose connection.	Torque to specification
14	13		13 To protect for over current	Don't trip	Electrical shock		
15	13		13 To protect for over current	Don't trip	Fire		Thermography and check cabl
16	13		13 To protect for over current	Heating at connection	Destroy electrical components	Loose cable connection	Thermography and check cabl
17	14		14 To protect for over current	Don't trip	Destroy motor		
18	14		14 To protect for over current	Heating at connection	Destroy electrical components	Loose cable connection	Thermography and check cabl
19	15		15 Give electrical power to motors	Don't activate	Motor don't start		
20	15		15 Give electrical power to motors	Heating at connection	Destroy electrical components	Loose cable connection	Thermography and check cabl
21	15		15 Give electrical power to motors	Connection blades can stick	Safety issue		
22	15		15 Give electrical power to motors	Connection blades don't give contact	Motor will not work properly		
23	16		16 Give signals	Connection blades don't give contact	Wrong signals		
24	17		17 Transform voltage or current	Not right value	Give wrong voltage	Insulation problem	Check insulation value
25	18		18 Provide right voltage and current	Not right value	Give wrong voltage	Component fault	Check voltage
26	19		19 Hold cables and protect	Isolation can be broken	Safety issue	Cable contaminated	Visual inspection Check look a
27	20		20 Connect cables	Heating at connection	Destroy electrical components	Loose cable connection	Thermography of connections
28	20		20 Connect cables	Don't give right signal	Loose machine function	Loose cable connection	Check cable connections
29	21		21 Conduct electrical energy	Don't conduct energy	No signal or power to components	Cables damaged	Visual Inspections
30	22		22 Connect cables out on the machine	Heating at connection	Destroy electrical components	Loose cable connection	Thermography of connections
31	22		22 Connect cables out on the machine	Don't give right signal	No signal or power to components	Loose cable connection	Check cable connections
32	12		12 Hold correct temperature	Poor ventilaltion	Overheating of electrical components	Dirty filter or fan not running	Check filter and exchange filt
33	23		23 Provide energy for the ballscrew	Don't start	Machine stop	Internal electrical problem	
34	23		23 Provide energy for the ballscrew	Vibrate	Quality issue	Broken bearings	
35	23		23 Provide energy for the ballscrew	Vibrate	Quality issue	Motor loose	
36	23		23 Provide energy for the ballscrew	Overheated	Machine stop	Motor dirty	
37	23		23 Provide energy for the ballscrew	Overheated	Machine stop	Fan damaged	
38	23		23 Provide energy for the ballscrew	Overheated	Machine stop	Fan damaged	
39	24		24 Counting pulses	Don't count	Machine stop	Electrical problem	Visual inspections of cables
40	25		25 Moving slide	Erratic movement	Machine stop	Broken coupling	Check coupling
41	25		25 Moving slide	Not working smoothly	Quality issue	Loosen coupling	Check coupling

Record: 1 of 62 No Filter Search

Master Data Table

APPENDIX C – VBA & SQL Codes

This appendix depicts the VBA and SQL codes written for programming the Create Machine Form in Access Database

```
CREATEMACHINE                                                    Click
Private Sub CREATEMACHINE_Click()

  Dim strSQL        As String
  Dim db            As DAO.Database
  Dim rs            As DAO.Recordset
  Dim ctl           As Control
  Dim varItem       As Variant
  Dim rs2           As DAO.Recordset
  Dim ctl2          As Control
  Dim rs1           As DAO.Recordset
  Dim ctl1          As Control
  Dim ID As Long
  Dim i As Integer
  Dim l As Integer
  Dim n As Integer
  Dim strWhrMachine1SystemID As String
  Dim strSQL4str As String
  Dim intMachineSystemID As Integer
  Dim rsnewData  As DAO.Recordset
  On Error GoTo ErrorHandler

  ID = Me.cboSelectMachine.Value
  |
    If Me.listMachine.Value = Me.cboSelectMachine.Value Then
       MsgBox "Identical Machines selected, please select a New Machine", vbOKOnly + vbInformation, "  I N P U T   N E E D E D   "
       Me.cboSelectMachine.Value = Null
       Me.cboSelectMachine.SetFocus
    Exit Sub
    End If

    strSQLstr = "SELECT  tblMachine.MO_TAG " & _
              "FROM tblMachine " & _
              "WHERE (((tblMachine.[MAchine ID])= " & ID & "))"

    Set rsMachine = CurrentDb.OpenRecordset(strSQLstr)

    With rsMachine
        .MoveFirst
        strMachineMoTag = .Fields(0).Value
    End With

    Set db = CurrentDb()
    Set rs = db.OpenRecordset("tblMachineSystem", dbOpenDynaset, dbAppendOnly)
    Set rs1 = db.OpenRecordset("tblMachineSubSystem", dbOpenDynaset, dbAppendOnly)
    Set rs2 = db.OpenRecordset("tblComponents", dbOpenDynaset, dbAppendOnly)
    Set rsmas = db.OpenRecordset("tblMasterData", dbOpenDynaset, dbAppendOnly)

For n = 0 To Me.listMachineSystem.ListCount - 1
   If Me.listMachineSystem.Selected(n) Then
    rs.AddNew
    rs!MachineSystem = Me.listMachineSystem.Column(1, n)
    rs![MAchine ID] = ID
    rs!MO_TAG = strMachineMoTag & "-"
    rs!MachineSystem_Details = Me.listMachineSystem.Column(4, n)
    rs.Update
  End If
Next n
```

Create Machine VBA Code

```
For i = 0 To Me.listMachineSubSystem.ListCount - 1
   If Me.listMachineSubSystem.Selected(i) Then
   rs.FindFirst "[Machine ID]=" & ID & " AND [MachineSystem]=  '" & DLookup("[MachineSystem]", "tblMachineSystem", "[Machine System ID]=" & Me.listMachineSubSystem.Column(2, i)) & "'"

   rs1.AddNew
   rs1![MachineSubsystem] = Me.listMachineSubSystem.Column(0, i)
   rs1![Machine Sytem ID] = rs![Machine System ID]
   rs1![MO_TAG] = strMachineMoTag & "-"
   rs1![MachineSubSystem_Details] = Me.listMachineSubSystem.Column(4, i)
   rs1.Update
End If
Next i

   Me.listMachine.Value = ""
    Me.listMachineSystem.RowSource = ""
    Me.listMachineSubSystem.RowSource = ""
    Me.lstAssigned.RowSource = ""
    Me.cboSelectMachine = Null
    Me.TextMachineSystemName.Value = ""
    Me.TextMAchineName.Value = ""

ExitHandler:
  Set rs = Nothing
  Set db = Nothing
  Exit Sub

ErrorHandler:
  Select Case Err
    Case Else
      MsgBox Err.Description
      DoCmd.Hourglass False
      Resume ExitHandler
  End Select
End Sub
```

Create Machine VBA Code