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TRIZ Methodology Applied to Maintenance Problem Solving on Industrial Steam Systems in Africa

Dissertação para obtenção do Grau de Mestre em Engenharia Mecânica

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Setembro, 2016

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Acknowledgments

I want to express my truly thanks to Eng. João Ribeiro, for his guidance during the work and for his support throughout the whole process.

To Professor Helena Navas I'm grateful for the availability and interest in guiding the present dissertation, as well as her constant concern with its development.

Mostly, I want to thank and dedicate this work to my family for their constant, concrete and unwearying help during my entire life. Without them the development of this work would not be possible, because despite the distance, with love and affection they have always given me courage, strength and confidence to never give up. In particular, want to thank my parents for all the sacrifices they made over the past years, all the support and understanding they gave me in difficult times. To my brothers I thank all the understanding for being away, they were just kids when I left, now they are teenagers.

Finally, I want to thank Mónica the understanding for the days I could not be present. Thank you for all the support and motivation in the most difficult times during my degree, without you I would not be able to do it. Thank you for being yourself, for your patience, companionship, trust, understanding, love, care and the power you transmitted.

I thank you all the support in the development of this work.

Abstract

The problems in steam systems installations in Africa have three main causes: lack of proper preventive and predictive maintenance actions; lack of awareness of the importance of availability and efficiency of the systems during design stage; and lack of care and misuse of the steam systems during operation due to the scarcity of specialized workforce.

The present study, carried out during a one year trainee program within the scope of Bosch Industrial Business Development in Africa, is focused on identifying potential improvement points and problems related to maintenance and efficiency in Steam Systems in Africa. Maintenance services offered by the company were studied and after thorough analysis, improvement points were identified using TRIZ methodology in order to propose enhanced solutions further adapted to the African necessities. A detailed analysis was performed regarding the problems of equipment availability in Africa, thus enlightening the importance of redundant solutions in a market where qualified workforce and spare parts for equipment are not easily and readily available.

A remote predictive and preventive maintenance solution was identified using Contradiction Matrix. An improvement to a maintenance contract was proposed using Substance-Field analysis. A suggestion to increase the availability of a steam system, and a proposal to increase the efficiency of a steam system were both also developed using Substance-Field analysis.

In this way, the study was focused on using innovative methodologies in the development of improvement proposals in Africa, without disregarding the importance of certain aspects that are often not taken into account as much as they should.

Keywords: TRIZ, Industrial Maintenance, Substance-Field Analysis, Equipment Availability, Redundancy, Efficiency Improvement

Resumo

Os problemas em sistemas de vapor instalados em África têm três causas principais: falta de ações de manutenção preventiva e preditiva adequadas; falta de sensibilização para a importância da disponibilidade e eficiência dos sistemas durante a fase de projeto dos mesmos; e falta de cuidado e má utilização dos sistemas de vapor durante a operação devido à escassez de mão-de-obra especializada.

O presente estudo, realizado durante um programa de estágio com duração de um ano no âmbito do Desenvolvimento de Negócio da Bosch Industrial em África, focou-se na identificação de potenciais pontos de melhoria e problemas relacionados com manutenção e eficiência em Sistemas de Vapor em África. Os serviços de manutenção oferecidos pela empresa foram estudados e após uma sucinta análise, pontos de melhoria foram identificados utilizando a metodologia TRIZ de modo a propor soluções aperfeiçoadas e adaptadas às necessidades Africanas. Foi efetuada uma análise detalhada em relação aos problemas de disponibilidade dos equipamentos em África, sublinhando-se a importância de soluções redundantes num mercado onde mão-de-obra qualificada e peças de reserva para os equipamentos não são de fácil e imediata disponibilidade.

Uma solução de manutenção preditiva remota foi identificada através da utilização da Matriz de Contradições. Uma melhoria ao contrato de manutenção, uma sugestão para o aumento da disponibilidade de um sistema de vapor, e ainda uma proposta para o aumento da eficiência de um sistema de vapor, foram propostos através da aplicação da análise Substância-Campo.

Desta forma, o estudo focou-se no uso de metodologias inovadoras no desenvolvimento de propostas de melhoria para sistemas de vapor em África, sem desconsiderar a importância de certos aspetos que muitas vezes são menosprezados.

Palavras-chave: TRIZ, Manutenção Industrial, Análise Substância-Campo, Disponibilidade de Equipamentos, Redundância, Melhoria de Eficiência

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Abbreviations and Symbology

A_A	Achieved Availability
A_I	Inherent Availability
A_O	Operational Availability
API	American Petroleum Institute
ARIZ	Algorithm for Inventive Problem Solving
BTU	British Thermal Unit
CBM	Condition Based Maintenance
CIWH	Condensate Induced Water Hammer
CM	Condition Monitoring
CRM	Customer Relationship Management
IoT	Internet of Things
LDI	Liquid Droplet Impingement
$\bar{M}$	Mean maintenance downtime
MAWP	Maximum Allowable Working Pressure
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
NB	National Board of Boiler and Pressure Vessel Inspectors
OPE	Overall Plant Efficiency
PED	Pressure Equipment Directive
PM	Preventive Maintenance
RCM	Reliability Centered Maintenance

SWP	Safe Working Pressure
TPM	Total Productive Maintenance
TRIZ	Theory of Inventive Problem Solving
TÜV	Association of Technical Supervision

1 Introduction

1.1 Motivation

Business is progressively becoming more complex and competitive. For companies to thrive in such environment a combination between innovation and maintenance is crucial. Every equipment, especially in the industry, needs maintenance actions in order to ensure its operability, reliability and safety. Proper maintenance actions and systematic innovation can be the perfect combination for success. One methodology able to transform innovation into a reliable tool is the Theory of Inventive Problem Solving (TRIZ).

