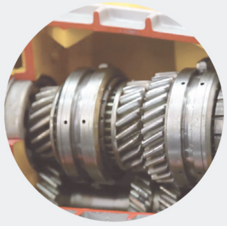
INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

MESTRADO EM ENGENHARIA MECÂNICA



ANALYSIS AND IMPLEMENTATION OF FMECA METHODOLOGY - VACUUM MACHINE

VISHVESH RAJAMANICKAM

novembro de 2018

POLITÉCNICO
DO PORTO

ANALYSIS AND IMPLEMENTATION OF THE FMECA METHODOLOGY - VACUUM MACHINE

Vishvesh Rajamanickam

2018

ISEP – School of Engineering
Department of Mechanical Engineering

Instituto Superior de Engenharia do Porto

POLITÉCNICO DO PORTO

POLITÉCNICO
DO PORTO

Instituto Superior de
Engenharia do Porto

ANALYSIS AND IMPLEMENTATION OF FMECA METHODOLOGY – VACUUM MACHINE

Vishvesh Rajamanickam

1160519

Dissertation presented to ISEP – School of Engineering to fulfill the requirements necessary to obtain a master's degree in Mechanical Engineering, carried out under the guidance of Professor Sandra Ramos.

2018

ISEP – School of Engineering
Department of Mechanical Engineering

.

POLITÉCNICO
DO PORTO

POLITÉCNICO
DO PORTO

JURY

President

Isabel Maria Garcia Sarmento Pereira

Assistant Professor, ISEP – School of Engoineering

Supervisor

Sandra Cristina de Faria Ramos

Assistant Professor, ISEP – School of Engineering

Second supervisor

Carlos Pereira

Maintenance Manager, SONAFI

Examiner

Filipe José Palhares Chaves

Assistant Professor, Instituto Politécnico do Cávado e Ave

ACKNOWLEDGEMENTS

My sincere gratitude towards my thesis advisor Professor Sandra Ramos. The door to Prof. Ramos was always open whenever I ran into a trouble spot or had a question about the way I was proceeding with my thesis work or had a question about my research or writing. She consistently allowed this paper to be my own work, but steered me in the right direction whenever she thought I needed it

I would like to thank my head of the department Professor. Francisco J. G. Silva for his keen interest in my work in despite his busy schedule. His prompt suggestion with kindness and enthusiasm aided me in completing my thesis.

I would like to thank Mr. Carlos Pereira, maintenance manager, for his invaluable assistance and, continuous input and support during the work at SONAFI. Without his passionate participation, the work would have not been completed on time.

Finally, I must express my very profound gratitude to my parents and my friends for providing me with unfailing support and continuous encouragement throughout my years of study and writing this thesis. This accomplishment would not have been possible without them. Thank you.

KEYWORDS

FMECA Methodology; Maintenance; Management; Criticality; Failure mode; Severity; Vacuum machine

ABSTRACT

The production of injection moulding components for the automotive market, meeting the highly demanding requirements of the industry, requires a continuous capacity of investment in the maintenance of the machine park. Although many companies perform this maintenance in a corrective lens, others already use the more sophisticated tools that have to avoid possible problems during the manufacturing process, ensuring levels of production and quality required by the automotive industry.

This report presents the contributions obtained during an internship in a company of production of injected casting components for the automotive market and whose objective was to apply the methodology of analysis of the mode of failure, effects and criticality (FMECA – Failure mode effects and criticality analysis) to one of the company's most critical machines, the vacuum pressure die-casting machine

Work begins with the understanding, in terms of operation and purpose, of the machine under analysis. Subsequently, and given its vital character for the high performance of the vacuum die-casting machine, an analysis is made of the type of failures that may occur in the vacuum equipment of the machine

The FMECA methodology is applied to the vacuum equipment in order to identify its potential failure modes and to evaluate the effects that these failures may have on the foundry machine.

The contributions resulting from the application of the FMECA methodology gave rise to a specific control plan for the detected problems and to a schedule and mandatory equipment maintenance.

PALAVRAS CHAVE

Metodologia FMECA; Manutenção; Gestão; Criticidade; Modos de falha; Severidade; Máquina de vácuo

RESUMO

A produção de componentes de fundição injetada para o mercado automóvel, cumprindo com os requisitos altamente exigentes da indústria, requer uma capacidade contínua de investimento na manutenção do parque de máquinas. Embora sejam muitas as empresas que executam esta manutenção numa ótica corretiva, outras já recorrem a ferramentas mais sofisticadas que têm com objetivo evitar possíveis problemas durante o processo de fabrico, assegurando níveis de produção e qualidade exigidos pela indústria automóvel.

Neste relatório apresentam-se as contribuições obtidas durante a realização de um estágio numa empresa de produção de componentes de fundição injetada para o mercado automóvel e que tinha como objetivo aplicar a metodologia de análise do modo de falhas, efeitos e criticidade (FMECA) a uma das máquinas mais críticas da empresa, a máquina de fundição sob pressão de vácuo.

Iniciam-se os trabalhos com a compreensão, em termos de funcionamento e propósitos, da máquina em análise. Seguidamente, e dado seu caráter vital para o alto desempenho da máquina de fundição sob pressão de vácuo, faz-se uma análise do tipo de falhas que podem ocorrer nos equipamentos para vácuo da máquina.

É aplicada a metodologia FMECA ao equipamento de vácuo por forma a identificar os seus potenciais modos de falha e avaliar os efeitos que estas falhas possam acarretar sobre a máquina de fundição.

As contribuições resultantes da aplicação da metodologia FMECA deram origem a um plano de controle específico para os problemas detectados e a um calendário e manutenção obrigatória dos equipamentos.

LIST OF SYMBOLS AND ABBREVIATIONS

List of abbreviations

AIAG	Automotive industry action groups
APQP	Advance product quality planning
CA	Critical analysis
CFT	Cross functional team
CP	Control plan
D	Detection
DV	Design Verification
FMEA	Failure modes and effects analysis
FMECA	Failure modes, effects and criticality analysis
HP	High pressure
ISO	International standard organization
LCL	Lower control limit
MIL-P	Military procedure
NADCA	The North American Die-casting association
NASA	The National Aeronautics and Space Administration
O	Occurrence
OEM	Original equipment manufacturer
PM	Preventive maintenance
PPAP	Production part approval process
QC	Quality control
RPN	Risk priority number

S	Severity
SPC	Statistical process control
SV	Service Visualization
TQM	Total quality management
UCL	Upper control limit
HMI	Human machine interface

List of units

Hrs	Hours
Mbar	Milli-bar pressure unit
Psi	Pounds per inch square
Ton	Tons

List of symbols

C_m	Criticality number for failure mode
$\propto$	Failure mode ratio
β	Conditional probability mission loss
λ_p	Part failure rate
T	Duration
C_r	Item criticality

GLOSSARY OF TERMS

Criticality	A relative measure of the consequences of a failure mode and its frequency of occurrences.
Severity	The consequences of a failure mode. Severity considers the worst potential consequence of a failure, determined by the degree of injury, property damage, or system damage that could ultimately occur.
Failure effect	The consequence(s) a failure mode has on the operation, function, or status of an item. Failure effects are classified as local effect, next higher level, and end effect.
Failure mode	The manner by which a failure is observed. Generally, describes the way the failure occurs and its impact on equipment operation.
Ishikawa diagram	It shows the causes of an event and is used in manufacturing and product development to outline the different steps in a process, demonstrate where quality control issues might arise and determine which resources are required at specific times.
Die-casting	Die casting is a metal casting process that is characterized by forcing molten metal under high pressure into a mold cavity. The mold cavity is created using two hardened tool steel dies which have been machined into shape and work similarly to an injection mold during the process.
Vacuum machine	In pressure die casting, since filling a cavity with an alloy is extremely rapid, vacuum technology is recognized as being the most efficient solution to evacuate air and gas. With this technology, superior quality parts can be produced. Today, vacuum technology plays a key role in the production of complex and high-quality parts such as structural parts.

FIGURES INDEX

TABLES INDEX

EQUATION INDEX

GRAPH/CHART INDEX

INDEX

INTRODUCTION

1.1 FRAMEWORK

1.2 MAIN GOALS

1.3 METHODOLOGY

1.4 DISSERTATION OUTLINE

1.5 WELCOMING COMPANY

1 INTRODUCTION

This introductory chapter provides an overview of the main points of this document and include five sections. To start with, the context which this study was conducted is presented. This also includes a presentation of the main objectives of this work and of the methodology followed. Finally, a schematic outline of the rest of the document and brief description of the company are provided.

1.1 FRAMEWORK

The business environment is increasingly fast-paced and ever-changing. For business leaders, today's environment can lead to challenges as well as opportunities to innovate and grow by capitalizing on the rapid speed of change. With this ever-changing the expectation of the customer also grows and the need to satisfy their demand is mandatory for the survival of companies. This results in added pressure and constant development in every department in an organization to satisfy the needs of the customer.

Given of its major stake in the automotive sector, die-casting industry is a good example of industry which is looking for a constant development. Die casting is an efficient, economical process offering a broader range of shapes and components for automotive industry as well as other applications than any other manufacturing technique.

Preventative maintenance for die-casting machines is widely recognized as one of the key prerequisites for the efficient and sustainable development of die-casting industry. A reliable system prevents loss of productivity due to malfunctions, wear and tear or other forms of degradation that leaves the system being unable to fulfil its intended purpose. The Failure Mode, Effects and Criticality analysis (FMECA) has been an effective ally in the implementation of preventive maintenance for die-casting machines, enabling the identification of each potential failure within a system and uses severity classifications to show the potential hazards associated with these failures.

In other words, FMECA is scientific tool to identify the assemblies, sub-assemblies and components that are critical for the satisfactory performance of die-casting machines (or other equipment). Once these critical items are identified, the most suitable and economical maintenance philosophy and practices can be applied to them in order to ensure the reliable performance of die-casting machines during the mission duration.

In this thesis, FMECA methodology is applied over a vacuum machine and a control plan is created in consideration with all the information available.

1.2 MAIN GOALS

The main goals of this thesis are as follows:

- To understand the purpose of the vacuum machine in the die-casting machine
- To analyze and determine the type of failures occurring in a vacuum machine
- To analyze and determine the cause and consequence of the failures occurring and reduce it with maintenance actions.

1.3 METHODOLOGY

To accomplish the objectives of this study, the following research methodology, that include 8 steps, was defined and executed:

- Stage I: Bibliographic research on the die-casting machine and vacuum machine used.
- Stage 2: Identification and analysis of defects. The analysis done by using quality tools (Pareto chart and Ishikawa diagram).
- Stage 3: FMEA analysis performed based on the defects figured out.
- Stage 4: Based on SONAFI parameters on FMEA, a criticality analysis is performed.
- Stage 5: Development of a control plan to assist technicians in the future with detailed explanation.
- Stage 6: ABC analysis performed on the spare parts of the vacuum machine.
- Stage 7: Development of a maintenance calendar.
- Stage 8: Implementation and follow up (monitoring of work for a period of one month).

1.4 DISSERTATION OUTLINE

The remainder of this thesis is organized as follows. Chapter 2 outlines the theoretical ideas behind the themes and methods used in this dissertation. This includes a brief introduction to subjects in different types of die-casting process and in vacuum machines. Since, the dissertation mainly focuses on reducing the machine break-down failure, Chapter 2 also present theoretical concepts behind FMEA and FMECA methods, and finally describe control plans and important quality tools. Chapter 3 presents all the results obtained in this work. Chapter 4 summarizes the thesis, and also includes some future outlooks and suggestions for further work based on the results found in this thesis.

1.5 WELCOMING COMPANY

Sonafi is an Aluminum alloy die-casting company founded in 1951, aimed at the automotive sector. Sonafi develops and manufactures components for various applications with complex geometry, with technologies such as die-casting, machining, shot blasting or vibration machining, machining, sub-component assembly, leak testing, and other anti-hazard and recording tests, according to the specification agreed with the customer.

STATE OF THE ART

2 THEORETICAL CONCEPTS

As the present chapter title implies, this chapter serves to give an overview of some of the theoretical concepts that underlie the themes and methods used in this work. Some central concepts in the fields die-casting process and vacuum machine are presented in sections 2.1 and 2.2 respectively. The following sections present theoretical concepts related to maintenance management, FMEA and FMECA methods and, finally, quality methods. While not a thorough review, this introduction is intended to give an overview of the theory that is relevant for this thesis work.

2.1 DIE-CASTING PROCESS

The North American Die Casting Association (NADCA) has defined the die casting as [1].

"A manufacturing process for producing accurately dimensioned, sharply defined, smooth or textured surface metal parts. It is accomplished by forcing molten metal under high pressure into reusable metal dies".

Die castings are among the highest volume, mass-produced items manufactured by the metalworking industry. Die castings are important components in thousands of consumers, commercial and industrial products such as automobiles, household appliances, recreation, farm and garden equipment, electrical equipment, general hardware, power tools, computers, toys, and a great many others too numerous to mention. In fact, die castings have greater utility and are used in more applications than components produced by almost any other metal forming process [2].

2.1.1 Types of Die-casting process

Die-casting can be done using a cold chamber or hot chamber process. The hot chamber machines are used primarily for zinc, and low melting point alloys which, do not readily attack and erode metal pots, cylinders, and plungers. Advanced technology and development of new, higher temperature materials has extended the use of this equipment for magnesium alloys.

In the hot chamber machine Figure 1, the injection mechanism is immersed in molten metal in a furnace attached to the machine. As the plunger is raised, a port opens allowing molten metal to fill the cylinder. As the plunger moves downward sealing the port, it forces molten metal through the gooseneck and nozzle into the die. Alter the metal has solidified, the plunger is withdrawn, the die opens, and the resulting casting is ejected.

Hot chamber machines are rapid in operation. Cycle times vary from less than one second for small components weighing less than one ounce to thirty seconds for a casting of several pounds. Dies are filled quickly (normally between five and forty milliseconds) and metal is injected at high pressures (1,500 to over 4,500 psi). Nevertheless, modern technology gives close control over these values, thus producing castings with line detail, close tolerances, and high strength. [3]

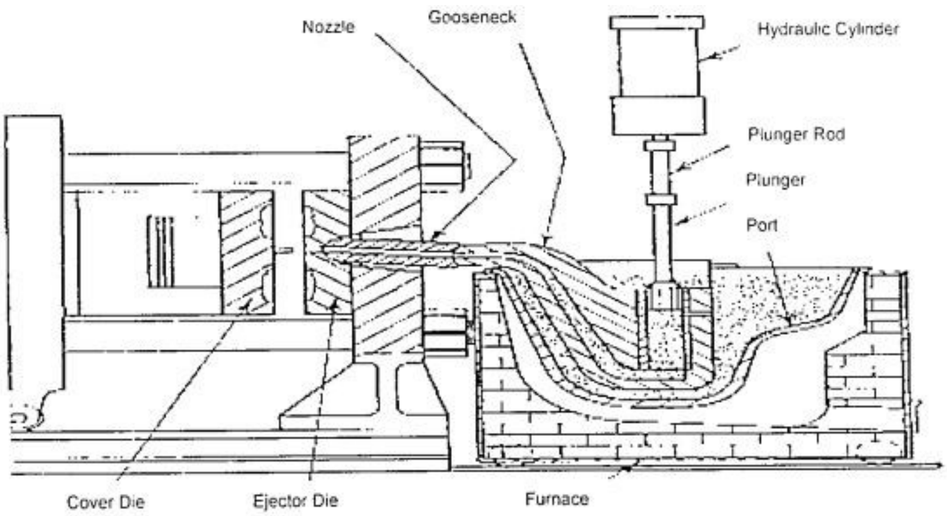


Figure 1 Hot chamber die-casting machine [4]

Cold chamber machines differ from hot chamber machines primarily in one respect, the injection plunger and cylinder are not submerged in molten metal. The molten metal is poured into a "cold chamber" through a port or pouring slot by a hand or automatic ladle. A hydraulically operated plunger, advancing forward, seals the port forcing metal into the locked die at high pressures. Injection pressures range from 3.000 to over 10.000 psi for both aluminum and magnesium alloys, and from 6.000 to over 15.000 psi for copper base alloys.

In a cold chamber machine Figure 2 more molten metal is poured into the chamber that is needed to fill the die cavity. This helps sustain sufficient pressure to pack the cavity solidly with casting alloy. Excess metal is ejected along with the casting and is part of the complete shot [5]. Operation of a "cold chamber" machine is a little slower than a "hot chamber" machine because of the ladling operation. A cold chamber machine is used for high melting point casting alloys because plunger and cylinder assemblies are less subject to attack since they are not submerged in molten metal.