During a one year trainee program in Bosch, it was possible to note that certain maintenance services provided to Africa offered the possibility to be further adapted to the market. After a comprehensive examination of the issues with equipment availability, it was evident the importance of redundant solutions in a market where there is an absence of qualified workforce and spare parts.

As so, it is intended with this dissertation to provide improvement proposals for these services through the use of a reliable and innovative approach. TRIZ methodology was the procedure used in order to propose these enhanced solutions further adapted to the African market. Several aspects related to this topic are discussed, such as: preventive and predictive maintenance activities in steam systems, availability issues in Africa, energy efficiency measures, and performance improvements.

1.2 Objectives

The objective of this dissertation is the development of improvement proposals for the problems identified throughout the trainee program in Bosch. For the development of this proposals, it is presented the use of a reliable and innovative approach in order to create solutions based on logic and data in a systematic way that can be used repeatedly and consistently to quicken the ability of teams to solve problems.

TRIZ methodology offers several tools that can be used in order to create improvement solutions. As such, Contradiction Matrix, one of the tools of TRIZ methodology, is used to determine a remote predictive and preventive maintenance solution with the objective of obtaining a method to perform additional actions remotely, which is one of the most efficient ways to provide a specialized service to very large and spread regions as is the case in Africa.

Substance-Field analysis, another tool of TRIZ methodology is used with the objective of identifying problematic situations in the existent maintenance contract and create specific solutions by analyzing the general solutions for those problematic situations.

Substance-Field analysis is also used in order to show how system availability can be improved with the addition of supplementary stand-by equipment that provides a higher degree of redundancy to the system. At last, it is used with the purpose of creating specific solutions for the efficiency improvement of a steam system, by analyzing the general solutions proposed by the tool for the problematic situations identified in that particular scenario.

1.3 Outline

The structure of this dissertation is divided in 7 different chapters, from the "Introduction" to the "Conclusion and Future Developments". These chapters are represented in Figure 1.1 where two main blocks can be distinguished:

- Block a) represents the investigation and literature review for all the relevant topics discussed in this dissertation;

- Block b) represents the analysis and developments performed.

1. Introduction

a) Investigation and Literary Research
2. TRIZ Methodology
3. Industrial Maintenance
4. Steam Systems Installation and Maintenance

b) Analysis and Developments
5. Analysis of Current Maintenance Services Offered by the Company in Africa
6. Development of Improvement Proposals

7. Conclusions and Future Developments

Figure 1.1 Dissertation Structure

In this first chapter, an introduction is made to the addressed subject, as well as the contribute of the work and its objectives. A brief description of each chapter of the dissertation is also presented.

In chapter 2 the theoretical concepts of TRIZ Methodology are covered. The methodology is described and the fundamental principles reviewed. The main techniques intrinsic to TRIZ are specified with a focus on the Contradiction Matrix and Substance-Field Analysis which will be used more in depth in this dissertation.

Chapter 3 addresses the theoretical aspects of Maintenance. Besides reviewing the concept, also the different types of Maintenance are mentioned with a focus on the topics discussed further on this dissertation.

In chapter 4 the main aspects of steam systems are described. This chapter starts with an introduction to steam systems where the concepts of steam creation, distribution and condensate recovery are briefly introduced. Thereafter, the more relevant aspects of each one of this topics is reviewed more in depth in separate subchapters. Lastly, a review is done to the best practices for some of the most important equipment in steam distribution installations and the most prominent problems are discussed.

In chapter 5, current maintenance services offered by the studied company are analyzed. Main emphasis is given to preventive and predictive maintenance services offered. Subsequently, the improvement aspects that were identified are described.

In chapter 6, improvement proposals are developed using the tools that were reviewed in the previous chapters. TRIZ methodology tools, namely, Contradiction Matrix and Substance-Field Analysis are used together with maintenance concepts in order to develop solutions.

Finally, in chapter 7, a succinct summary of the work developed through the present dissertation is made; a breakdown of the conclusions that were obtained is presented, with the achieved results being discussed. Lastly, future developments are proposed with the intention of continuing the work developed in this dissertation.

2 TRIZ Methodology

Business is progressively becoming more complex and competitive. For companies to thrive in this environment, innovation is crucial. However, in order to achieve reliable results, innovation cannot be seen as a product of sporadic inspiration, but instead, as a product of systematic learning and management capacity.

Systematic innovation is a concept that uses predefined inventive tools to reliably generate new ideas, and incorporate them into new products and processes. The use of systematic innovation increases design effectiveness, enhancing competitiveness and profitability. One method able to transform innovation into a reliable approach is TRIZ [1].

2.1 A Description of TRIZ

TRIZ, a Russian acronym for "Theory of Inventive Problem Solving", is a predictable problem solving method invented between 1946 and 1985 in the former U.S.S.R by G.S. Altshuller and his colleagues. A methodology based on logic and data that quickens the ability of project teams to solve project related problems, which uses an algorithmic and structural approach to study problem patterns and solutions.

From project management to six sigma projects, the application of TRIZ methodology in the resolution of problems is becoming widely common in the industry.

The basic principle of TRIZ is based on using creativity principles in such a predictable way that they can be used repeatedly and reliably. What first initiated research about this methodology was the principle that for any given problem, somebody somewhere had already solved that problem or one very similar to it. So finding that solution and adapting it to that particular problem was considered a reliable and repeatable creativity process. Figure 2.1 shows the problem solving steps used by TRIZ [2], [3].

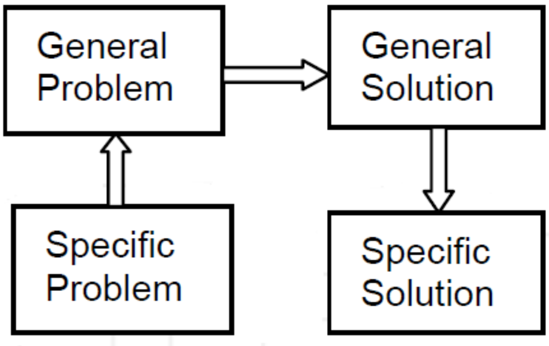


Figure 2.1 Steps used by TRIZ for problem solving [1]

2.2 Fundamental Concepts of TRIZ

2.2.1 Ideality

TRIZ ideology is based in two major ideas: Ideality and Contradiction. Ideality can be defined as the subject of creating ideal objects that represent the limit of real objects. Such objects cannot exist in reality and cannot be obtained as a result of any experiment. As so, ideality is an abstraction that represents the reflections of reality, useful for the studies of various phenomena [4].

The Law of Ideality states that any technical system tends to reduce costs, energy waste, space and dimensional requirements, to become more effective, reliable and simple. Any technical system, during its lifetime, tends to become more ideal [1]. Every time a technical system is improved, that system is closer to ideality. Ideality always reflects the maximum utilization of existing resources, both internal and external to the system [5].

In TRIZ, ideality can be applied to define different ideal categories that represent the boundaries of what can be achieved in reality. Such categories include [4]:

- The Ideal Process: which is the process result without the process itself;
- The Ideal Method: which expend no energy or time but obtains the necessary effect;
- The Ideal Machine: which has no mass or volume but can accomplish the required work;
- The Ideal Substance: which is actually no substance, but whose function is performed;
- The Ideal Technique: which occupies no space, has no weight, requires no labor or maintenance, and delivers the benefit without the harm, without any additional energy, mechanisms, cost or raw material.

By analyzing the description of each bullet, one can confirm that an ideal system is something unrealistic. However, ideality can be used to improve existent systems and make them closer to the ideal solution. In order to expand Ideality of a system, one should increase benefits and/or decrease expenses and/or decrease harm.

The level if ideality can be calculated as follows:

$$\text{Ideality} = \frac{\sum \text{Useful Functions}}{\sum(\text{Harmful Functions} + \text{Costs})} \qquad (1)$$

2.2.2 Contradiction

One of the two major ideas of TRIZ ideology, as stated in the previous chapter, is Contradiction, the basic law of material dialectics. Often, the most effective inventive solution of a problem is the one that overcomes some contradictions. A contradiction shows where (operative zone) and when (operative time) a conflict happens, and occurs when the improvement of one characteristic of a technique negatively affects the same or other characteristics of said technique [4].

Usually, when the contradictions existent in a problem are not overcome, the problem is not solved. In order to find creative and effective solutions for the problem, the solver must extract its contradictions. Figure 2.2 shows a detailed scheme of different types of contradictions.

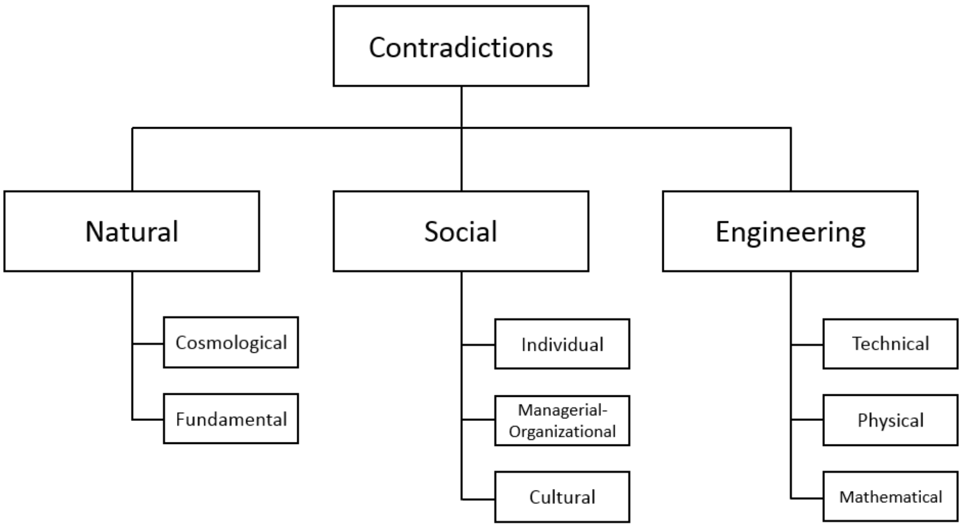


Figure 2.2 Types of contradictions (adapted from [4])

During the resolution of a problem in the framework of TRIZ, there is consecutive reformulation of contradictions generated by the problem. Each successive contradiction improves the solver's understanding of said problem.