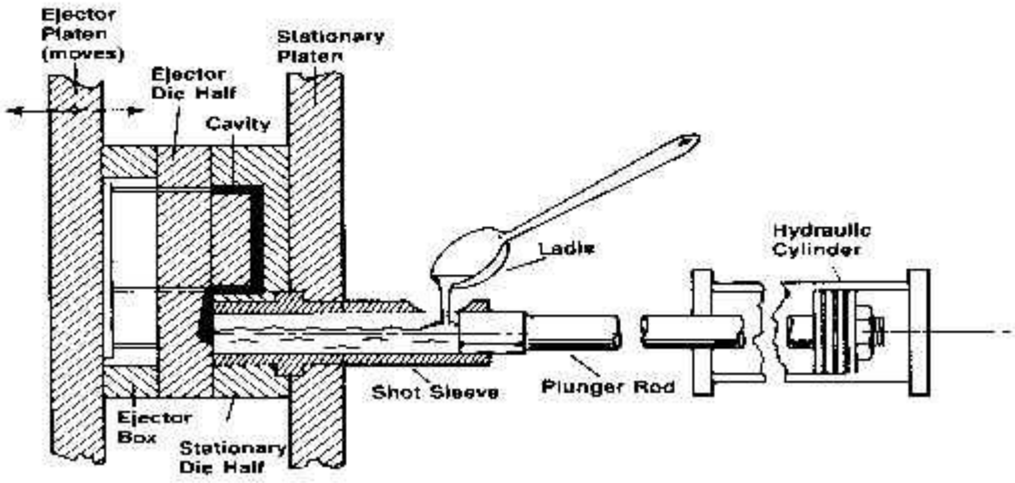


Figure 2 Cold chamber die-casting process [6]

2.1.2 Die Casting defects

Die casting defects can be classified into external and internal defects. External defects are normally related to surface defects which can be visually identified whereas the internal defects are those defects that built internally and can be seen when the certain operation has been carried out such as X-Ray, Ultrasound or any destructive process. Both internal and external defects also have many different categories depending on geographical areas and when or how the defect has been accrued. Some of the typical effects are described below in the Table 1 [7] [8].

Table 1 Typical defects (self-elaborated)

Defects	Causes
Surface defect	Those defects are called cold flow
Laminations	Defect from layers of metal forming during the process
Gas porosity	Internal porosity from the trapped gas of various kinds.
Blisters	Surface manifestation of trap gas
Flow porosity	Surface or internal porosity from poor pressure condition
Shrink porosity	Porosity from the volume change as the metal changes state
Sinks	Surface depression from shrinkage porosity problems
Leakers	Porous sections of the casting
Cracks	Visible and not-so-very visible cracks in the casting

Inclusions	Foreign material that may cause machining problems
Holes	Like crack, but it is a hole

2.2 VACUUM MACHINE

Vacuum system serves the purpose to evacuate air and gases out of the closed die cavity before and during the injection of the molten metal. The vacuum system consists of the following main components:

- VACUPAC unit, vacuum make-up station
- Mobile Vacuum Control Unit (HMI) including Display
- Interface unit for machine integration
- SUPERVAC-valve
- Interconnecting hoses and cables

The system is designed as auxiliary equipment to die casting production line and can be installed on new or existing die casting machines. The modern control system of the VACUPAC unit optimizes the operation and eliminates the need of manual supervision of the system and therefore increases the quality of the entire production. It also provides and accepts the necessary communication signals for the integration of the system into a fully automated die production line [9].

Vacuum machine is the principal component of a vacuum die-casting machine, in general, is a metal die mold having a cavity therein for forming a cast product or casting. The cavity is connected at its one end via a vacuum valve and a vacuum piping to a vacuum creating means. A vacuum gage is installed in the vacuum piping to indicate visually the degree of vacuum therein. The degree of vacuum within the cavity is controllable by the opening and closing of the vacuum valve. The cavity communicates at an opposite end thereof to the inner end of an injection sleeve. An injection plunger fitted in the sleeve and is operable therewith to inject molten metal or melt, to be die cast, into the cavity. The injection plunger has a rod extending out of the sleeve and being drivable by driving means. Detection devices such as limit switches provided to detect certain critical positions of the rod and to thereby operate a relay for opening and closing the vacuum valve.

The relay thereby operates to energize a solenoid to open the vacuum valve. Thus, reduction of the pressure within the cavity begins while the plunger continues to advance further, causing the melt to fill the cavity. For this reason, there is the possibility of gas sucked into the cavity as swept in together with the melt. More specifically, in a case such as that wherein the vacuum valve is opened prematurely when the liquid surface of the melt within the injection sleeve is lower than the centerline of the sleeve, a gap which is not sealed by a portion of the melt exists between the inner wall surface of the sleeve and the outer peripheral surface of the plunger. Consequently, a large quantity of outside air flows through this gap into the interior of the sleeve. Thus, as molted metal sucked into the cavity, it entraps and sweeps this air into the cavity. This air-infiltration phenomenon gives rise to the formation of cavities or blowholes in the resulting casting. Thus, it becomes a cause of degradation of the product quality.

Furthermore, the timing of the opening and closing of the vacuum valve established by only the positional relationships between the detection devices and the rod of the injection plunger. For this reason, adjustment of this timing cannot carry out during the operation of the die-casting machine.

In addition to this timing, the supervisory control of the degree of vacuum applied to the cavity is also a crucial factor for stabilizing the quality of the cast products. Heretofore, however, control of this timing and control of the degree of vacuum have carried out separately and independently. Especially with respect to control of the degree of vacuum, this control procedure carried out exclusively by visual supervision with the use of a vacuum gage [10].

2.3 MAINTENANCE

The management and control of maintenance are equally important to performing maintenance activities. Maintenance may be described as the function of supplying guidance for maintenance activities, in addition to exercising technical and management control of maintenance programs. As the size of the maintenance activity and group increases, the need for better management and control become essential [11].

Good maintenance engineering is essential to the success of any manufacturing or processing operation. One of the major components to a company’s success is to have a quality maintenance department that can be depended upon to discover systematic flaws and recommend solid, practical solutions.

This definition clearly shows two distinct activities in maintenance; the technical and the administrative. The technical activities are grouped under maintenance engineering and deal with the actual tasks carried out on equipment while the administrative activities are grouped under maintenance management and deal with the management aspects of maintenance. It is worth noting that a best and efficient interaction between the two fields is necessary to achieve best results. Maintenance management has become more predominant and has become a major factor in achieving overall productivity in industrial organizations.

Maintenance has evolved from a non-recognized function which comprises of simple tasks such as cleaning, lubrication and simple repairs to be an important element in industrial management and productivity. The need for maintenance engineering and management is increasingly becoming important to manufacturing industries due to rising prices of equipment, systems, machinery, and infrastructure.

Manufacturing companies, the global economy, and the world have undergone significant changes and there is competition everywhere. The world has turned global and competition is everywhere. These new challenges have led to deep transformations in companies thereby affecting maintenance as well. Because of this transformation, maintenance has come to a position of enhanced and well-deserved importance, due to its incidence of overall company competitiveness.

In an organization, when maintenance is neglected it leads to ever frequent breakdowns which result in costly repairs and faster deterioration of valuable and usually expensive equipment and inevitably has far-reaching detrimental consequences on production. This makes a high state of maintenance efficiency not only desirable but also very obligatory for industrial well-being at all levels [12].

2.3.1 Objective of maintenance

The goals of maintenance are to:

1. ensures maximum availability of plant, equipment, and machinery for productive utilization through planned maintenance;
2. maintain plant equipment, and facilities at an economic level of repairs at all times, to conserve these and increase their lifespan;
3. provide the desired services to operating departments at optimum levels, through improved maintenance efficiency;
4. provide management with information on the cost and effectiveness of maintenance; and
5. achieves all the above-mentioned objectives as economically as possible.

The objectives of maintenance can, therefore, be summarized as the systematic and scientific upkeep of equipment for prolonging its life, assuring instant operational readiness and optimal availability for production at all times whilst making sure that the safety of man and machine is never jeopardized at any cost [13]

2.3.2 Maintenance related failure

Maintenance related failure means the failure which is caused by improper maintenance management. Maintenance related failure could lead to reliability problems and will generate potential risks to the system. The maintenance-related issues are caused due to the following reasons:

Improper maintenance – Most maintenance functions allow the crafts to determine how the maintenance activities will be executed. As a result, many of these tasks are done incorrectly and incompletely. The result is a chronic reliability problem.

Poor planning – Too many maintenance functions have cut the planning and scheduling functions. Instead, work requests are compiled, routed to the supervisors and issued for execution without proper planning. As a result, critical activities are not executed in a timely manner or the procedures used are inadequate.

Failure to perform effective preventive maintenance tasks – Preventive maintenance, that is inspection, lubrication, calibration, and adjustments must be performed in a timely manner to sustain reliable asset operation. Failure to adhere to these schedules and effective execution of these tasks results in reduced asset reliability [14]

2.4 FMEA

This very particular analytical methodology aims to ensure that potential problems are identified and addressed during the product and process development phases. It is a structured methodology that allows analyzing how a system can potentially fail and carry out the respective risk analysis, based on multidisciplinary teams.

Failures prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones [15]

It is not a method of problem-solving but a method that, together with other tools, allows to prevent the occurrence of potential failures. It is a living document that, together with the Control Plan, allows documenting the latest changes to a given product or process. It is a continuous preventive methodology. [16]

Its objective is to establish the classification, in terms of severity, of the effects of these faults on the system. It also takes account, the causes of these potential failures and their likelihood of occurrence. Also taking account of which controls, in terms of prevention and detection, will also determine the probability of detection of the failure if it occurs. The failure mode will be the way the system fails to meet its objectives, especially those that affect the customer.

It is an integral part of Advanced Quality Planning and execution done in the following situations, each with a different scope: [17].

- New products, innovative technologies or new processes; the scope of the FMEA will be the entire product, technology or process.
- Modifications to existing products or processes; the scope should focus on the modification and implications of the same, in the history, including regulatory aspects.

The first applications of the FMEA date back to the period after World War II, through the application of the document "Procedure for performing a failure mode effect and criticality analysis United States Military Procedure, MIL-P-1629", November 1949. It was subsequently used in the aerospace sector, in the development of rockets, with emphasis on the Apollo program in the 1960s, in developing the means to transport humans to the moon and then return them safely back to the earth. As early as the late 1970s, Ford introduced the tool in the automotive industry to increase safety and regulatory compliance. Subsequently, the use of the FMEA extended to the improvement of product (D-FMEA) and of the productive process (P-FMEA). Currently, FMEA is a mandatory requirement of ISO / TS16949: 2002 to minimize risk and as the preventive tool par excellence; is an integral part of Advanced Product Quality Planning – APQP [18]

FMEA is a technique practiced by those companies that have adopted the philosophy of “Total Quality Management” (TQM) Figure 3. This technique identifies potential problems and opportunities for early corrective action. FMEA will lead to a better product or service and improved customer satisfaction.

Source 1 Sonafi FMEA manual (self-elaborated)

Figure 3 Place of FMEA in TQM

2.4.1 Types of FMEA

There are four types of FMEAs. The relationships of the four FMEAs shown with their respective focus and objective [19] [20].**Erro! A origem da referência não foi encontrada.**

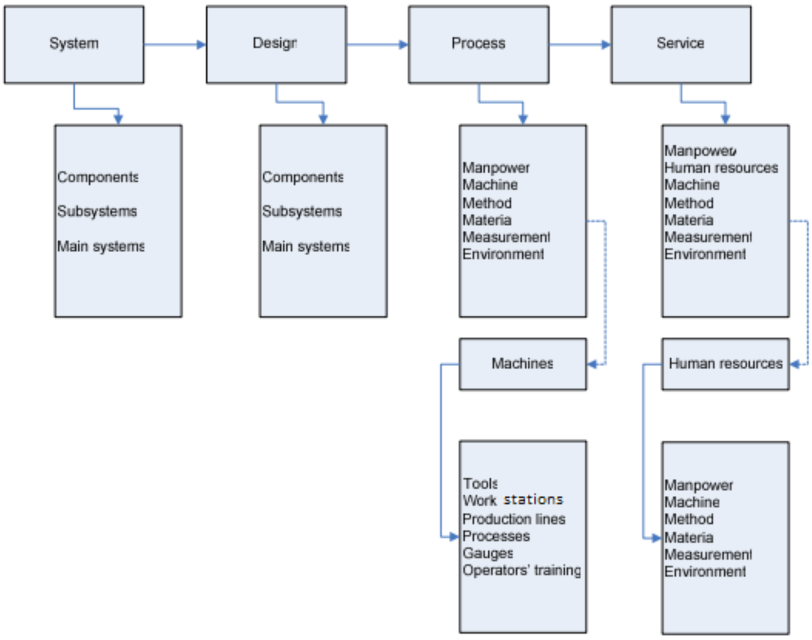


Figure 4 Types of FMEA (self-elaborated)

The system FMEA is the highest FMEA performed. Used to identify and prevent failures that are related to systems or subsystems in early design concept stages. The system FMEA performed to validate the system design specifications minimize the risk of functional failure during operation. Benefits and objectives of the system FMEA.

It identifies potential systemic failure modes caused by system interacts with other systems and/or by subsystem interactions, including those that may adversely affect safety or compliance with government regulations and It identifies potential system design parameters that may include deficiencies before hardware and/or software released to production. Furthermore, it helps in selecting the optimum system design alternative and enables actions to ensure that customer wants/ expectations are satisfied to initiate as early as possible in the development cycle and quality planning phases of the system design [21].

It acts as the basis for developing system diagnostic and system fault management techniques.in an organized, systematic approach to identifying all potential effects of subsystem, assembly and part failure modes for inclusion in design FMEAs.

It serves as a historical record of the thought processes and the action taken in product development efforts for the engineers to focus on eliminating product concerns and minimizing the probability of poorly performing products reaching the customer.

Determining, evaluating and improving the system design verification (SV) test programs and also it helps in generating the failure mode occurrence ratings that can estimate a system design alternative's reliability and hardware redundancy is required to meet the reliability requirements [22].

The design FMEA used as a tool to help identify and prevent product failures that are related to the product design. This FMEA can perform over a system, subsystem or component design proposal and intended to validate the design parameters selected for a given functional performance requirement. Benefits and objectives of the design FMEA are it identifies potential design related failure modes at a system, subsystem or component level that may adversely affect safety or compliance with government regulations during initial period (prior to hardware release) so that design actions to eliminate or mitigate the concerns identified.

It increases the probability that potential failure modes and their effects on vehicle/system performance considered in the design/development process and key critical and significant characteristics of a design. Ensures that customer wants/expectations are satisfied to initiate as early as possible in the product development cycle and quality planning phases of the product design.

Aids in the objective evaluation of design requirements and design alternatives and provides a reference to aid in analyzing field concerns to develop advanced designs in future. Also, provides an organized, systematic approach to criticality reduction and risk reduction and establishes a priority for design improvement actions and serves as a historical record of the thought processes and the action taken in product development efforts.

It helps to documents the rationale behind product design changes to guide the development of future product design and aids to focus on eliminating product concerns and minimizing the probability of poorly performing products reaching the customer and assists in the evaluation of product design requirements and alternatives. Finally, It enhances organizational learning by serving as a depository for valuable "lessons learned" to help organizations avoid making the same error repeatedly [22].

Identification of potential process failure modes at a system, subsystems or operation level that may adversely affect safety or compliance with government regulations so that actions taken to eliminate the concern or mitigate its effects. The key process critical and significant characteristics and aids in the development of through control plans. Which along with potential process deficiencies early in the process planning cycle, enabling engineers to focus on the control that will reduce the incidence of unacceptable products and the use of unacceptable methods and increase detection capability well before production begins.

Ensures what customer wants/expectations are satisfied to initiate as early as possible in the process development cycle and quality planning phases of the process design. By this process, it eliminates or reduces product criticality through manufacturing and/or assembly process design improvements. It provides an organized, systematic approach to process change and process update prioritization.to establishes priorities for process improvement actions. Plus, it also serves as a historical record of the thought processes and the action taken in process development efforts [22].

The process helps engineers focus on eliminating product concerns caused by the manufacturing or assembly process, thus minimizing the probability of poorly performing products reaching the customer and in determining, evaluating and improving the production verification (PV) test programs.

2.4.2 Benefits of FMEA

In general, the benefits of FMEA is immense. Since it is such a flexible tool. The result is immeasurable, it can upgrade until zero defects achieved. [23].

- Improvements in quality, reliability, and safety.
- Reduction in development times and costs.
- Early identification and elimination of potential conformities.
- Emphasis on the prevention and elimination of systematic errors.
- Minimize alterations as well as respective costs before and after.
- Reduction of claims in guarantee period after entry into production.
- Knowledge for future reduction of failures and technical advantages.
- The catalyst for teamwork multidisciplinary.
- Improvement in the image of the organization and its respective competitive advantage.
- Improved customer satisfaction.

2.4.3 Common FMEA errors

Humans are prone to error and the possibility of making an error is high. Below mentioned are few of the area where errors are common. [24] [25].

- Incorrect scope definition;
- Failure to define the function of the system or sub-system (D-FMEA) or process function requirement (P-FMEA);
- Failure to define the performance requirement for the function;
- Not identifying all potential failure modes;

- Incorrect customer identification;
- Incorrect interpretation of classifications
- Confusing modes of failure with effects or causes of failure;
- Inability to implement recommended actions or recommended actions that are not feasible;
- Too much optimism in the classification of Occurrence and Detection;
- Failure to recognize the "potential" of failure, effect or cause.

2.4.4 Evaluation of error modes

Risk Priority Number (RPN) is a measure used when assessing risk to help identify critical failure modes associated with design or process and is given by:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

Equation 1 Risk priority number

where S is the Severity, O is the Occurrence and D is the Detection.

The Occurrence is the frequency of the failure. Severity is the seriousness (effects) of the failure. Detection is the ability to detect the failure before it reaches the customer. There are many ways to define the value of these components. The useful way is to use numerical scales (called critical guidelines).

The ranking for the criteria can have any value. There is no standard for such value; however, there are two-way common ranking used in all industries today. One is ranking based on a 1 to 5 scale and the second, 1 to 10 scale.

The ranking of 1 to 5 is limited in nature but offers expediency and ease of interpretation. It does not provide for sensitivity (accuracy) of specific quantification, because it reflects a uniform distribution. The ranking of 1 to 10 is used widely and, in fact, is highly recommended because it provides ease of interpretation, accuracy, and precision in the quantification of the ranking. Rankings of higher than 1 to 10 scales are not recommended (even though they can be very precise and accurate) because they are difficult to interpret and lose their effectiveness [26].

The Occurrence is the occurrence frequency of failure mode that a potential cause of failure will occur. Occurrence number does not refer to the occurrence frequency of any failure, but it expresses meaning in accordance with occurrence number. Table 2 FMEA - Occurrence rankings [27] represents occurrence criteria in FMEA. Occurrence number is obtained by the rating which related to definitions expressing frequency of occurring failure. To obtain occurrence frequency, it is needed some initial information related to the same or related products [28].

Table 2 FMEA - Occurrence rankings [27]

Prob. Failure	Criteria: Case-P-FMEA (Incidents by machine)	Class
Very high	>= 100 per 1000 >= 1 in 10	10
High	>= 50 per 1000 >= 1 in 20	9
	>= 20 per 1000 >= 1 in 50	8
	>= 10 per 1000 >= 1 in 100	7
Moderate	>= 2 per 1000 >= 1 in 500	6
Moderate	>= 0.5 per 1000 >= 1 in 2.000	5
	>= 0.1 per 1000 >= 1 in 10.000	4
Low	>= 0.01 per 1000 >= 0.01 in 100.000	3
	<= 100 per 1000 >= 1 in 1.000.000	2
Very low	Failure is eliminated by preventive control.	1

Severity is effect degree of a potential failure mode on the customers. Severity number is used for rating severity of potential failure mode on the customers. As set out in [27], the severity number for FMEA is Table 3.

Table 3 Severity numbers of FMEA [27]

Effect	Criteria: Effect severity on the product (effect on the customer)	Class	Effects	Effect on the process (effect on manufacture/assembly)
Safety failure and/or regulatory requirements	The potential failure mode affects safety in the operation of the vehicle and/or involves non-compliance with governmental legislation without notice	10	Safety failure and/or regulatory requirements	It can endanger the operator (machine or assembly) without prior notice.
	The potential failure mode affects safety in the operation of the vehicle and/or involves non-compliance with governmental legislation without notice	9		It may endanger the operator (machine or assembly) with prior notice
Loss or degradation in the primary function	Loss of primary function (vehicle inoperative, does not affect safety in the operation of the vehicle)	8	Larger Disruptions	100% of the product may have to be discarded. Line stop or expedited blocking.
	Degradation of primary vehicle (operational vehicle, but with reduced performance level)	7	Significant Disruptions	Part of the total production may have to be rejected. Deviation from the main proceedings including increase of labor
Loss or degradation in secondary function	Loss of secondary function (operational vehicle, but functions relating to comfort/convenience)	6	Moderate disruptions	100% of production may have to be reworked and approved off-line
	Degradation of the secondary function (operational vehicle, but functions related to comfort/convenience with a reduced level of performance)	5		Part of the total production may have to be reworked and approved off-line.
Inconvenience	Appearance or audible noises, operational vehicle, item not compliant and detectable by the majority of customers (made 75%)	4	Moderate disruptions	100% of production may have to be reworked in the workstation before being processed

	Appearance or audible noises, operational vehicle, item not conformable by many customers (50%)	3		Part of the total production may have to be reworked at the workstation before it is processed.
Inconvenience	Appearance or audible noises, operational vehicle, item not compliant and detectable by demanding customers (<25%)	2	Minor disruptions	Small inconvenience to the process, operation or operator.
None	No discernible effect	1	No effect	No discernible effect

Detection is the probability that potential design or process failures are detected before the products reach to the customers. Detection number is related to detection probability of failure mode in design or process FMEA before the products reach to the customer. It can be seen the detection numbers in Table 4.

Table 4 - FMEA- Detection rankings [27]

Prob. Fail	**Criteria: Case P-FMEA (Incidents by machine)**	**class**
Very high	>= 100 per 1000	10
	>= 1 in 10	
High	>= 50 per 1000	9
	>= 1 in 20	
	>= 20 per 1000	8
	>= 1 in 50	
	>= 10 per 1000	7
	>= 1 in 100	
Moderate	>= 2 per 1000	6
	>= 1 in 500	
Moderate	>= 0.5 per 1000	5

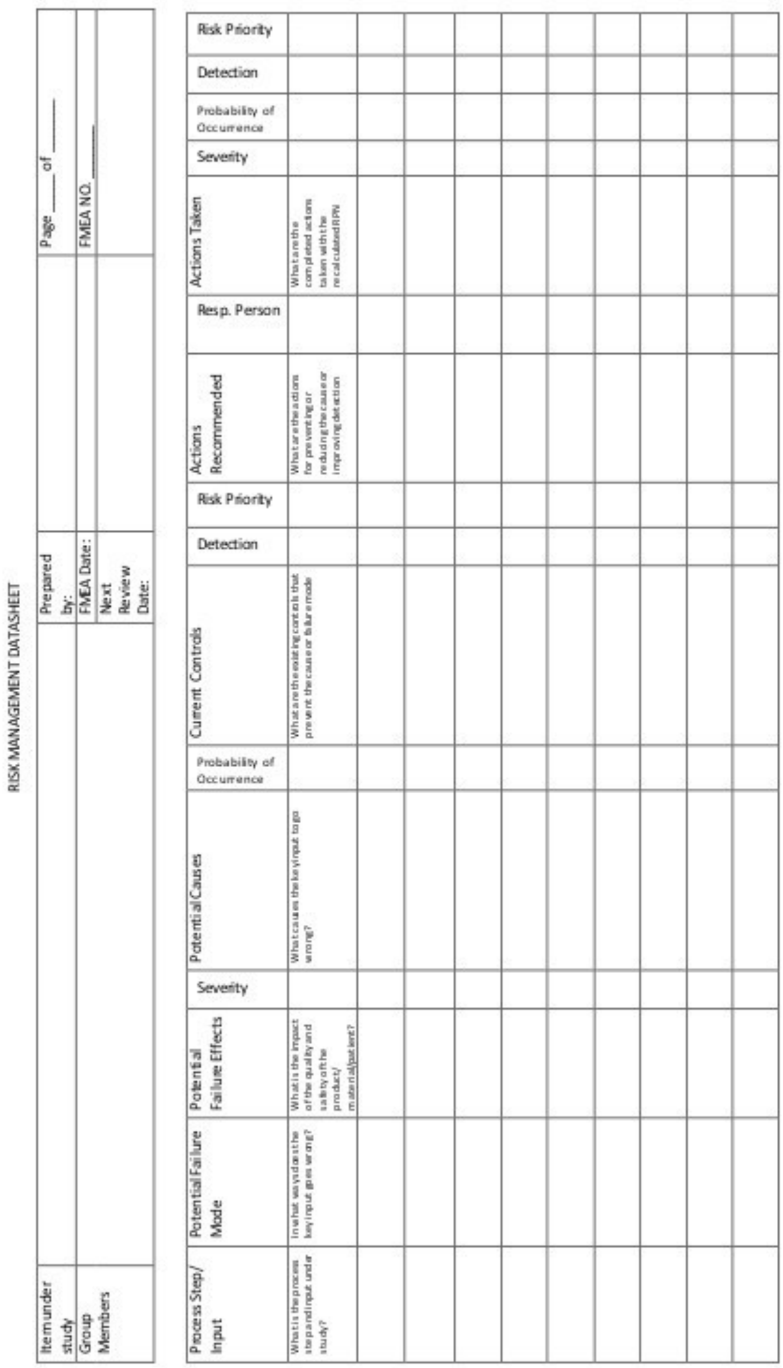
	>= 1 in 2.000	
	>= 0.1 per 1000	4
	>= 1 in 10.000	
	>= 0.01 per 1000	3
Low	>= 0.01 in 100.000	
	<= 100 per 1000	2
	>= 1 in 1.000.000	
Very low	Failure is eliminated by preventive control.	1

Considering the previous tables, the RPN values range from 1 (absolute best) to 1000 (absolute worst). The threshold of pursuing failures/problems is an RPN equal to or greater than 50 based on a 95 percent confidence and 1 to 10 guideline scale. By no means is this a standard or a universal number. It can and does change with the scale chosen and the statistical confidence the engineer wants. Of course, there is no limit to pursuing all failures, if that is the goal. At that point, the order is determined by the magnitude of the RPN for each failure (the high RPN failures are addressed first, then the lower and so on until all failures have been resolved). To undertake an analysis of all problems at the same time is not recommended and is contrary to the philosophy of the FMEA.

As stated above, the threshold can be changed for any given statistical confidence and/or scale. For example, say 99 percent of all failures must be addressed for a very critical system, design, product, process and/or service on a guideline scale of 1 to 10. What is the threshold? The maximum number possible for RPN is 1000 (10 x 10 x 10 from occurrence, severity, and detection). Ninety-nine percent of 1000 is 990. Now subtract 1000–990=10. Therefore, the threshold of examining the failures would be anything equal to or greater than a 10 RPN. If the statistical confidence is 90 percent with a scale of 1 to 10, then the threshold becomes 100, and so on. If the scale is 1 to 5, then the threshold changes accordingly. The method is the same, however, the total number is 125 instead of 1000. Thus, in a 90 percent, 95 percent, and 99 percent confidence the RPN of concern is 13, 7 and 2, respectively [29].

2.4.5 FMEA form

FMEA forms are used to record regularly information that is obtained by FMEA study, to make the FMEA process easy and to create a certain standard. In these forms, there is general information about FMEA type, error mode, the cause, effects and results of the error, present controls, RPN values, FMEA responsible and the precautions that will table. An example FMEA form is represented in the below Figure 5



RISK MANAGEMENT DATASHEET

Item under study		Prepared by:		Page ____ of ____	
Group Members		FMEA Date:		FMEA NO. ____	
		Next Review Date:			

Process Step/ Input	Potential Failure Mode	Potential Failure Effects	Severity	Potential Causes	Probability of Occurrence	Current Controls	Detection	Risk Priority	Actions Recommended	Resp. Person	Actions Taken	Severity	Probability of Occurrence	Detection	Risk Priority
What is the process step and input under study?	In what ways does the key input goes wrong?	What is the impact of the quality and safety of the product/ material/patient?		What causes the key input to go wrong?		What are the existing controls that prevent the cause or failure mode			What are the actions for preventing or reducing the cause or improving detection		What are the completed actions taken with the recalculated RPN				

Figure 5 FMEA Form [30]

2.4.6 FMEA APPROACH

There are two approaches to knowledge-based FMEAs – prediction of RPN, and automation of FMEA reports. Prediction of RPN has been performed by the use of fuzzy FMEA systems. where the investigation of the failure mode and failure consequence for a component is performed by the engineer without any decision support. The engineer uses linguistic variables (such as low, medium, high) to indicate the occurrence, severity and detection. Based on these linguistic variables, fuzzy logic is applied to provide/predict a crisp RPN value. Such systems may reduce the inconsistency associated with assessment of O, S and D. They may also increase consistency in the RPN values obtained by different engineers. However, they do not provide decision support to engineers while they analyze components for failure modes and failure consequences, and do not provide users with suggested improvements to current situations [31].

2.5 FMECA

Failure mode, effects and criticality analysis (FMECA) is an extension of FMEA. FMEA is a bottom-up, inductive analytical method which may be performed at either the functional or piece-part level. FMECA extends FMEA by including a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences.

FMECA originated in the United States in the 1950s. Grumman Aircraft Corporation used a method called" failure mode and effect analysis" when developing primary flight control system. Although failure mode and effect analysis were held without criticality analysis, it still achieved good results. In the mid-1960s, FMECA was officially used for the Apollo program in the USA's aerospace industry. The academic discussion on FMEA began in 1960. In the early 1980s, FMECA entered the microelectronics industry, and the FAA also expressly required aviation system design and analysis process must be carried out with FMECA. American automotive industry began to use FMEA methods in the mid-1980s. After the 1990s, FMECA has been formed a set of the scientific and complete analysis method [32].

The failure mode may then be charted on a criticality matrix using severity code as one axis and probability level code as the other. For quantitative assessment, modal criticality number $\mathrm{C_m}$ is calculated for each failure mode of each item, and item criticality number $\mathrm{C_r}$ is calculated for each item. The criticality numbers are given by:

$$C_m = \lambda_p \alpha \beta t,$$

Equation 2 Criticality number for failure mode

Where λ_p is the part failure rate, α is the failure mode ratio, β is the conditional probability and $t$is the duration of applicable mission phase usually expressed in hours or number of operating cycles

The item criticality number is computed as

$$C_r = \sum (C_m)^n$$

Equation 3 Item criticality

The failure mode ratio may be taken from a database. For functional level FMECA, engineering judgment may be required to assign failure mode ratio. The conditional probability number β represents the conditional probability that the failure effect will result in the identified severity classification, given that the failure mode occurs. For graphical analysis, a criticality matrix may be charted using either C_r or C_m on one axis and severity code on the other

2.6 CONTROL PLAN

Most companies are looking for methods to reduce cost and eliminate waste in their processes. In the business world today controlling waste and maintaining a high level of quality is imperative for a company to succeed. The cost of doing business is ever increasing. Rising costs of raw materials combined with labor and equipment costs have brought scrap reduction into the critical to business category.

But many falls short when it comes to sustaining those corrective actions or process improvements over a long period of time. In many cases, the process gradually returns to its previous state and the problems eventually resurface. A Control Plan is often a Production Part Approval Process (PPAP)requirement for suppliers of parts to companies in these industries. The primary resource for information regarding Control Plan Methodology in the automotive industry is the Advanced Product Quality Planning and Control Plan manual published by the Automotive Industry Action Group (AIAG) [33].

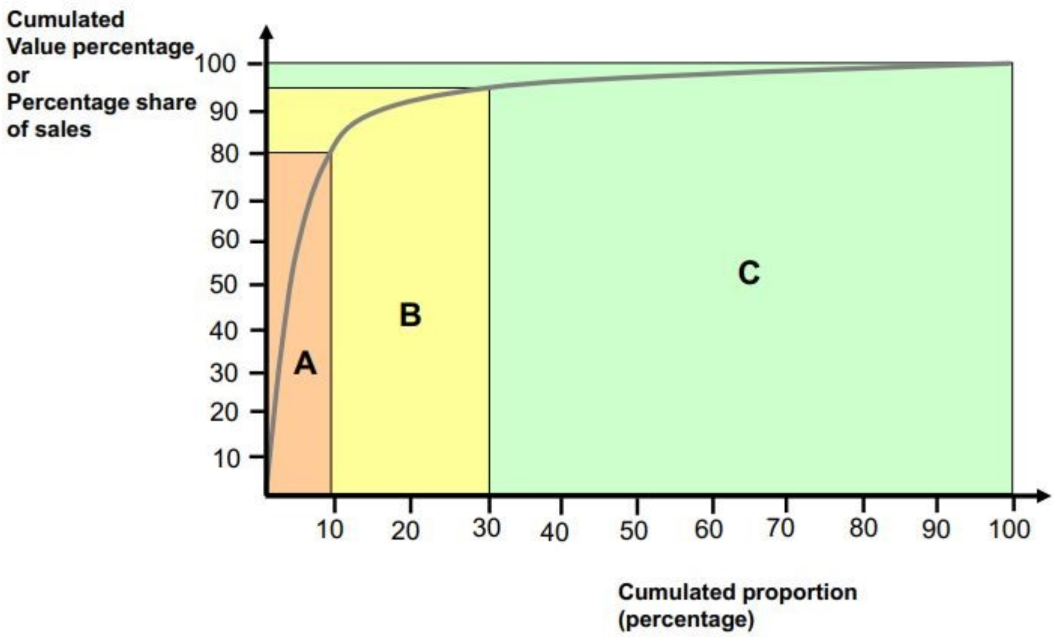
There are three designations for a Control Plan level based upon what point the product is at in the New Product Introduction (NPI) process. They are as follows:

1. *Prototype* – This level Control Plan should include descriptions of the dimensions to measure and the material and performance tests to be completed during the prototype build
2. *Pre-Launch* – This level of Control Plan should contain descriptions of the dimensions to be measure and the material and performance tests to be completed after prototype but prior to product launch and regular production.
3. *Production* – This level of Control Plan should contain a comprehensive listing of the product and process special characteristics, the process controls,

measurement methods and tests that will be perform during regular production.

2.7 ABC CLASSIFICATION

The ABC-Analysis represents a simple method of material classification in respect of value and quantity. The so-called Pareto principle indicates that for many phenomena's the following is valid: 80 % of effects are reached by 20 % of causes. The principle traces back to Vilfredo Pareto (Italian economist) who, related to Italy, had noticed that 80 % of property belonged to 20 % of the Italian population [34].



Chart/Graph 1 ABC analysis [34].

The separation between essential and non-essential, the identification of starting points for improvement and the avoidance of uneconomical efforts are de main goals of ABC analysis [34].

ABC analysis procedure include the following steps

1. Determination of absolute total costs

$$Absolute\ total\ cost = yearly\ demand\ X\ piece\ price$$

Equation 4 Absolute total cost

2. Determination of relative proportions of the total costs.

$$Cost = \frac{Absolute\ total\ cost}{total\ cost}$$

Equation 5 Relative proportion of total cost formula

3. Sorting according to relative contribution to total costs (in descending order)

4. Accumulation of relative contributions to total costs

5. Classification of materials into three categories (Accumulation of individual relative total costs)

6. Determination of relative quantity proportions

$$\text{Relative quantity propotion} = \frac{\text{Yearly demand}}{\text{Total demand}}$$

Equation 6 Relative quantity proportion formula

7. Summation of relative quantity proportions per material class

2.8 EQUIPMENT MAINTENANCE CALENDAR

It a planned maintenance that ensures all the activity proceeds as planned, it falls under preventive maintenance.