2.2.3 Evolution Patterns

Through an extensive analysis of patents, Genrich Altshuller and its colleagues found that technological systems often followed regularities during their evolution process. Altshuller identified those regularities and established eight patterns of technical systems evolution used in the resolution of complex problems and in the prediction of future evolution of techniques [6]. The eight established patterns are [7]:

1. Technology follows a life cycle of birth, growth, maturity and decline;
2. Increasing ideality;

3. Uneven development of subsystems resulting in contradictions;
4. Increasing dynamism and controllability;
5. Increasing complexity, followed by simplicity through integration;
6. Matching and mismatching of parts;
7. Transition from macrosystems to microsystems using energy fields to achieve better performance or control;
8. Decreasing human involvement with increasing automation.

2.3 TRIZ Techniques and Principles of Application

2.3.1 Substance-Field Analysis

Substance-Field analysis (also known as SuField analysis) is one of TRIZ analytical tools and is considered a useful tool to identify problems and find solutions. This analysis has the capacity to modulate a technological system with simple graphic symbology of easy interpretation [6].

Functions performed by technological systems can be viewed as transformations of various types of energy and substances. A process performed by a technological system should involve at least three components; a tool, an article and a field source; which are described in TRIZ as substances and fields [6].

In TRIZ, the term "substance" can be a technological system of various degrees of complexity. The term "field" refers to the energy needed for interaction/control of two substances. These can be physical fields and engineering fields [8].

A substance acts over other substance in order to perform an action. Actions can provide benefits or damage. Can also be good, sufficient, insufficient, incomplete or harmful. The diagram is designed as a triangle with the problems represented graphically with different types of lines. Each line represents a different effect, which helps identifying what needs to be changed or improved [1]. These lines are represented on Table 2.1.

Table 2.1 Symbology used in Substance-Field diagrams [9]

Symbol	Effect
	Desired action or effect
	Insufficient or inefficient action or effect
	Harmful action or effect

There are five major types of relationships between substances [1]:

1. Useful impact;
2. Harmful impact;
3. Excessive impact;
4. Insufficient impact;
5. Transformation.

Once identified the type of problem, a standard solution can be selected and applied to that specific problem in order to improve it. This action is done by changing, removing or adding substances or fields [1].

The model of a minimal technological system is represented by two substances S_1 and S_2 and a field F, as represented in Figure 2.3.

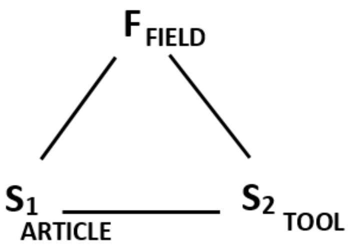


Figure 2.3 Connection between field and substances [8]

An absence of even one member of this triangle makes the system deficient.

The process of functional model construction follows the subsequent stages [1]:

1. Survey of available information;
2. Construction of Substance-Field diagram;
3. Identification of problematic situation;
4. Selection of a general solution (standard solution);
5. Development of a specific solution for the problem.

Substance can be defined as any object, independent of its complexity, and is represented as S. Substance S_1 is the article changed, repaired, transformed, discovered, inspected, etc. And substance S_2, known as tool, is the action that needs to be performed. The field F supplies the force and energy that ensures the action from S_2 to S_1. These three interactive agents are necessary and sufficient to achieve the necessary solution for the problem [9].

The Substance-Field analysis tool uses 76 standard solutions which are described in Appendix B. Developed by G.S. Altshuller and his associates between 1975 and 1985, these solutions were grouped into five large categories as shown below, in Table 2.2 [10]:

Table 2.2 Substance-Field standard solutions

Category Number	Solution Category	Number of Standard Solutions
1	Construct or destroy a substance-field	13
2	Develop a substance-field	23
3	Transition from a base system to a super-system or to a subsystem	6
4	Measure or detect anything within a technical system	17
5	Introduce substances or fields into a technical system	17
	Total	76

There are three different problematic situations applied in a Substance-Field analysis [1], [11]:

- Problematic Situation 1 (Figure 2.4) - Incomplete model. It is necessary to complete the model by adding a field.

Figure 2.4 Problematic situation 1 [1]

- Problematic Situation 2 (Figure 2.5) - Complete model with harmful interactions between the substances. There is a negative effect that needs to be eliminated. This can be done by modifying the field or adding an additional one.

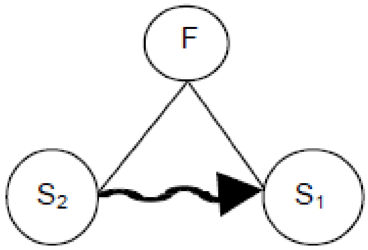


Figure 2.5 Problematic situation 2 [1]

- Problematic Situation 3 (Figure 2.6) - Complete model with insufficient or inefficient impact between the substances. It is necessary to improve the model by modifying S_1, S_2, F, or by adding a new substance to achieve the necessary action.

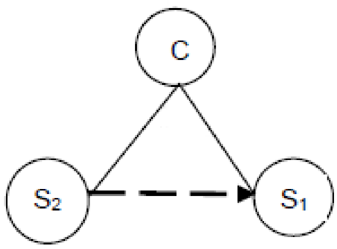


Figure 2.6 Problematic situation 3 [1]

For these situations the 76 solutions referred on Table 2.2 can be applied. These solutions can be condensed and generalized into seven general solutions. The problematic situations are represented below:

- General Solution 1 (Figure 2.7) - Complete an incomplete Substance-Field model.