The maintenance is scheduled based on a time or usage trigger. A typical example of an asset with a time-based preventative maintenance program schedule is an air-conditioner which is serviced every year, before summer. A typical example of an asset with a usage-based preventative maintenance program schedule is a motor-vehicle which might be scheduled for service every 10,000km.

Working with operations to create a preventive maintenance schedule for vital equipment & facilities can become a challenge for maintenance managers. Breakdown maintenance is a priority since equipment needs to be up and running again. However, regular preventive maintenance is essential to keep equipment running smoothly and within operational limits.

Sadly, doing such maintenance usually falls low on the list. Maintenance departments are often overextended dealing with breakdowns. Shutting down critical machinery will cause production backlogs or other operational issues. This makes it hard to convince operations staff to do a shut down just for planned maintenance.

Many maintenance software programs allow you to create an equipment maintenance calendar. This will be a report or a display on the screen. Using this calendar, it is possible to see several months ahead. You can find what preventive maintenance is due for different equipment. Armed with such a calendar you can make changes to the schedule settings for each preventive maintenance task. This will help get as many maintenance jobs as possible to fall within the shutdown period. [35]

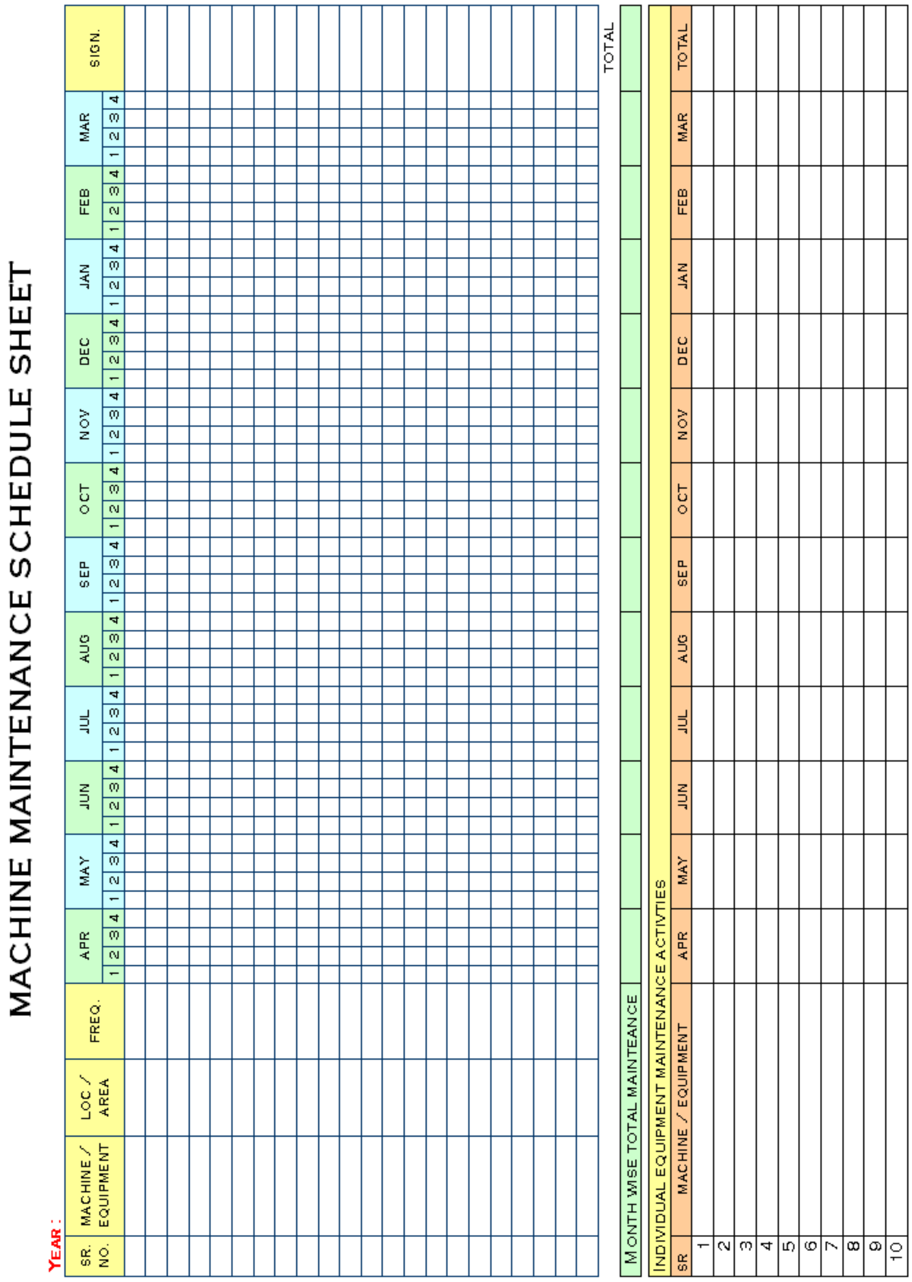


Figure 6 Equipment maintenance calendar [36]

2.9 QUALITY TOOLS

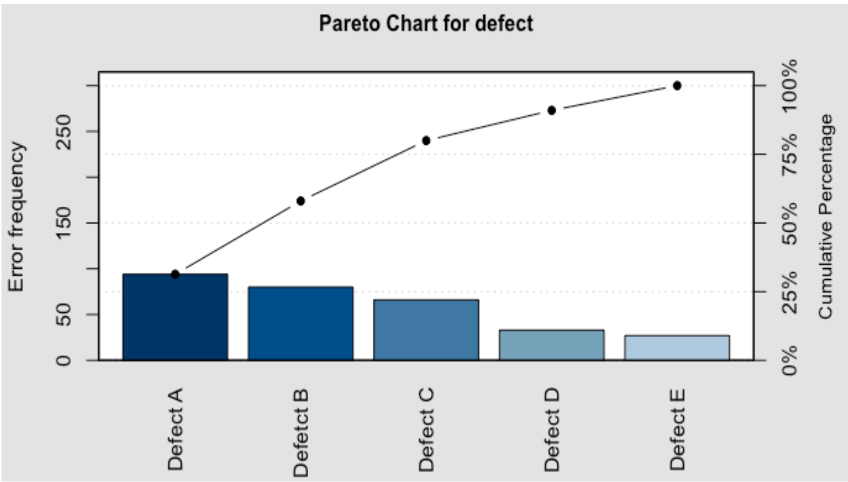
There are several quality tools and their sole purpose is to improve the quality level of manufacturing processes by applying it. Quality tools are the means for collecting data, analyzing data, identifying root causes and measuring the results. these tools are related to numerical data processing. All of these tools together can provide great process tracking and analysis that can be very helpful for quality improvements. These tools make quality improvements easier to see, implement and easy to track. These 7 quality are often called as simple statistical tools used for problem-solving and are listed below:

- Pareto diagram;
- Cause-effect diagram;
- Histogram;
- Control charts;
- Scatter-plot graphs;
- Check lists.

All these tools are important tools used widely in the manufacturing field to monitor the overall operation and continuous process improvement. These tools are used to find out root causes and eliminate them, thus the manufacturing process can be improved. The modes of defects on the production line are investigated through direct observation on the production line and statistical tools.

Are detailed, below, two of the quality tools applied in this work: Pareto diagram and cause-effect diagram.

Pareto Diagram (Graph 2) is a tool that arranges items in the order of the magnitude of their contribution, thereby identifying a few items exerting maximum influence.



Chart/Graph 2 Pareto chart example (self-elaborated)

Pareto diagram is a tool used in SPC and quality improvement for prioritizing projects for improvement, prioritizing setting up of corrective action teams to solve problems, identifying products on which most complaints are received, identifying the nature of complaints occurring most often, identifying most frequent causes for rejections or for other similar purposes. The Pareto principle also is known as the 80/20 rule is used in the field of materials management for ABC analysis. 20% of the items purchased by a company account for 80% of the value. These constitute the A items on which maximum attention is paid.

A Cause-and-Effect Diagram (Figure 7) is a tool that shows a systematic relationship between a result or a symptom or an effect and its possible causes. It is an effective tool to systematically generate ideas about causes for problems and to present these in a structured form. This tool was devised by Kouro Ishikawa and as mentioned earlier is also known as Ishikawa diagram.

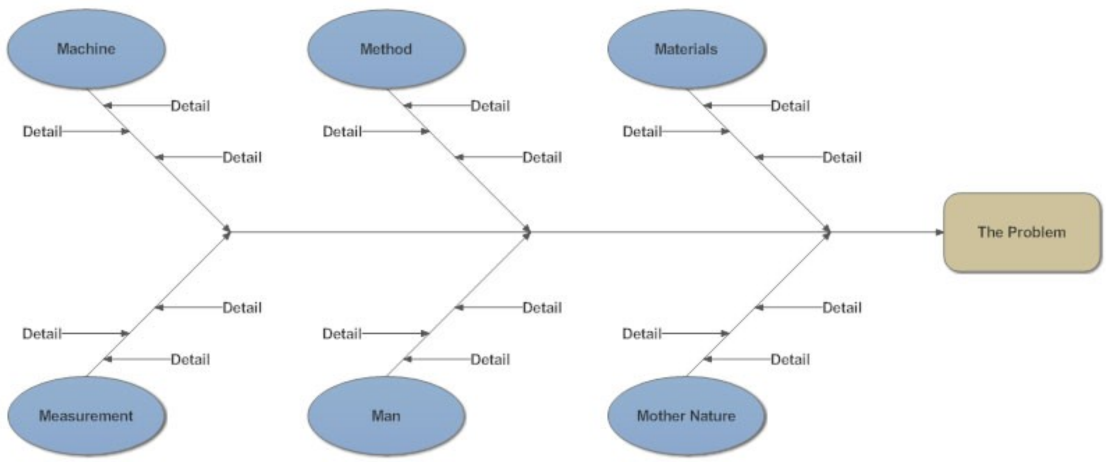


Figure 7 Cause and effect / Ishikawa diagram [37]

To finalize this section, an introduction to the bow-tie method is made. The bow-tie tool is a qualitative analysis incorporating management system techniques.

The bow-tie has become popular as a structured method to assess risk where a quantitative approach is not possible or desirable. The success of the diagram is that it is simple and easy for the non- specialist to understand. The idea is a simple one of combining the cause (fault tree) and the consequence (event tree). When the fault tree is drawn on the left-hand side and the event tree is drawn on the right-hand side with the hazard drawn as a "knot" in the middle the diagram looks a bit like a bowtie as shown

This method of analysis uses the risk matrix to categorize the various scenarios and then carries out a more detailed analysis (in the form of fault and event trees) on those with the highest risks. The essence is to establish how many safety barriers there are available to prevent, control or mitigate the identified scenarios and the quality of those barriers.

When managing major hazards there are four key objectives of using bowties

- To give an overview of the framework relating to managing major accident hazards;

- To illustrate the interdependencies between the various stages in the framework;
- To show how the process needs to be applied to any analysis:
- To ensure we all have a mutual understanding of what we're doing, why and how we're doing it [38].

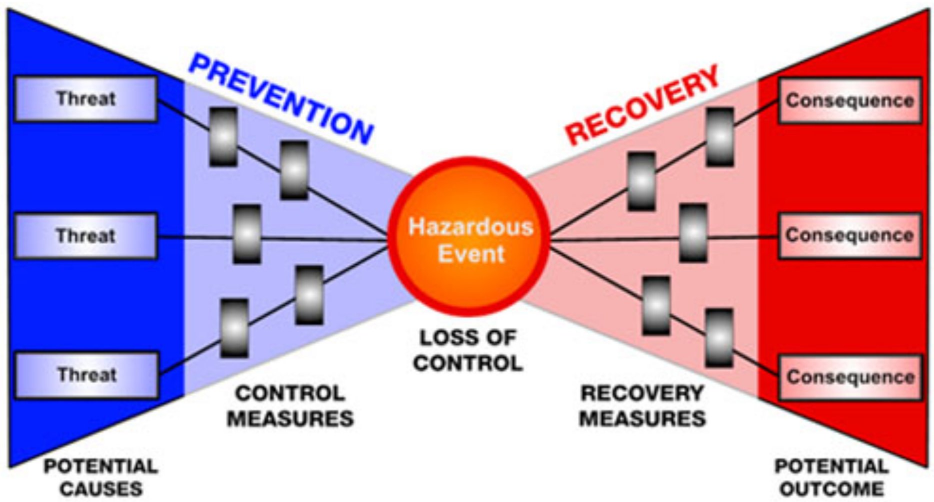


Figure 8 - Bow-Tie Analysis diagram [39]

2.10 INDUSTRY 4.0

While many organizations might still be in denial about how Industry 4.0 could impact their business or struggling to find the talent or knowledge to know how to best adopt it for their unique use cases, several others are implementing changes today and preparing for a future where smart machines improve their business.

Internet of Things and the cloud: A key component of Industry 4.0 is the Internet of Things that is characterized by connected devices. Not only does this help internal operations, but through the use of the cloud environment where data is stored, equipment and operations can be optimized by leveraging the insights of others using the same equipment or to allow smaller enterprises access to technology they wouldn't be able to on their own [41].

While Industry 4.0 is still evolving, and we might not have the complete picture until we look back 30 years from now, companies who are adopting the technologies realize Industry 4.0's potential. These same companies are also grappling with how to upskill their current workforce to take on new work responsibilities made possible by Internet 4.0 and to recruit new employees with the right skills.

THESIS DEVELOPMENT

3 THESIS DEVELOPMENT

This chapter describes, briefly, Sonafi company and presents the findings of the present research, which was conducted to answer the stated research problem. The area of discussion will be focused on the area of research objectives.

3.1 COMPANY PRESENTATION

Sonafi is an Aluminum alloy die-casting company founded in 1951, aimed at the automotive sector. Sonafi develops and manufactures components for various applications with complex geometry, with technologies such as die-casting, machining, shot blasting or vibration machining, machining, sub-component assembly, leak testing, and other anti-terror and recording tests, according to the specification agreed with the customer. Figure 9 shows the entrance of Sonafi company.

Figure 9 Office entrance (self-elaborated)

It is located in the North of Portugal, within 10km from Porto's airport. Sonafi stands for Sociedade Nacional de Fundição Injecteda. The company consists of various departments such as process control, production department, quality control, human resource department, IT division, maintenance department, logistics, finishing process department, and medical division.

The company employs around 55 employees spread across all the departments. Under the supervision of the employees, the production capacity of the company is high. In terms of production capabilities, the company has set-up four smelting furnaces and twenty-four die casting cells. The four furnaces are capable to produce 20 ton/day.

Similarly, the company has set-up machines and equipment for machining. For surface finishing, three shot blasting machines, one tumbling machine, and four vibration machines are utilized. To complete major machining jobs, thirty-four CNC machines, from different brands, such as Chiron vertical machine, Heller horizontal machine and Makin D horizontal machines are present. The company also has 17 transfer machines. Apart from all these machines, other equipment such as a washing machine, leak-proof test devices, assembly transfer machine, and test and control devices are used. Figure 10 and Figure 11 show the die-casting machine and the robotic arm which is used to transfer the casted part from inside the manufacturing cell to the dispatch area, respectively.

Figure 10 Die-Casting machine (self-elaborated)

Figure 11 Robot arm used to remove the casting from the die-cavity (self-elaborated)

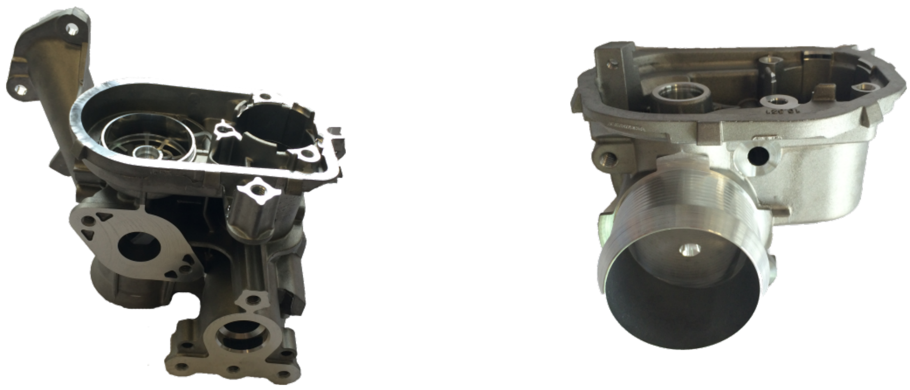


Figure 12-a) Valves EGR; b) Throttle (self-elaborated)

Figure 12 show some product which are manufactured in the die-casting machine number 823.

3.2 VACUUM MACHINE – FONDAREX

In pressure die casting, since filling a cavity with an alloy is extremely rapid, vacuum technology is recognized as being the most efficient solution to evacuate air and gas. With this technology, superior quality parts can be produced. Today, vacuum technology plays a key role in the production of complex and high-quality parts such as structural parts.

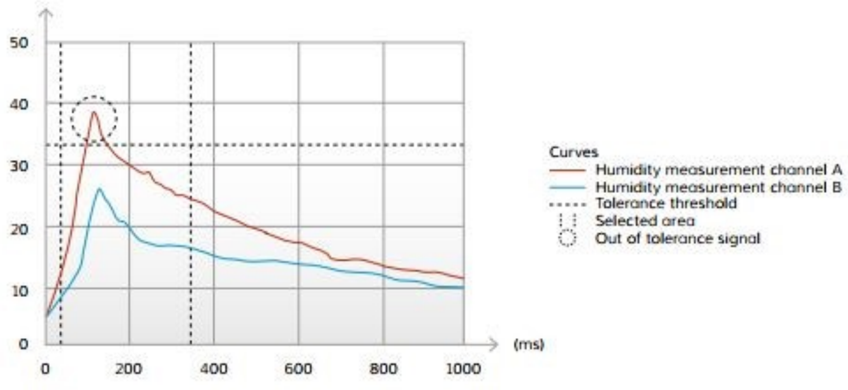
The innovative vacuum technology which is used by the Fondarex vacuum machine (Figure 13) manufacturer uses two methods of guaranteeing optimum evacuation until the end of the filling phase: patented mechanical valves that close in 1 millisecond or chill-blocks with an ingenious aerodynamic profile.