Figure 2.7 General solution 1 [1]

- General Solution 2 (Figure 2.8) - Modifying substance S_1 to eliminate or reduce the negative impact or to produce or improve the positive impact.

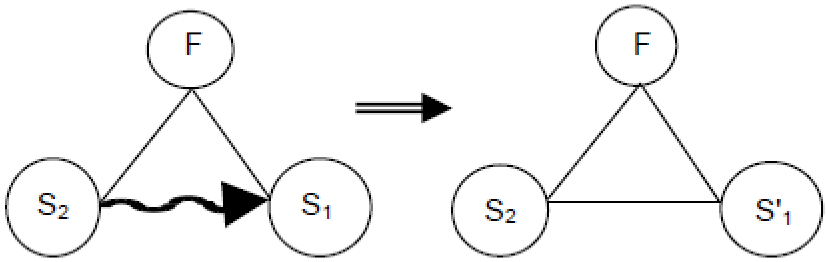


Figure 2.8 General solution 2 [1]

- General Solution 3 (Figure 2.9) - Modifying substance S_2 to eliminate or reduce the negative impact or to produce or improve the positive impact.

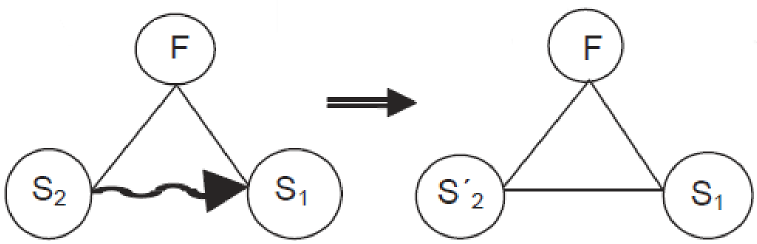


Figure 2.9 General solution 3 [1]

- General Solution 4 (Figure 2.10) - Modifying filed F to eliminate or reduce the negative impact or to produce or improve the positive impact.

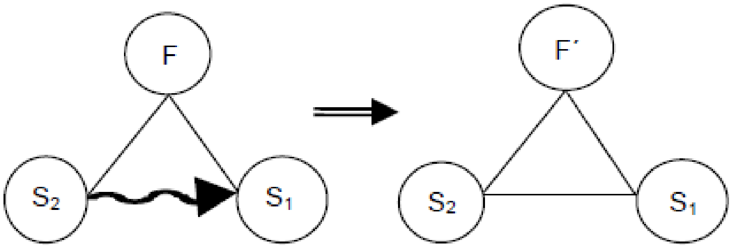


Figure 2.10 General solution 4 [1]

- General Solution 5 (Figure 2.11) - Eliminate, neutralize or isolate the negative impact using another field F_x that interacts with the system.

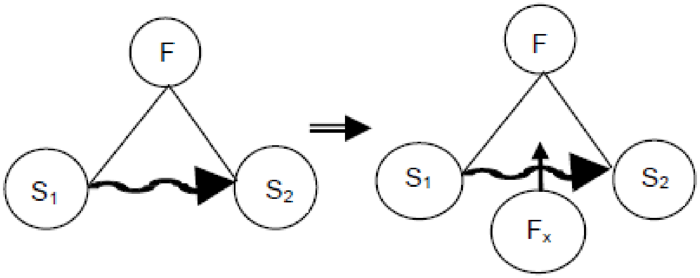


Figure 2.11 General solution 5 [1]

- General Solution 6 (Figure 2.12) - Introduce a new positive field in the model.

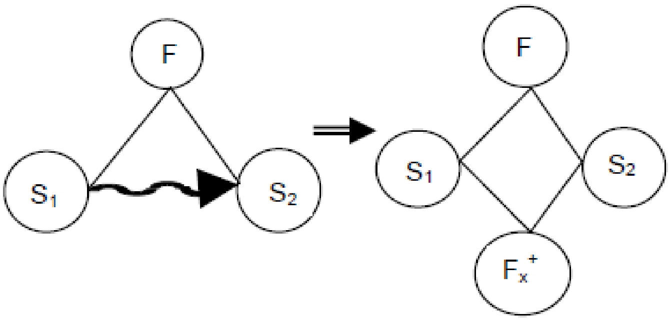


Figure 2.12 General solution 6 [1]

- General Solution 7 (Figure 2.13) – Expand an existent Substance-Field model to a chain by introducing a new substance S_3 to the system.

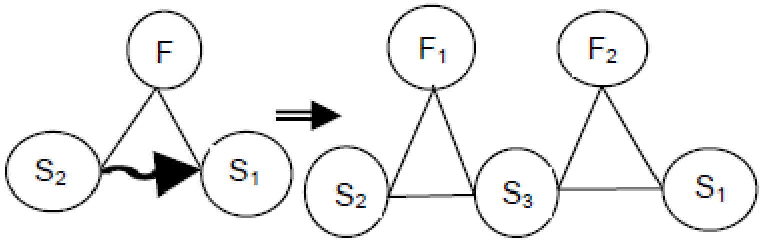


Figure 2.13 General solution 7 [1]

2.3.2 Inventive Principles and Contradiction Matrix

Upon a deep analysis work to a vast amount of patents done by Altshuller, it was possible to create a contradiction matrix that solves many of the technical problems encountered today [12].