Figure 13 Fondarex vacuum machine for machine 823 (self-elaborated)

The Fondarex vacuum system is suitable for all production cells and molds. It is the technology peripheral device for pressure die casting providing additional injection process control. Vacuum systems can help achieve the most difficult structural components, such as automotive structural parts, heat treated parts, thin-walled parts, surface parts, and safety parts.

Fondarex has developed an optical sensor capable of precisely determining the humidity content of air evacuated from the cavity. Fast, accurate and reliable, it measures and processes production data for each vacuum channel and each shot. This is the most innovative analytical equipment for vacuum die casting.

In the below graph (Chart/Graph 3) the red line represents the humidity in channel A and the blue line represents the humidity in channel B of the Fondarex vacuum machine. Normally, the humidity measured is out of tolerance with the usage of vacuum machine and with the aid of the humidity sensor the tolerance can be controlled.



Chart/Graph 3 Humidity measurement graph [42]

Efficient evacuation until the die is entirely filled. Solidification of metal in the aerodynamic profile. Figure 14 shows the chill-blocks used in the vacuum machine.

Figure 14 Chill-blocks [42]

One of the major challenges faced by die-casting industries is to eliminate porosity caused by air-entrapment. The parts with porosity are rejected. The cost of rejection is high and is usually under-estimated by die-casting industries. The includes the cost of production time and energy.

That is where a vacuum machine comes into use, it reduces the machine downtime, production cost, and energy. In addition, the casted products will have high-quality surface finishing.

Generally, the vacuum machine is used to increase the strength to weight ratio in cold chamber die-casting. The alloy is forced into the mold cavity with high pressure and velocity that small quantity of air and other gases are trapped during casting. Before the injection actions take place, the vacuum is drawn in both short sleeve and mold cavity.

The vacuum maintained until the injection cycle is completed. When the liquid aluminum filled up to the chill vent cavity, the chill vent sends signal once aluminum reaches near the steel wool exhaust and closes immediately. Almost, all the gases trapped in the mold is pushed out from the mold. Since the parts manufactured are complex in shape the vacuum enables the alloy to reach all areas of the die.

The chill vents in a vacuum unit which has a high thermal conductivity can increase the quality and reduce the porosity thereby reducing the scrap. So, no additional cooling water required and at the same time guarantee's solidification of the aluminum.

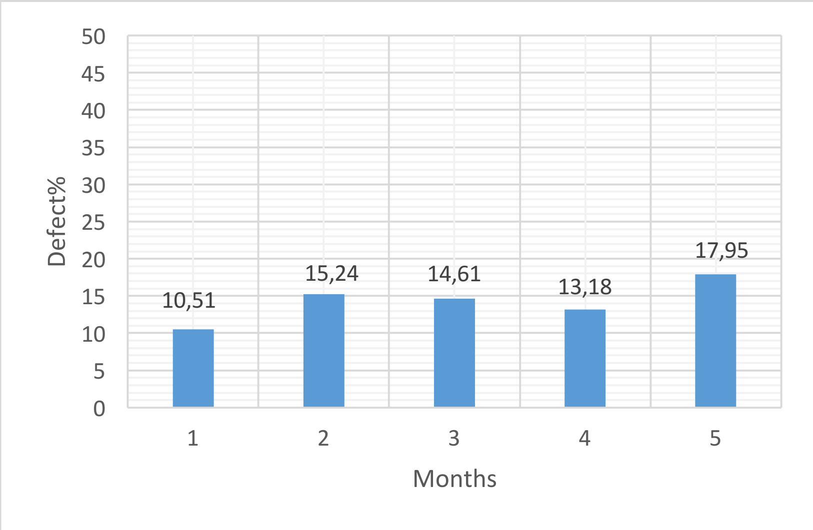
3.3 PROBLEM STATEMENT AND INFORMATION COLLECTION

Sonafi is pioneer through a maintenance plan and an improve in the manufacturing of throttle body along with various other components in the automobile sector. The throttle body is an air intake system of the automobile which controls the amount of air flowing to the engine, in response to the driver accelerator pedal into the main.

The part is manufactured in the company by using cold chamber process. The scrap rate for this very particular part, produced in the machine 823, was analyzed between January 2018 and May 2018. The details of the scrap fraction are given below in the form of bar graph (Chart/Graph 4).

The bar graph depicts that, during the observed five months, the fraction of scrap range between 10,51% (January) and 17,95% (May). February and March revealed a similar scrap fraction.

During the month of January, the Fondorex manufacturer does a periodic maintenance (annual maintenance service). The very next month the scrap rate shoots up over 5% extra and during the month of May, there is a rise of about 7% in comparison to defects in January. Thus, there is great interest in reducing the stoppage frequency of the machine through a maintenance plan and improve the efficiency of the machine by a predictive maintenance scheme.



Chart/Graph 4 Bar plot of % defect from January - May 2018

3.3.1 Information collection

The information was collected through interviews, observation, and documents investigations. The data collection was preceded by a period of surveillance that included two phases. The first one was through the interaction with the production technicians. Were all the details regarding the usage of the machine was studied for a period of 5 days. During that period the whole operational process of the vacuum machine was learned. The few key points for a smooth and continuous process which were constantly referred by the production technicians are:

- To constantly note down the shot time for one injection process. The average duration of filling up of molten aluminum in the die is 13 seconds and has a tolerance of +3 seconds.
- Monitor chill vent efficiency in the control panel of the vacuum machine so that the steel wool does not get clogged.

The second phase of observations was carried along with the maintenance technicians. Where all the mandatory maintenance work which is required before the starting of the machine were closely monitored for a period of another five days. During this observation, all the maintenance activities which were done are preventive maintenance. It was to ensure all day to day activities proceed without any hindrance.

Through keen observation, it was clear what are the activities performed by the maintenance department vital for the production and for the profit of the organization. It is believed that the execution of these activities will minimize the machine stoppage.

The stoppage in vacuum machine is a hindrance regarding the production target. Whatever which affects the performance of the vacuum machine implies its stop, requiring intervention of the operator in solving the problem. Almost 75 – 78% of all the failure which happens is mentioned in the control panel of the vacuum machine. Depending upon the criticality, the production department decides between solve the issue on their own or call for aid from the maintenance department.

The period of surveillance facilitated the in-depth study of the vacuum machine which was based on the manual of the vacuum machine Fondarex and on a process structure manual developed by the process department at Sonafi.

During the study, it was understood that the three most important aspects that must be followed during the maintenance of a vacuum machine where: preparation, planning, and execution. It was also observed that the positioning of the machine plays a key role in the maintenance plan. The period of surveillance allowed also identify exceedingly small aspects, like the connecting wires that had to be installed in such a way that they are shielded from the molten metal and like the power supply connection that must be installed along with 13Ah circuit-breaker close to the unit, but which can cause the machine stoppage implying time and production loss which is very critical in die-casting industries.

Throughout the observation were identified factors that disturb the performance of the machine, however, during the latter stages of the study, it was noticed that every component of the machine is vital for the proper functioning machine and is linked with each other. For example, the control panel which is connected to the vacuum unit by means of a USB port is the most vital output unit in the system. It shows all the information necessary for the effective functioning of the machine.

It was understood from the study and physical observation that it requires a minimum of 6 bars and anything below that pressure will trigger the alarm. This could be monitored by means of an electronic manometer with is integrated along with the air pressure unit.

Next phase of the study was on the chill blocks. It is used to cool down the molten metal in the die. The basic connection is in-between the vacuum unit and chill blocks. Firstly, the vacuum measurement is done at the cavity during the warm-up for which the connecting hoses should not have any goosenecks in order to prevent siphon-effect.

Another major study is the understanding of the codes in the control panel. The are many keys representing various activities, like function key, entry keys. The entry keys are of high importance since it outlines various key functions like turning on/off the unit, turning on/off the automated production system, vacuum test, pollution control test.

Next is the understanding of using different function keys, like F1 for production data, F4 for recoding the data, F2 is to monitor the pressure parameter, pollution control limits and profile check limit (where, P3 indicates minimal pressure, P4- nominal pressure, P5- maximum pressure). It was understood that profile check works only when the die is closed. In this most of the parameters can be customizable based on the need.

Datasheet with can be created with all the necessary vacuum machine data. Once all the necessary parameters are entered we can automatically generate a datasheet. For example, data's like operating hours, injection count, etc. will be mentioned in the datasheet.

Then, the system failure – red control lamp – was analyzed in detailed. Here, the study began with the understanding about why the system failure occurred and what are the different possibilities to solve the problem identified (like, no signal die open, synchronizing failure, wrong time setting, profile control out of tolerance, etc…).

Technical maintenance, which is the basic maintenance plan given in the manual which can be followed by the maintenance and production technicians on a day to day basis. There are few mandatory checks with must be observed before the usage of the vacuum unit like checking the oil level in the vacuum pump, all the lights in the operating display should be green during operation.

Next mentioned is the weekly cleaning of the vacuum hoses along with compressed air unit and every six months a full-fledged service is done for the oil filter, air filter, oil separator, and oil change. All the above activities are explained in detailed to the technicians by the manufacturer. The troubleshooting problems which arises from the vacuum machine is mostly based on the above problems.

Finally, the different accessories which are used in the vacuum machine were studied with all the details and alternative spare parts which can be used for a component was also discussed along with the technicians.

3.3.2 Break down timings

After the brief study of the vacuum machine, there was a clear understanding on how the process must be implemented in consideration of FMECA and IATF 1629 standards. However, before going ahead with the proceedings, more concordant details were required to perform effective FMECA analysis. One such details required was to know the history of maintenance breakdowns which happened during the period between January 2018 and June 2018. All failures happened was categorized based on the criticality of the failures. Further, failure time of vacuum machine was taken from the year 2016 and 2017 to know how the vacuum machine had been halted due to maintenance activities. The table below show maintenance break times observed in the vacuum machine between 2016 and 2018.

Table 5 Maintenance break times since 2016 January (Sonafi)

Year	Designation	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016	Vacuum system	8.7	3	0	0	3.6	0.3	4.5	4.2	6	0	2.3	3.7	36.5
2017	Vacuum system	11	1	2.8	1.5	0	3.8	2.7	2.4	0	0.5	0	1.2	26.7
2018	Vacuum system	0	0	11.6	5.17	0	0	0	0	-	-	-	-	16.77

*the values mentioned above are in hours.

From the table, it is understood that during the year 2016 a total of 36.5 hours was spent on repairing the vacuum machine and the very next year the duration dropped down considerably during the year 2017 to 26.7 hours and in 2018, just during the 6 months, period the duration of breakdown is 16.77. During the month of April, a full maintenance service was done by the manufacturer – FUNDAREX. Normally, the annual maintenance service takes place in the month of August. Due to sudden system failure, it had to be done during the month of April.

3.4 BRAINSTORMING

Having regard the preliminary observation of general functioning of the vacuum machine, it was concluded that there are two problems to solve:

1. Alarm trip that causes unavailability of the machine and consequent loss of production.
2. Formation of bubbles on the surface of the final die-casted product.

Brainstorming sessions, used for generating new ideas and solutions to problems identified, were conducted among the people of the maintenance department. The lead preventive maintenance technicians, foundry maintenance coordinator and maintenance manager were constantly involved in the discussions. The brainstorming session began with the detailed explanation of the vacuum machine process by the maintenance manager. From then the decision to focus on cause first and later address the issue of consequence. Since knowing the consequence, it would aid the understanding and come up with solutions for predictive maintenance.

3.4.1 Performing cause and effect analysis

After the brainstorming session, as a part of the quality analysis, Ishikawa diagram was created to address two major issues faced: formation of bubbles and triggering of the alarm. The Ishikawa diagram below Figure 15 shows the causes contributing to formation of bubbles.

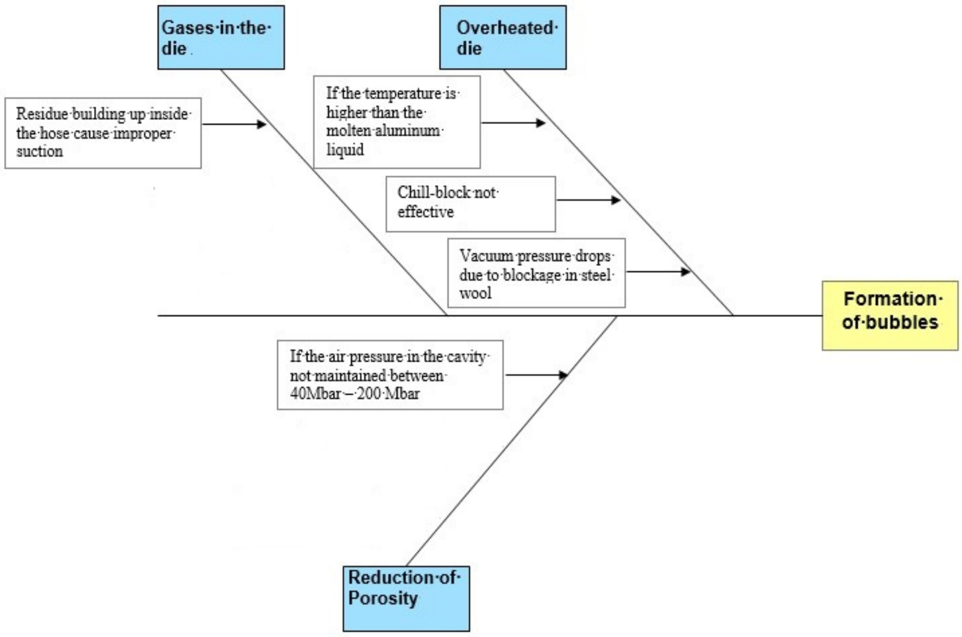


Figure 15 Ishikawa diagram for formation of bubbles (self-elaborated)

Formation of bubbles on the final product is either sent for re-work or goes into scrap. After discussion with the core maintenance team and production technicians, the above cause was found out and the issue to be addressed was noted down.

The formation bubbles happen during the stage when injecting the molten metal into the cavity of the die. Due to the oxidation process, the molten metal reacts with the atmospheric air resulting in the formation of gases, these gases ejected out of the die else porosity/formation of bubbles will be created on the surface. The below Figure 16 Figure 17 depict how the formation of bubbles looks like on the metal before going to re-work or to scrap which is again the loss of time and money.

Figure 16 formation of bubbles at the diameter with mold - 10529.02a (self-elaborated)

Figure 17 formation of bubbles with mould - 10529.01b (self-elaborated)

For addressing the issue with triggering of alarms, Ishikawa analysis Figure 18 was performed. During the analysis, it was again found that it contributed to the loss of production.

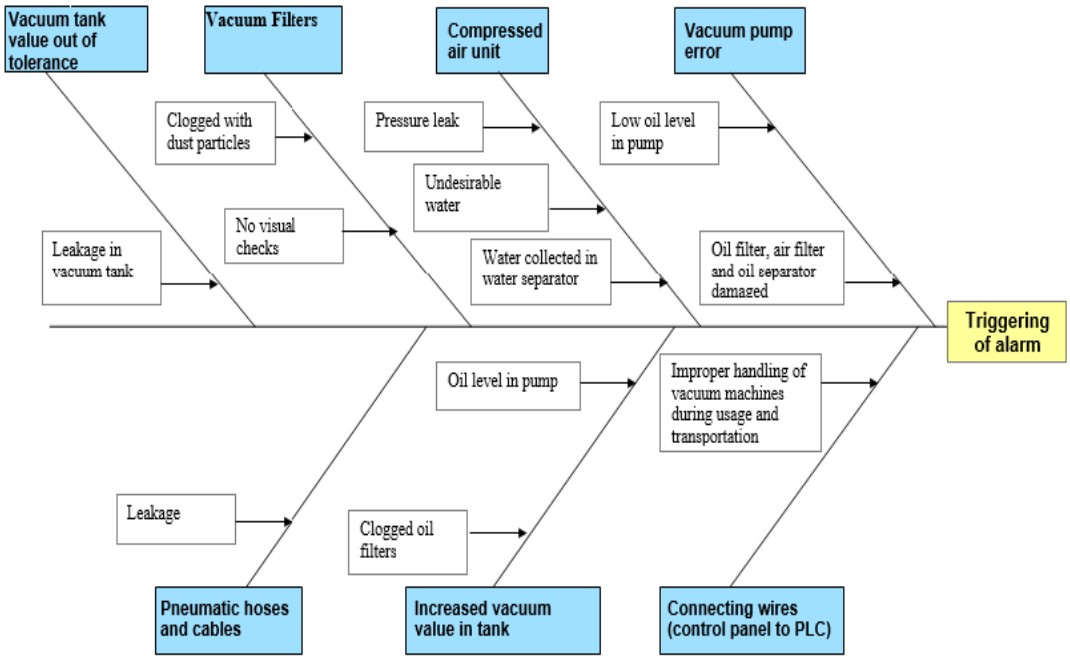


Figure 18 Ishikawa diagram for triggering of alarms (self-elaborated)

Stoppage of machines has been a major concern since even a minute error can cause the machine to stop and after a brief discussion among the staffs from the maintenance department and study of vacuum machine manual – FONDAREX the above diagram was created to aid the further process of performing FMECA on vacuum machine. With this very particular quality tool analysis more effects for a cause was found.