This contradiction matrix is one of the most used tools by TRIZ users. It consists in 39 engineering parameters, represented in Table 2.3 and 40 inventive principles, represented in Table 2.4 which can be chosen in accordance with their applicability to the studied conflict [11].

Table 2.3 Engineering Feature [13]

Nº	Engineer Feature	Nº	Engineer Feature
1	Weight of moving object	21	Power
2	Weight of stationary	22	Loss of energy
3	Length of moving object	23	Loss of substance
4	Length of stationary object	24	Loss of information
5	Area of moving object	25	Loss of time
6	Area of stationary	26	Quantity of substance
7	Volume of moving object	27	Reliability
8	Volume of stationary	28	Measurement accuracy
9	Speed	29	Manufacturing precision
10	Force (Intensity)	30	Object-affected harmful
11	Stress of pressure	31	Object-generated harmful
12	Shape	32	Ease of manufacture
13	Stability of the object	33	Ease of operation
14	Strength	34	Ease of repair
15	Durability of moving obj.	35	Adaptability or versatility
16	Durability of non-moving obj.	36	Device complexity
17	Temperature	37	Difficult of detecting
18	Illumination intensity	38	Extent of automation
19	Use of energy by moving	39	Productivity
20	Use of energy by stationary		

Table 2.4 Inventiveness Principles [14]

Nº	Inventiveness Principle	Nº	Inventiveness Principle
1	Segmentation	21	Skipping
2	Taking out	22	Turning loss into profit
3	Local quality	23	Feedback
4	Asymmetry	24	Intermediary
5	Merging	25	Self-service
6	Universality	26	Copying
7	Nested doll	27	Cheap short-living objects
8	Anti-weight	28	Mechanics substitution
9	Preliminary anti-action	29	Pneumatics and hydraulics
10	Preliminary action	30	Flexible shells and thin films
11	Beforehand cushioning	31	Porous materials
12	Equipotentiality	32	Color changes
13	The other way around	33	Homogeneity
14	Spheroidality - Curvature	34	Discarding and recovering
15	Dynamics	35	Parameter changes
16	Partial or excessive actions	36	Phase transitions
17	Another dimension	37	Thermal expansion
18	Mechanical vibration	38	Strong oxidants
19	Periodic action	39	Inert atmosphere
20	Continuity of useful action	40	Composite materials

In order to solve a conflict using the contradiction matrix, a statement of the problem must be drawn so that the contradictions contained in the system can be revealed. Then the parameters that affect and improve the performance of the system must be identified [1].

The search process, using the contradiction matrix, begins with the identification, line by line, of the engineer parameter that needs to be improved. When this parameter is identified the next step is to identify, column by column, the engineer feature that gets worsened by the improvement of the first parameter. In the intersection between the parameter that needs to be improved with the parameter that gets negatively affected, are the inventive principles considered more useful by Altshuller to solve the contradiction [15]. The contradiction matrix can be seen in Appendix A.

2.3.3 Algorithm of Inventive Problem Solving (ARIZ)

ARIZ is the Russian acronym for Algorithm of Inventive Problem Solving and is the main analytical solution tool of TRIZ. The conventional approach to a creative problem implies a search for a solution to the problem. In the TRIZ approach the problem-solving as a procedure of seeking solution is replaced with a process of problem reformulation.

The concept of consecutive reformulations of the initial problem is realized in ARIZ, which is a set of successive logical procedures directed at reinterpretation of a given problem through two different concepts: System Conflict and Ideality, as seen in Figure 2.14.

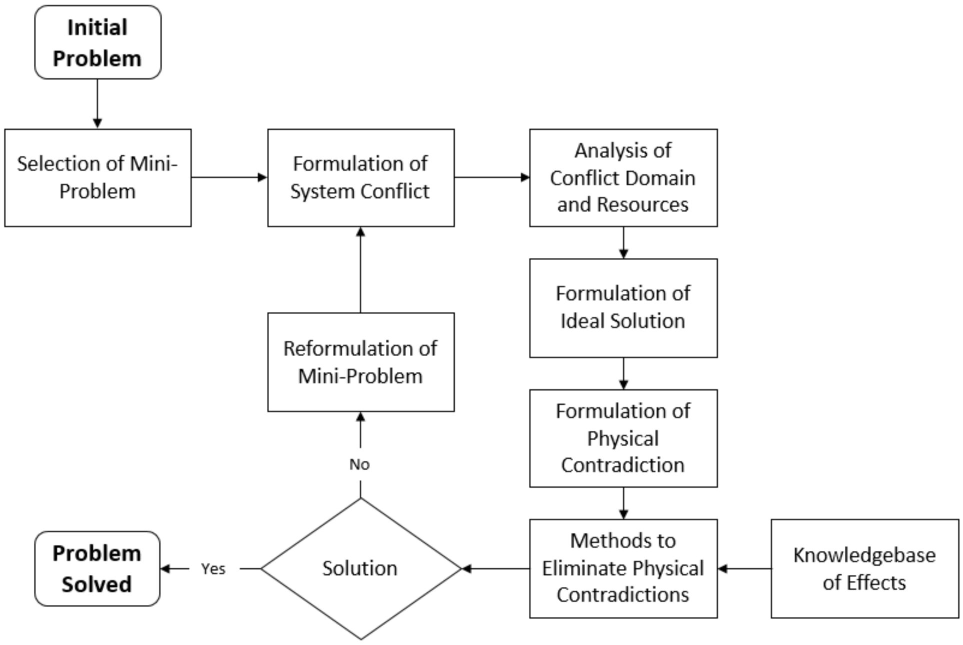


Figure 2.14 ARIZ flowchart (adapted from [16])

ARIZ defines the ideal final result and identifies the contradictions. Usually, to realize the Ideal Final Result, the critical component of the system in the Conflict Domain must possess contradictory physical properties.