3.5 FMEA APPLICATION

Based on the information obtained from the Ishikawa diagram and from the maintenance action plan devised by Fondarex vacuum machine technician, FMEA plan for formulated along with the aid from the maintenance department.

3.5.1 Company's guidelines

Sonafi, previously have a set of guidelines based on IATF 16949 standards for both process and design FMEA and the analysis used is process FMEA. Sonafi's basic guidelines are:

- FMEA must be done based on client requirements;
- Actions to be taken if the severity is greater than 9;
- Failure modes with the highest occurrence rate in cases where the severity is below 8;
- When RPN is ≥ 100;

- When the required actions are taken for a potential cause of failure the severity will not change at any cause.

3.5.2 FMEA analysis

The main goal of this section was to perform FMEA, based on the company's guidelines, to identify risks of failures causes, which were discussed in the previous section and were depicted using the Ishikawa diagram, and determine the RPN after implementation of intervention programs.

3.5.2.1 FMEA analysis for formation of bubbles

Firstly, the process of formation of bubbles was addressed along with the maintenance department team. Here, the potential effects of failure are overheated die and there are two types of potential causes of mechanism failure:

1. Clogging of steel wool filter.
2. Flexible pipes connecting to the vacuum unit.

After a brief discussion, the clogging of steel wool filter was the main cause for machine failure and severity was decided to be 5. The current process control prevention is by checking the graph in the control panel where it shows the effectiveness, represented by means of a bar graph. The occurrence index is 5, the decision was based on the frequency of replacement of the part. The current process control has been a visual inspection by constantly checking the control panel and there is a moderate chance that it would cause a failure to the machine. So, the detection is to be 5. The RPN value for this case is:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 5 \times 5 \times 5 = 125$$

Equation 7 Old RPN for over-heated-Die (clogging of steel wool)

The necessary corrective measures were performed on the basis of the results of initial FMEA. The decided recommended actions were at the first level of maintenance and included a weekly cleaning. The responsibility falls on the production department and it is monitored by preventive maintenance. The duration of the cleaning is approximately 2 hours. It was decided to replace the steel wool whenever it is completely clogged. This being so, and since there is monitoring and cleaning weekly the detection is moderately high and so it was decided that the new value of the detection is 4. The new RPN values are now:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 5 \times 5 \times 4 = 100$$

Equation 8 New RPN for over-heated die (Clogging of steel wool)

In to respect to flexible pipe, the potential cause of mechanical failure could be due to gooseneck in any of the flexible pipes that are connected to the vacuum machine. Thus, the severity is considered low (effect the level of performance minimally). The current process control prevention is through constant checking and the probability of occurrence is 1 in 15.000 (very few times), thus, a ranking of 3 was given. The current process control detection is 2 and thus it is extremely high to figure out the failure. In this case, the RPN is:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 5 \times 3 \times 2 = 30$$

Equation 9 Old RPN for over-heated die (Goosenecks)

The necessary actions must be done by the 1st level of maintenance technicians and the responsibility falls on the production department and average duration to perform this action is 1 hour. The actions taken were to re-wound the flexible pipes which are connected to the connected to vacuum machine and the mold in the die-casting machine. Through re-wounding the flexible pipes, the probability of occurrence is 1 in 150.000 and thus relatively low failure so the occurrence ranking to 2. Considering the actions proposed, the RPN is:

$$\mathrm{RPN} = \mathrm{Severity} \times \mathrm{Occurance} \times \mathrm{Detection}$$

$$RPN = 5 \text{ x } 2 \text{ x } 2 = 20$$

Equation 10 New RPN for over-heated die (Goosenecks)

The FMEA analysis for the problem of formation of bubbles was summarized in the FMEA worksheet present in the Table 9.

Clogging of steel wool process got the highest RPN. Obtained RPN for clogging before performing the corrective actions was 120 and the score was reduced to 100 after performing corrective measures. In to respect to flexible pipe, the RPN decrease from 30 to 20 after performing corrective measures. Score of RPN in all studied processes effectively decreased after performing corrective actions.

3.5.2.2 FMEA analysis for alarm triggering

The low level in the oil pump and problems in oil filter (air filter is clogged or damaged) and in oil separator are potential reasons for triggering of alarm.

Starting the analysis by the quantification of the RPN for low oil level pump failure. Here, the severity is 9, because this problem will cause a hazard to the environment due to the low oil level in the pump and the consequence is enormous. The current process control prevention is visual check and refills it when needed. The probability of occurrence is high, thus a ranking of 8 was given. The current process control detection is either through visual inspection and when the technician realizes that the vacuum machine takes longer to reach the optimal vacuum pressure. The detection is moderately high, and the potential cause can be figured out, thus a ranking of 4 is given. In this case, the value of the RPN is:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 9 \times 8 \times 4 = 288$$

Equation 11 RPN before taking actions (Oil pump)

The recommended action for this very particular type of failure is to check the oil level in the machine before using the machine. The responsibility falls on the production department and the duration of replacement averages between 5 – 10 minutes. Action taken for this cause of failure is to refill the oil if it has a leak and change the bush and change the oil completely, based on the number of hours the vacuum machine has run which is 1600 hours. With the recommended actions taken, the probability of occurrence will reduce to 7 and detection to 3. Thus, the new RPN is

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 9 \times 7 \times 3 = 189$$

Equation 12 RPN after taking actions (Oil pump)

Another cause of mechanical failure in vacuum pump error is due to the clogging of air filter, oil filter, and oil separator. The severity ranking for it is 2 since the problem is a minor hazard compared to others and happens 1 in 15.000 and it is given a ranking of 3. The current process control prevention is through preventive maintenance. Because it is always replaced based on the running hours of the machine. Generally, replacement is done every 1500 hours. The detection is 9 because the vacuum machine control panel shows the number of durations the machine had run but does not specify or give out an alarm to indicate that the filters must be replaced. Thus, it must be noted down in a control plan and executed. The RPN is

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 2 \times 3 \times 9 = 54$$

Equation 13 RPN before taking actions (Air, oil filter)

The recommended action is through periodic checking of filters and the duration of hours the machine has run. The responsibility falls under the maintenance department and the duration it will take for replacement is 1 day. The action which is taken is cleaning, replacing the filters and perform a test run of the machine. With careful and periodic observation, the detection can be increased to 7 and thus the new RPN will be

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 2 \times 3 \times 7 = 42$$

Equation 14 RPN after taking actions (Air, oil filter)

The FMEA analysis presented above was summarized in the FMEA worksheet present in the Table 10. Low oil level pump failure got the highest RPN. Obtained RPN for pump failure before performing the corrective actions was 288 and the score was reduced to 189 after performing corrective measures (very high value). Score of RPN in all studied processes effectively decreased after performing corrective actions.

Table 6 FMEA analysis - overheated die (self-elaborated)

FMEA process step: Formation of bubbles												**Action results**			
Potential failure mode	**Potential effects of failure**	**SEVERITY**	**Potential cause of mechanism failure**	OCCURANCE	**Current process control prevention**	DETECTION	**Current process control detection**	**RPN**	**Recommended action done by**	**Responsibility and target completion date (Duration)**	**Actions taken and completion date**	**SEVERITY**	**OCCURANCE**	**DETECTION**	**RPN**
Defective parts	Over-heated die	**5**	Clogging of steel wool filter.	**5**	Check the graph in control panel	**5**	Constantly checking.	**125**	1st level maintenance; Weekly cleaning	Production & Preventive maintenance:	Replacement and cleaning	**5**	**5**	**4**	**100**
		5	Goosenecks in flexible pipes connecting to vacuum unit	**3**	Constant checking	**2**	Constantly checking	**30**	1st level maintenance	Duration: 2 hrs. Production; Duration: 1 hr.	Re-wound the flexible pipes	**5**	**2**	**2**	**20**

Table 7 FMEA analysis – Vacuum pump error (self-elaborated)

FMEA process step: Triggering of alarm.																**Action results**
Potential failure mode	**Potential effects of failure**	**SEVERITY**	**Potential cause of mechanism failure**	OCCURANCE	**Current process control prevention**	**DETECTION**	**Current process control detection**	**RPN**	**Recommended action done by**	**Responsibility and target completion date (Duration)**	**Actions taken and completion date**	**SEVERITY**	**OCCURANCE**	**DETECTION**	**RPN**	
Stoppage of vacuum machine	Vacuum pump error	9	Low oil level in pump and	8	1st level of maintenance - Visual check and replace oil when required	4	When it takes longer to reach the optimum vacuum pressure/ visual inspection	288	Before using the machine, the oil level has to be checked	Production department; Duration: 5-10 mins	Refill the oil if it less and replace if the oil is old based on number of hours the machine has run	9	7	3	189	
		2	Oil filter, air filter, oil separator is clogged or damaged	3	based on running hours (Replacement done every 1500 hours)	**9**	When the tank finds it difficult to achieve the required vacuum pressure	**54**	2nd level of preventive action checking of filters and the duration of hours replacement and periodic.	Maintenance; Duration: 1day	Replacement of filters, cleaning and test run	**2**	**3**	**7**	**42**	

Other potential effect of failure for the stoppage of vacuum machine is a compressed air unit. The severity given is 8 in consideration of the cost of replacement. It has three major potential cause for this type of mechanical failure: pressure leak, undesirable water and water if collected in the water separator. The probability of occurrence is moderate and is an occasional failure which happens 1 in 2000. The current preventive method is through the first level of maintenance which is through cleaning. Detection ranking is very high and thus a ranking of 2 was given. RPN is:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 8 \times 4 \times 2 = 64$$

Equation 15 RPN before taking actions (Compressed air unit)

The recommended action for these types of failures is to clean the air filters periodically and check the connections with the compressed air unit in the control panel. The responsibility falls over the production department. Through this means the probability of occurrence will reduce and obtained a new ranking of 3. The new RPN will be:

$$\mathrm{RPN} = \mathrm{S}\times \mathrm{O}\times \mathrm{D}$$

$$\mathrm{RPN} = 8 \times 3 \times 2 = 48$$

Equation 16 RPN after taking actions (compressed air unit)

Another potential effect which trigger the alarm and stops the vacuum machine is when the connecting wires between the control panel to PLC gets damaged. The severity is 8 since it stops the main hub of the vacuum machine. It is mainly caused due to improper handling of the machines during operation and transportation. The probability of occurrence is also high 1 in 8 times and thus a ranking of 8 is given to it. The current detection method is through visual inspection. The current RPN is

$$\mathrm{RPN} = \mathrm{S}\times \mathrm{O}\times \mathrm{D}$$

$$\mathrm{RPN} = 8 \times 8 \times 1 = 64$$

Equation 17 RPN before taking action (connecting wires)

The recommended action is to handle the machine with care during usage and transportation of the machine. The responsibility lies with the production department and the duration to change and clean will take around 4hours. The action which has to be taken is by replacing the connecting wires. Here, if the maintenance is properly done the probability of occurrence can be reduced to 5. Thus, the new RPN will be

$$\mathrm{RPN} = \mathrm{S}\times \mathrm{O}\times \mathrm{D}$$

$$\mathrm{RPN} = 8 \times 5 \times 1 = 40$$

Equation 18 RPN after taking actions (Connecting wires)

The FMEA analysis presented above was summarized in the FMEA worksheet present in the next two tables. The RPN values are low for all causes.

Table 8 FMEA analysis – Compressed air unit (self-elaborated)

FMEA process step: Triggering of alarm.												Action results			
Potential failure mode	**Potential effects of failure**	**SEVERITY**	**Potential cause of mechanism failure**	OCCURANCE	**Current process control prevention**	DETECTION	**Current process control detection**	**RPN**	**Recommended action done by**	**Responsibility and target completion date (Duration)**	**Actions taken and completion date**	**SEVERITY**	**OCCURANCE**	**DETECTION**	**RPN**
Stoppage of vacuum machine	Compressed air unit	8	Pressure leak Undesirable water Water collected in water separator	4	Preventive action - 1st level of maintenance	2	Visual check	64	Clean the filters periodically to avoid the potential causes	Production; Duration: 10minutes	Filters cleaned and connection to the compressed air unit is checked	8	3	2	48

Table 9 FMEA analysis – Connecting wires (self-elaborated)

FMEA process step: Triggering of alarm												Action results			
Potential failure mode	**Potential effects of failure**	**SEVERITY**	**Potential cause of mechanism failure**	OCCURANCE	**Current process control prevention**	**DETECTION**	**Current process control detection**	**RPN**	**Recommended action done by**	**Responsibility and target completion date (Duration)**	**Actions taken and completion date**	**SEVERITY**	**OCCURANCE**	**DETECTION**	**RPN**
Stoppage of vacuum machine	Connecting wires (control panel to PLC)	8	Improper handling of machines during operation and transportation.	8	Not using fork lift for transportation. Transportation is done by wheels which has been attached to it.	1	Visual inspection; Machine stops	64	During transportation handle the machine with care.	Production; Duration: 4 hrs (if materials are available); 2-3 days (if the materials are not available)	Replace the connecting wires.	8	5	1	40

Vacuum tank has an optimal value of 20mbar and less than 20 will cause the system to trigger the alarm. The severity for this failure is 7 and might cause performance failure. Cause of this type of failure is due to leakage in a vacuum tank and the probability of occurrence is less, it happens 1 in 2000 so a ranking of 4 is given to it. The current control process is through preventive maintenance by checking the valves and filters. Detection for these types of errors are very high and it is of ranking 2. The current process control for detection is indicated in the control panel or when the operator finds that the vacuum machine is finding it difficult to reach the optimum pressure. The RPN is:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 7 \times 4 \times 2 = 56$$

Equation 19 RPN before taking actions (Vacuum tank tolerance)

The recommended actions are to check the filters and the valves when the alarm is raised. The responsibility of the maintenance department. Periodically the valves and the filters must be checked to know the state of the machine it is in. For these types of errors there are no solutions, and the ranking of occurrence and detection does not change. The new RPN is:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 7 \times 4 \times 2 = 56$$

Equation 20 RPN after taking actions (Vacuum tank tolerance)

The potential effects of failure are damage of vacuum filters. The severity ranking level is of 8 and cause of this failure is due to the filter clogged with dust particles and no periodic visual check. The probability of occurrence is very less so it has a value of 3. The current process control prevention is through preventive maintenance and the filter is replaced based on the number of hours it has run. The detection is very high and has a ranking of 2. The current process control detection is through visual check if the filter will get damaged and will be indicated by triggering the alarm. The RPN Is

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$RPN = 8 \times 3 \times 2 = 48$$

Equation 21 RPN before taking actions (Vacuum filters)

The recommended action is to clean the filter's periodically by using compressed air. Filters should not be cleaned by means of water. The cleaning of filter falls under the responsibility of the maintenance department. The final actions taken are to replace the filter if damaged or clean if it is filled with dust particles. By this means, the occurrence is very high and thus the new RPN will be:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$RPN = 8 \times 2 \times 2 = 32$$

Equation 22 RPN after taking actions (Vacuum filters)

Table 10 FMEA analysis – Tolerance of vacuum tank (self-elaborated)

FMEA process step: Triggering of alarm												Action results			
Potential failure mode	**Potential effects of failure**	**SEVERITY**	**Potential cause of mechanism failure**	OCCURANCE	**Current process control prevention**	DETECTION	**Current process control detection**	**RPN**	**Recommended action done by**	**Responsibility and target completion date (Duration)**	**Actions taken and completion date**	**SEVERITY**	**OCCURANCE**	**DETECTION**	**RPN**
Stoppage of vacuum machine	Vacuum tank value out of tolerance	7	Leakage in vacuum tank	4	Preventive maintenance – check the valves and filters	2	Indicated in control panel by alarm; The tank finds it difficult to achieve the required vacuum pressure	56	Check the filters and valves when the alarm indicates.	Maintenance; Duration-1day	Check the valves for leaks and filters if it is clogged.	7	4	2	56

Table 11 FMEA analysis – Vacuum filters (self-elaborated)

FMEA Process step: Triggering of alarm.												Action results			
Potential failure mode	**Potential effects of failure**	**SEVERITY**	**Potential cause of mechanism failure**	OCCURANCE	**Current process control prevention**	DETECTION	**Current process control detection**	**RPN**	**Recommended action done by**	**Responsibility and target completion date (Duration)**	**Actions taken and completion date**	**SEVERITY**	**OCCURANCE**	**DETECTION**	**RPN**
Stoppage of vacuum machine	Vacuum filters	8	Clogged with dust particles No visual checks	3	Preventive maintenance – replace it based on the hours it has run.	2	Visual check	48	Filters must be cleaned weekly	Maintenance; Duration: 1day	Complete cleaning of all the filters.	8	2	2	32

The FMEA analysis for vacuum tank and vacuum filters was summarized in the FMEA worksheet present in the previous two tables. Score of RPN is low in both cases, but effectively decreased after performing corrective actions for damage of vacuum filters.