This algorithm has five important steps that define a cycle. The steps are described below [16]:

1. Formulation of the problem statment;
2. Formulation of the contradictions;
3. Conflict analysis;
4. Application of methods for contradiction elimination;
5. Verification of the problem statement, reformulation and restart of a new cycle.

The process of elimination of the Physical Contradiction involves maximum utilization of material resources in the system and is supported by the Knowledgebase of Effects.

If the problem has not been solved, ARIZ recommends to go back to the starting point of the analysis and reformulate the problem. As a rule, absence of a solution after a thoroughly performed analysis is an indicator that a wrong problem was initially formulated. In many cases, a more general problem should be stated [8].

3 Industrial Maintenance

3.1 Historical Evolution of Maintenance

In the period previous to the industrial revolution in the XIX century, the manufacturing of goods and products was made manually and in a small scale, as so, there was neither a concern nor a necessity for the existence of maintenance. However, with the industrial revolution there was an introduction of a major quantity of equipment, leading engineers and business owners to start having a bigger concern with the maintenance of those equipment [17].

In 1930 military units introduced with more frequency the term "maintenance", relating it with the act of maintaining combat units and materials in better state of conservation and operation [18].

After the Second World War, in 1950, with the industry reconstruction, namely the German and Japanese industries, there was an increasing development of market competitiveness. This surge of competitiveness demanded an increase on the operating speed of the machines and an increase in the number of machines at service, simultaneously with a lower tolerance in the occurrence of outages in production. As a consequence of the high demand this machines were subjected to, they would wear much faster. In order to avoid such accelerated wear, it was demanded by the Production Departments a more careful maintenance of the equipment, which lead to the development of Preventive Maintenance [19].

The technical development of the 1950s, namely the introduction of the computer and an increase in the control of production techniques accelerated the creation of new maintenance techniques, such as the indication of eminent failure occurrence, decreasing the need for periodic intervention procedures to equipment [20].

The subsequent implementation of microelectronics led to the introduction of measuring devices that enabled real time monitoring of equipment conditions, allowing the detection of failure occurrences on those equipment. It was then created a new type of maintenance: Predictive Maintenance [21].

Niebel [22], refers that in 1981 only 1 to 12% of employees of industrial organizations worked in maintenance departments. However, nowadays, the increasing use of automation and reduction of manual work led to a responsibility increase of maintenance departments in the industry, which has caused a remarkable amplification on the workforce on those departments [17].

Figure 3.1 shows the temporal evolution of maintenance since it has gained more prominence in the 50s decade.

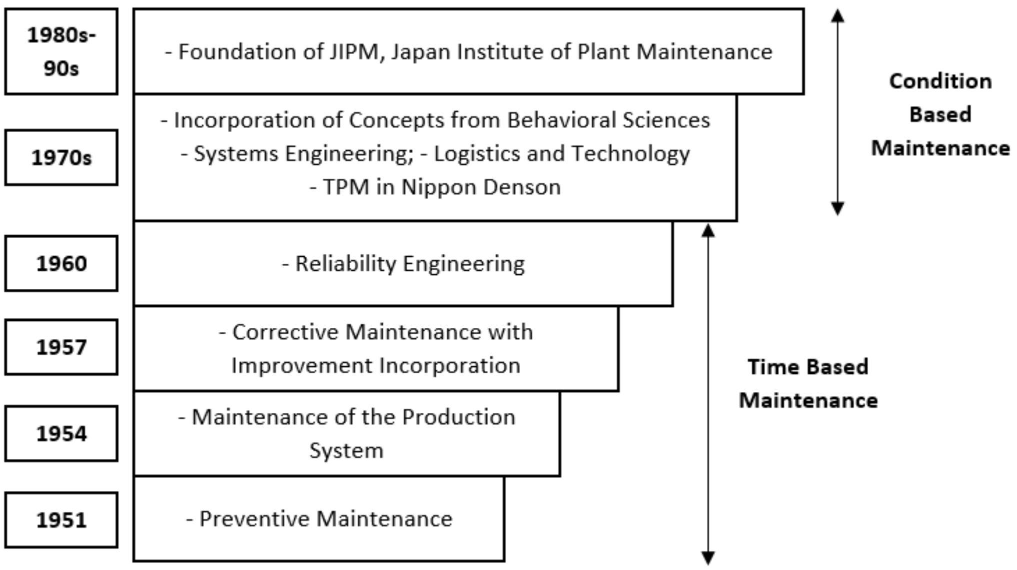


Figure 3.1 Temporal evolution of maintenance [23]

3.2 The Concept of Maintenance

According to the European standard of Maintenance Terminology [24], maintenance is "the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function". It is a set of organized activities that are carried out, with the minimum possible cost, in order to keep an item in its best operational condition. Such activities, like repair and replacement, are necessary for an item to reach its acceptable productivity condition [25].

The standard maintenance workflow is represented by a set of sequenced steps to be followed in order to accomplish a maintenance operation, from the first preparatory activities, such as study and defining policies, to the analysis once the work is finish and action to be taken to improve future similar cases [26].