Other important potential effects of failure which causes the triggering of alarm are the pneumatic hoses and cables. The severity rating of 8 was given to it cause the primary function might be halted. The potential cause is due to leakage and the probability of occurrence is 6 since it might happen 1 out of 80 times. The current process control prevention is through visual check in the control panel and to make sure that there is no gooseneck and it is neatly wound over a hook which was welded over the vacuum machine. The detection is very high thus it has a ranking of 2. The current process of detection is when the vacuum pressure drops it will be indicated in the control panel. The RPN is

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$RPN = 8 \times 6 \times 2 = 96$$

Equation 23 RPN before taking actions (Pneumatic hoses and cables)

The recommended action is to check the pneumatic hoses and cables before the start of the operation of the machine and after transportation of the machine. The responsibility is for first level maintenance and generally, it will take 2 hours for the problem to be rectified. Actions taken are to make sure that the hoses which are very long are not interlocked and the connecting screw is tightened. Thus, through visual check, the occurrence can be reduced partially from 6 to 5 in ranking. The new RPN will be

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}$$

$$\mathrm{RPN} = 8 \times 5 \times 2 = 80$$

Equation 24 RPN after taking actions (Pneumatic hoses and cables)

The FMEA analysis for the pneumatic hoses and cables was summarized in the FMEA worksheet present in the next table. Score of RPN is low (less than 100, company guidelines) and effectively decreased after performing corrective actions.

Table 12 FMEA analysis – Pneumatic hoses and cables (self-elaborated)

FMEA process step: Triggering of alarm												Action results			
Potential failure mode	**Potential effects of failure**	**SEVERITY**	**Potential cause of mechanism failure**	OCCURANCE	**Current process control prevention**	**D**ETECTION	**Current process control detection**	**RPN**	**Recommended action done by**	**Responsibility and target completion date (Duration)**	**Actions taken and completion date**	**SEVERITY**	**OCCURANCE**	**DETECTION**	**RPN**
Stoppage of vacuum machine	Pneumatic hoses and cables	8	Leakage	6	Visual check; Neatly wound over a hook	2	Vacuum pressure drop will be indicated in the control panel	96	Need to check it before and after transportation.	1st level maintenance; Duration: 2hrs	Check the hoses if there are interlocked.	8	5	2	80

3.5.3 Performing cause and consequence analysis (Bow-tie)

According to the Sonafi's guidelines, the action is taken only when severity is ≥ 8, RPN values are ≥ 100, occurrence value is ≥ 8 despite low severity ranking and the detection value is ≥ 7. There are two failures which satisfy the above conditions and they are:

- Over-heated die
- Vacuum pump

The main reason a bow-tie diagram used instead of other quality tools was to find out the consequence of concrete proof. Since it would answer what are the cause and control measures. The ranking of cause and consequence shows the level of effect, while 1 being the minimum and rest being the vice versa. In the overheated die on the right-hand side, two consequences are possible first being formation of bubbles over the surface of the metal when there is a huge temperature difference between a die and the molten metal. The die must be cooler than the molten metal, hotter in comparison to the molten metal, porosity forms on the outer surface of the die-casted product which either goes to scrap or re-work the part. If the cavity of the die-is over-heated and exceed the tolerance the sensors detect it and then stops the machine.

The causes of this failure are, firstly not checking the graph in the control panel where the temperature character is shown, secondly the vacuum exhaust is ineffective and thus making the chill block inefficient, thirdly there is a leak in the vacuum valve which makes the suction of gases in the die ineffective and thus slowly the gases contribute to the rise of temperature in the die and finally chill vent failure

In the vacuum pump, there are 5 consequences. When there is a fault in vacuum machine there is a high possibility that air stop switch will get closed, another consequence is that there will a loss of pressure during the function blow out, the air pressure will drop and it will take a long time to reach the necessary Mbar, the pump will overheat and there is a high possibility that it will fail and it has to be replaced and finally stoppage of machine indicating that there is a system error or vacuum tank out of tolerance. The causes are due to the oil leak, the air filter is damaged or clogged due to dust, the insufficient lubricant in the system, filter polluted by wax particles. Air filter, oil filter, oil must be changed every 1500hours at the earliest. But, if the filters get damaged it must be replaced. The next two figures show the cause and consequence diagram for over-heated die and for vacuum pump.

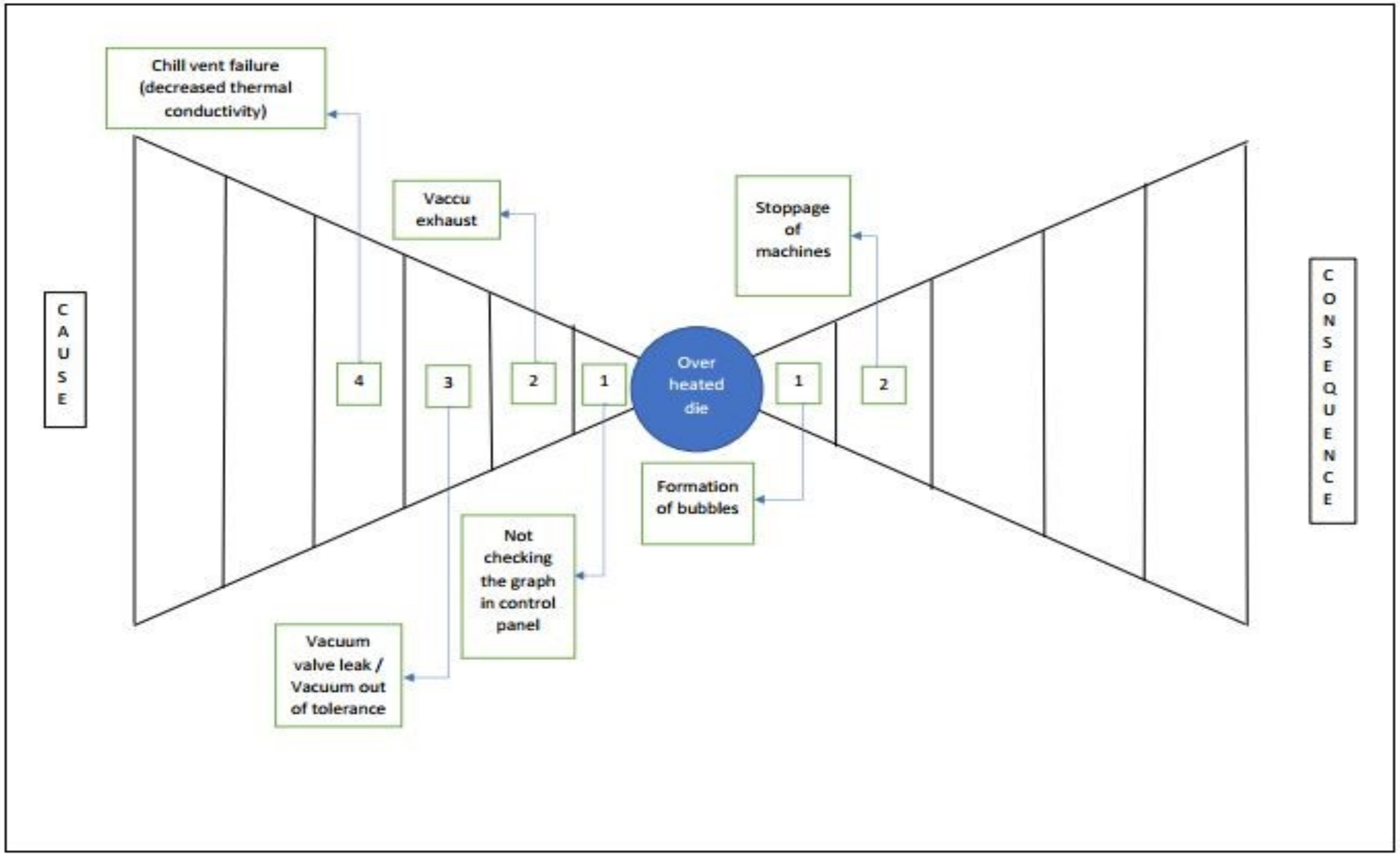


Figure 19 Cause and consequence diagram for over-heated die (self-elaborated)

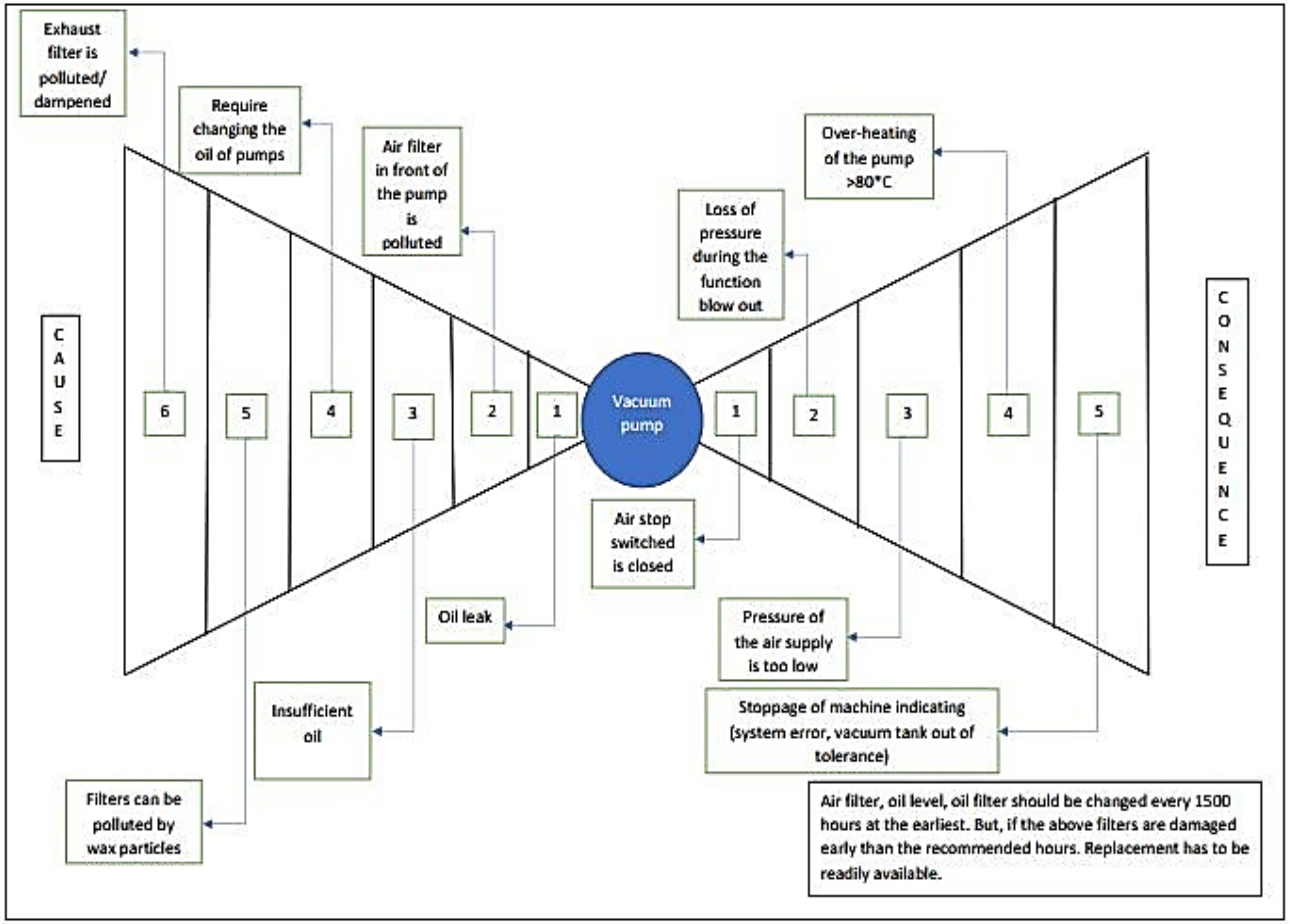


Figure 20 Cause and consequence diagram for vacuum pump (self-elaborated)

3.6 CRITICALITY

Criticality analysis were done to measure the frequency of occurrence of an effect on the vacuum system. Quantitative analysis was performed based on the failure rate data to calculate criticality numbers. With the help of these numbers, failure mode criticality (C_m) where found out, which leads in determining the severity classification to take further actions.

3.6.1 Breakdown timings and reasons

Breakdown timing was recorded for the vacuum machine which related to machine number 823. The breakdown from all the 3 shifts was noted for the period of January 2018 to August 2018. Here, the type of mold used in the die-casting machine, customer code for the part, when the machine was stopped and again started due to maintenance work and finally what type of failure caused the breakdown of the vacuum machine was mentioned in the table The details that were taken into notice are, the type of the mold used for production, customer code for the part, the duration of indefinite starting and stopping of machine and finally the type of failure that caused the vacuum machine to breakdown. with the help of the table, the calculation for qualitative analysis can proceed.

Table 13 Vacuum machine break down timings (self-elaborated)

Machine number	Shift	Date	Mold	Stop Time	Start time	Duration of stoppage	Type of failure
823	A	22-Jan	10529.01b	6:00	8:00	02:00:00	5
823	A	02-Mar	10529.02a	21:00	21:35	00:35:00	7
823	A	06-Mar	10529.02a	12:30	12:45	00:15:00	3
823	A	06-Mar	10529.02a	13:45	14:00	00:15:00	3
823	A	19-Mar	10529.02a	12:40	12:52	00:12:00	10
823	A	20-Mar	10529.02a	6:00	6:50	00:50:00	9
823	A	20-Mar	10529.02a	7:15	7:30	00:15:00	3
823	A	20-Mar	10529.02a	8:30	8:50	00:20:00	9
823	A	20-Mar	10529.02a	9:45	10:00	00:15:00	1

823	A	20-Mar	10529.02a	11:00	11:12	00:12:00	9
823	A	21-Mar	10529.02a	6:00	12:00	06:00:00	1A
823	A	20-Apr	10529.02a	6:00	6:20	00:20:00	6
823	A	20-Apr	10529.02a	7:15	7:30	00:15:00	1
823	B	19-Mar	10529.02a	14:00	14:50	00:50:00	7
823	B	19-Mar	10529.02a	18:40	19:00	00:20:00	1
823	B	19-Mar	10529.02a	20:00	20:17	00:17:00	2
823	B	20-Mar	10529.02a	17:30	17:45	00:15:00	2
823	B	20-Mar	10529.02a	18:15	18:30	00:15:00	3
823	B	12-Apr	10529.01b	10:15	10:30	00:15:00	4
823	B	12-Apr	10529.01b	11:45	12:00	00:15:00	4
823	B	18-Apr	10529.02a	14:00	15:00	01:00:00	8
823	B	19-Apr	10529.02a	16:15	16:30	00:15:00	3
823	B	20-Apr	10529.02a	17:05	17:20	00:15:00	3
823	B	21-Apr	10529.02a	17:35	17:50	00:15:00	2
823	B	22-Apr	10529.02a	18:20	18:35	00:15:00	2
823	C	23-Apr	10529.02a	0:15	0:43	00:28:00	6
823	C	24-Apr	10529.02a	22:00	22:50	00:50:00	7
823	C	25-Apr	10529.02a	23:10	23:17	00:07:00	1B
823	C	26-Apr	10529.02a	0:40	0:52	00:12:00	1
823	C	27-Apr	10529.02a	5:15	5:35	00:20:00	1
823	C	28-Apr	10529.02a	23:40	23:55	00:15:00	3
823	C	29-Apr	10529.02a	5:30	6:00	00:30:00	10

3.6.2 Criticality analysis

Criticality analysis was performed based on the details obtained from vacuum machine breakdown timings, the below table will describe the on how the criticality values were obtained:

Table 14 Criticality analysis for vacuum machine (self-elaborated)

Item	Failure rate (λ_p) per million hrs.	Failure Modes	Failure mode ratio (α)	Severity	Failure effect probability (β)	Time (hrs.)	C_m X 10-^{6}
Vacuum Machine	0.01	1s	0.06	IV	1	0.25	0.00015625
	0.01	1s	0.06	IV	1	0.333333	0.00020833
	0.01	1s	0.03	IV	1	0.2	0.00006250
	0.01	2	0.03	III	1	0.283333	0.00008854
	0.01	2	0.09	III	1	0.25	0.00023438
	0.01	6	0.03	III	1	0.466667	0.00014583
	0.01	6	0.03	III	1	0.333333	0.00010417
	0.01	1B	0.03	IV	1	0.116667	0.00003646
	0.01	9	0.03	IV	1	0.833333	0.00026042
	0.01	9	0.03	IV	1	0.333333	0.00010417
	0.01	9	0.03	IV	1	0.2	0.00006250
	0.01	1A	0.03	II	1	6	0.00187500
	0.01	3	0.22	IV	1	0.25	0.00054688
	0.01	8	0.03	III	1	1	0.00031250
	0.01	7	0.03	III	1	0.583333	0.00018229
	0.01	7	0.06	IV	1	0.833333	0.00052083
	0.01	10	0.03	IV	1	0.2	0.00006250
	0.01	10	0.03	IV	1	0.5	0.00015625
	0.01	5	0.03	III	1	2	0.00062500
	0.01	4	0.06	II	1	0.5	0.00031250

Failure mode codification:

- Cleaning of air filter – 1
- Cleaning of air filter – 2
- Oil leak – 3
- Leakage in compressed air unit – 4
- Pneumatic hoses and cables - vacuum pump – 5

- Connecting wires –6
- Vacuum pump error–7
- Vacuum Filters –8
- Mount the valves–9
- Valve cleaning–10
- Oil filter, air filter, an oil separator is clogged or damaged–1A
- Low level in oil pump–1B

The values of part failure rate λ_p were obtained from the appropriate reliability prediction as mentioned in the MIL-HDBK-217. Where, the application factors, environmental factors, and factors are considered in the handbook. The value which was obtained from the handbook for $\lambda_p = 0.01$

The failure modes are listed below the table to have more clarity and in the table, it is mentioned numerically. The failure mode ratio (α) is calculated by the number of similar failures with same time divided by the total number of the failures.

The failure effect probability (β) is a conditional probability that it will enable us to figure out criticality classification. In this scenario the failure effect is an actual loss since all the failures which happen in the system will lead to stoppage of the machine and there is an actual loss so β = 1. The time which was in minutes in the vacuum machine breakdown table were converted into hours by dividing the values by 60.

The severity classification was done along with the head of the maintenance department. The below are the four categories on which the failures were categorized.

- Category 1 – Catastrophic
- Category 2 – Critical
- Category 3 – Marginal
- Category 4 - Minor

As said before, failure mode criticality is found using the formula $C_m = \lambda_p \alpha \beta t$. The item criticality number is computed as $C_r = \sum_{n=1}^{j} (C_m)^n$

Thus, the criticality found out based on the severity ranking.

Table 15 Item criticality based on severity rankings

Severity	Item criticality
II	0.002188
III	0.001693
IV	0.002177

3.7 CONTROL PLAN

Control plan was created with the focus on the reaction plan for a particular part failure and who will be responsible for that very particular failure. Initially, all the parts which are to be replaced have been mentioned in the part or process number and what type of failures it is. Followed by this the cause for the failure which was figured out using the quality tool Ishikawa diagram is used to figure out the cause for the failure. Next, the potential consequences which could happen are mentioned so that when the technicians read the document for reference they would know about it. Next, mention the actions to be taken if the problem occurs. If there is a period for a part to be replaced it will be mentioned, for example in the case of air filters there is a during of six months after which the filter must be replaced. Vacuum machine is taken care of by both the production and the maintenance. So, the responsibility falls over both the department and the control measure are also mentioned so that the responsible department can do it.

3.7.1 ABC analysis

ABC analysis was performed on the vacuum machine spare parts in the inventory. It is categorized into three major categories

Table 16 ABC categorization

A	Recommended spare parts always in stock (highly important)
B	Recommended spare parts by the manufacturer, if possible in stock (moderately important)
C	Spare parts which are used less often (least important)

This categorization was done on the percentage of the quantity required

- A - 10% quantity
- B - 20% quantity
- C - 70% quantity

And categorized based on the value of importance too

- A – 70% value of the machine
- B – 20% value of the machine
- C – 10% value of the machine

With this analysis, there was a smooth flow without too much disturbance in the production. EOQ (economic order quantity) was maintained so that there were cost savings and standardization of work was improved efficiently.

.

Table 17 Control plan for the vacuum machine (self-elaborated)

Control Plan – Fondarex vacuum machine									
Part/process number	**Process name/ work description**	**Machine/device/tool failure**	**Causes**	**Potential consequences**	**Actions**	**Replacement periodicity**	**Responsibility**	**Control method**	**Category**
Steel wool 100g MS 1000		Steel wool	Clogging of steel wool	Stoppage of the Vacuum machine	Replacement		Production		A
800-040 Vacuum hose DN25 x 4000		Hoses	Due to high vacuum pressure and improper handling	Vacuum drop and temporary stoppage of the machine	Checking and tighten the hose when indicated in the control panel;		Production	Check all screws are tightened and avoid tangling of hoses; use compressed air to clean; Once put back into position	C
800-050 Vacuum hose DN25 x 5000									C
800-060 Vacuum hose DN25 x 6000									C
800-070 Vacuum hose DN25 x 7000									C
800-080 Vacuum hose DN25 x 8000									A

800-130 Vacuum hose DN20 x 3000	check pollution test if OK; Weekly or after 160 hours of operations general check for tidiness and tightness has to be performed	C
800-140 Vacuum hose DN20 x 4000		C
800-150 Vacuum hose DN20 x 5000		A
200-191 Hose M Teflon L6, lg.1.5m		A
200-201 Hose M Teflon L6, lg.2.5m		C
200-211 Hose M Silver DN4 lg.1m		C
200-221 Hose M Silver DN4 lg.2m		C
200-231 Hose M Silver DN4 lg.3m		C
200-241 Hose M Silver DN4 lg.4m		A
200-251 Hose M Silver DN4 lg.5m		C

200-261 Hose M Silver DN4 lg.6m	C
200-271 Hose M Silver DN4 lg.7m	C
200-192 Hose S Teflon L8, lg.1.5m	A
200-194 Hose S Teflon L8, lg.1.5m MINI	C/B
200-195 Hose S Teflon L8, lg.1.5m MICRO	C
200-202 Hose S Teflon L8, lg.2.5m	C
200-212 Hose S Silver DN 6, lg.1m	C
200-222 Hose S Silver DN 6, lg.2m	C
200-232 Hose S Silver DN 6, lg.3m	C
200-242 Hose S Silver DN 6, lg.4m	A

200-252 Hose S Silver DN 6, lg.5m	C
200-262 Hose S Silver DN 6, lg.6m	C
200-272 Hose S Silver DN 6, lg.7m	C
200-193 Hose P Teflon S8, lg.1.5m	A
200-196 Hose P Teflon L8, lg.1.5m MINI	C/B
200-203 Hose P Teflon S8, lg.2.5m	C
200-213 Hose P Silver DN 6, lg.1m	C
200-223 Hose P Silver DN 6, lg.2m	C
200-233 Hose P Silver DN 6, lg.3m	C
200-243 Hose P Silver DN 6, lg.4m	A

200-253 Hose P Silver DN 6, lg.5m								C
200-263 Hose P Silver DN 6, lg.6m								C
200-273 Hose P Silver DN 6, lg.7m								C
200-185 Hose Silver compressed air lg.3m								B
054-001100 Spin on oil filter 160-250m3/h	Oil filter - (Vacuum pump)	If there is a blockage in oil return circuit	The old will cause excess wear on the bearings and even building up of debris which stops the oil to flow freely which overheats the pump	Clean the oil filter periodically	every 6 months or after 1500 hours it has to be replaced	Maintenance		A
053-100 Spin on oil filter 25-100m3/h								A
054-001017 Air filter cartridge 160-250m3/h	Air filter - (Vacuum pump)	Clogged due to dust in the atmosphere or	The system takes more time to reach the required vacuum	replacement of air filters is done when the	every 6 months or after 1500	Maintenance	Do not wash the filter, it has to be cleaned with compressed air; In	A

054-026 Air filter cartridge 100m3/h		polluted by wax particles	pressure and stoppage of the machine.	vacuum data in the tank of 20mbar will not be obtained in 130sec	hours it has to be replaced		case of pore blockage, it has to be replaced; after replacement check pollution test if OK	A
080-017 Air filter cartridge 25m3/h **Economie, Vacuplast								A
054-026 Air filter cartridge 100m3/h *HV 200-500-800								A
080-032 Oil for pump 1l	Oil level	Low oil level in pump due to leakage; old oil	Takes longer to reach the required vacuum pressure	Before using the machine, the operator has to check the level of oil in the pump; if it is less it has to be replaced	Oil should be changed every 1500 operating hours at the latest	Production	Oil-level has to be checked daily on the indicator glass	A
Compressed Air Unit	Compressed Air unit	Pressure leak; water collected in the water separator	Stoppage of the Vacuum machine	Cleaning of filters periodically		Production	Manometer should show minimum 6bars and all pneumatic connections should be	

								tightened; Dump the water collected.	
Control box		Control Box	When the control box is exposed to extreme thermal radiation; Ambient temperature is too high	Overheating might lead to stoppage of the machine	the temperature is controlled by means of a control device which is fixed on a mounting plate monitor it periodically.		Production		
Vacuum tank		Vacuum tank	Collection of liquid deposit and remainder of lubrication like piston greasing, etc.				Maintenance	The drain screw at the bottom of the tank must be opened, for this purpose the tank must be ventilated.	

3.8 EQUIPMENT MAINTENANCE CALENDAR

A calendar template Figure 22 was developed for all the activities which have to be done for the vacuum machine by the technicians on the daily/ weekly/ monthly basis. Here, in this calendar, the department that is responsible to note, the maintenance technician and the document that must be referred are all mentioned during all the 52 weeks of a year, corresponding to the activity.

Colour code
Daily
Weekly
Monthly

Figure 21 Color codes for the equipment maintenance calendar (self-elaborated)

Color codes with a text mentioning daily, weekly and monthly were given based on the tasks, so that it would be easy for the technicians to follow up. These tasks are now, followed whether they are being performed or not. We can avoid the failure by performing these activities If the failure persists, more improvements could be done for that very particular type of failure.

3.9 MAINTENANCE PROCESS IMPLEMENTATION

The process has been implemented at Sonafi and is under trial and observation. The maintenance head and coordinator held a meeting to explain the process of FMECA to the technicians and how and when to use the control plan, how and when to raise a flag when there is a new type of failure occurs or the same failure persists and what they expect from both production and maintenance technicians. The FMECA implemented is documented whenever failure occurs, and the progress will be monitored.

Currently, the process is followed by the technicians from both the maintenance and production department and the total number of defects in machine number 823 has reduced considerably.

			Months	JANUARY					FEBRUA				MARCH				APRIL					MAY				JUNE				JULY					AUGUST				SEPTEMBER				OCTOBER					NOVEMBER				DECEMBER			
Responsibility	Technician Name	Doc Number	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
Production																																																							
Production																																																							
Maintenance																																																							
Process																																																							
Production																																																							
Production																																																							
Production																																																							
Production																																																							

Figure 22 Equipment maintenance calendar (self-elaborated)

CONCLUSIONS

4 CONCLUSIONS AND PROPOSALS OF FUTURE WORKS

4.1 CONCLUSIONS

This thesis was done on account of problems faced by SONAFI in terms of maintenance. The maintenance department was facing several technical problems from the vacuum machine Fondarex. Firstly, understanding of why the need of vacuum machine in die-casting machine is of high importance was understood and a brief study of the machine was done along with the technicians and the maintenance coordinator for a period of 2 weeks. It was understood that a breakdown in vacuum machine would lead to stoppage of die-casting machine which in turn would lead to production loss and porosity on the surface of the casted products.

Then a study on failures occurred in the past on the vacuum machine was done to understand the cause of these failures. Based on it, a brainstorming session was conducted along with the maintenance manager, maintenance coordinator, preventive maintenance and chief -technicians of both maintenance and production department. To discuss in brief and address the root causes of the failure of vacuum machine a cause and effect analysis were performed. Better known as Ishikawa diagram to find out the failure causes and sub-causes leading to it. After three brainstorming sessions the reason was obtained for the stoppage of vacuum machine and over-heated die to further get deep into the analysis of failure, a previous failure data was compared with the data of cause and effect diagram to know that direction has not deviated.

The next phase was to perform the FMEA analysis, for each and every failure which was found out in the cause and effect diagram. First the effects of the failures were mentioned followed which potential cause, current process control method and current detection method was figured and written down. Then the severity, occurrence and detection values were found out during the discussions, followed by which the initial RPN was figured out. The next stage in FMEA analysis was to figure out what will be the recommended actions for the very particular type of failure along with it address the responsibilities, target completion dates and action taken for it. After this, again the severity, occurrence and detection were figured out based on the reasonings and a new RPN was found out.

Next was performing criticality analysis, it was done on parameter which was previously set by SONAFI. RPN ≥ 100, Severity > 8, Detection is very less and occurrence ranking greater than seven. When the failure satisfied the condition, the criticality was done, before which a bow-tie diagram was done for the failures to know out the consequence and extent of the failures and finally performing quantitative criticality analysis from the breakdown timings values obtained from the vacuum machine 823. A control plan was created to address the problem in detail for future reference. Here, the type of spare parts required for a failure and what action must be taken is mentioned in detail further an ABC analysis was done on the spare parts required so that the ware house department can be informed on the requirements.

Finally, an equipment maintenance calendar was created for the technicians to perform mandatory maintenance actions which is of daily, weekly and monthly task.

A week after implementation, it was noted that machine 823 showed improvement on 3 fronts.

- Reduction of scrap by 1.7% (weekly)
- No breakdowns happened in the first week
- Improved surface quality of the product

4.2 PROPOSALS OF FUTURE WORKS

The FMECA performed over the vacuum machine 823 is under observation after implementation and it has started to show improvements through reduction scrap/rework and stoppage of machines. Future work is to improve the existing process and perform FMECA on die-casting machine in Sonafi to

- Reduce the machine breakdown
- Reduce the percentage of scrap/rework
- Improve overall maintenance OEE.

REFERENCES AND OTHER SOURCES OF INFORMATION

REFERENCES

[1] "NADCA - North maerican die-casting association," [Online]. Available: https://www.diecasting.org/wcm/Die_Casting/FAQ/wcm/Die_Casting/FAQ.aspx?hkey=01ccba73-b463-4980-b3b4-a2c28815a015.

[2] M. Wahab, "DEFECT DETECTION IN HIGH PRESSURE DIE CASTING PRODUCT SING IMAGE PROCESSING TECHNOLOGY," 2003.

[3] Campbell.J, "Complete casting handbook: metal casting processes, metallurgy techniques and design," Elsevier, 2011.

[4] "Mechtech," [Online]. Available: http://4mechtech.blogspot.com/2014/09/die-casting-process.html.

[5] Campbell.J, "Complete casting handbook: metal casting processes, metallurgy techniques and design," Elsevier, 2011.

[6] "Paceind," [Online]. Available: http://www.paceind.com/die-casting-101/die-casting-faqs/what-is-die-casting/.

[7] A. Handbook, "ASM Handbook. Volume 15 Casting," ASM International, 2008.

[8] V. Nandakumar, "Process and Tool Design for the High Integrity Die Casting of Aluminum and Magnesium Alloys," Ohio, 2014.

[9] FONDAREX S.A, "VACUPAC UNIT," St.Legier, Switzerland.

[10] N. Iwamoto, "Method and apparatus for vacuum die casting". Patent US5511605A, 07 July 1993.

[11] G. Sullivan, "Operations & Maintenance Best Practices," 2010.

[12] M. Ward, "A performance improvement case study in aircraft maintenance and its implications for hazard identification," *Taylor and Francis online,* 2010.

[13] M. W. J Nisula, "Challenges of maintenance SMS practical implementation".

[14] M. HOLMGREN, "MAINTENANCE-RELATED INCIDENTS AND ACCIDENT," 2006.

[15] A. -. T. A. S. f. Q. Quality, "ASQ," [Online]. Available: http://asq.org/learn-about-quality/process-analysis-tools/overview/fmea.html.

[16] I. -. T. I. M. C. Association, "Guidance on Failure Modes & Effects Analyses (FMEAs)," 2002.

[17] ASQC, "ASQC," 1983.

[18] H. Dussault, "THE EVOLUTION AND PRACTICAL APPLICATIONS OF FAILURE MODE AND EFFECTS ANALYSES," New York, 1983.

[19] A. E. V. S. Swapnil B. Ambekar, " Review: Implementation of Failure Mode and Effect Analysis," International Journal of Engineering and Innovative Technology (IJEIT), 2013.

[20] H. Schneider, "Failure Mode and Effect Analysis: FMEA From Theory to Execution," 2012.

[21] R. M. M. B. R McDermott, "The basics of FMEA," SteinerBooks, 1996.

[22] M. A. Morris, "Failure Mode and Effects Analysis based on FMEA 4th Edition," ASQ - The American Society for Quality, 2011.

[23] F. M. COMPANY, "FMEA Handbook Version 4.2," 2011.

[24] L. W. Shoults, "Implementation of Design Failure Modes and Effects Analysis for Hybrid Vehicle Systems," Blacksburg, 2016.

[25] AIAG, "FMEA-3 Potential Failure Mode and Effects Analysis, 2nd edition - Automotive Industry Action Group," 2002..

[26] U. D. O. DEFENSE, "MILITARY STANDARD - PROCEDURES FOR PERFORMING FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS," WASHINGTON,DC.

[27] U. D. o. Defense, "MIL-STD-1629A: Procedures for Performing a Failure Mode ffects and Criticality Analysis," November, 1984..

[28] D. H. Stamatis, Failure Mode and Effect Analysis, ASQ quality press, Milwaukee, Winconsin, 2003.

[29] Ford, "Failure mode and effect analysis: FMEA handbook (with Robustness linkages); Version 4.2," 2011.

[30] "Slideshare," [Online]. Available: https://www.slideshare.net/AntonioRegadio/fmea-form.

[31] D. V. S. K. G. M. J. S. Rahul Renua, "A Knowledge Based FMEA to Support Identification and Management of Vehicle Flexible Component Issues," 2016.

[32] C. Y. B. L. R. K. Ying Chen, "Status of FMECA Research and Engineering Application," Beijing, China, 2012.

[33] "Quality one," [Online]. Available: https://quality-one.com/control-plan/.

[34] P. D. B. Noch, "ABC-/XYZ Analysis," Duisburg.

[35] B. o. R. U.S. Department of the Interior, "Facilities Instructions, Standards, and Techniques Volume 4-1A, Maintenance Scheduling for Mechanical Equipment," Denver, Colorado, 2009.

[36] "Keni confortzone," [Online]. Available: http://keni.candlecomfortzone.com/template-for-maintenance-schedule/.

[37] "Smartdraw," [Online]. Available: https://www.smartdraw.com/cause-and-effect/..

[38] "The Bowtie Methodology," *BowTie Pro - Enterprise business center.*

[39] "CGE - Risk management solutions," [Online]. Available: https://www.cgerisk.com/2017/02/bowtie-risk-assessment-for-inspection-authorities/.

[40] N. L. J. P. d. S. G. D. P. M. M. C.-C. P. S. Á. Luís Ferreira, "Technological Developments in Industry 4.0 for Business Applications," 2018, p. 451.

[41] J. Li, C. Xuan, B. Shao, H. Ji and C. Ren, "A new connected device-based Failure Mode and Effects Analysis model," in *IEEE*, Qingdao, China, 2014.

[42] "Fondarex," Fondarex, [Online]. Available: https://www.fondarex.com/.