Maintenance and production should be interconnected in order to achieve the best success in the industry. For instance, maintenance objectives should be consistent with production goals, like the action of keeping production machines and facilities in the best possible condition [27].

Every equipment, especially in the industry, needs maintenance actions in order to ensure its functionality, operability, and safety. Maintenance activities go beyond those actions, being also directly interconnected with legal and economic reasons.

From an economic point of view the objective of maintenance is to maintain the operability of an equipment for the maximum allowable time, without putting at risk the safety of the facilities where the equipment is being operated as well as the personnel who operates it [28].

Proper maintenance work has a direct impact in the quality of the manufactured products, and without it, there can be no production. Figure 3.2 shows several steps that allow for a proper production process.

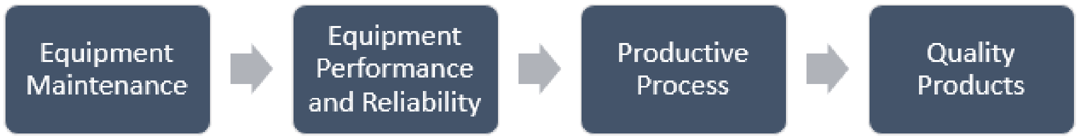


Figure 3.2 The importance of maintenance in the production process (adapted from [28])

3.3 Types of Maintenance

There are multiple types of maintenance used in the industry, as can be seen in Figure 3.3.

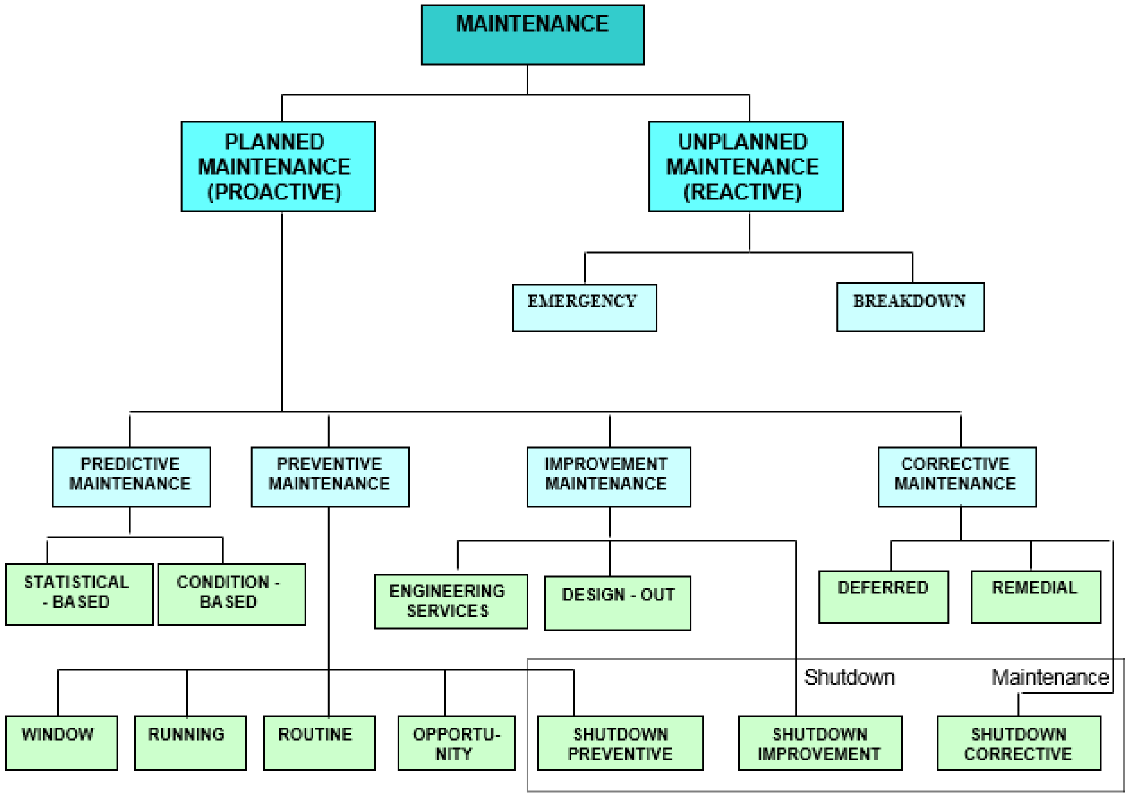


Figure 3.3 Different types of maintenance [27]

Depending on the way of proceeding in relation to a given anomaly or failure, the maintenance interventions can essentially be separated in two categories: planned and unplanned maintenance.

Planned maintenance is used when the degradation of a given equipment happens in such a progressive way that allows for a planned maintenance action to be set in the most appropriate time.

Unplanned maintenance is used when equipment failure happens in such a sudden and unpredictable way that it doesn't allow for a planned action [29].

Reactive Maintenance

Reactive maintenance is an unplanned type of maintenance where no actions or efforts are taken to maintain the equipment as it was originally planned by the designer in order to ensure that design life was reached.

Studies show that this type of maintenance is still one of the most used due to its low capital cost and low labor needs. However this is often misunderstood, because although this approach in the short time has lower costs, in reality, during the time that is believed to be savings in maintenance and capital costs, there is being spent more money than it would have under a different maintenance approach. This happens because while waiting for the equipment to break, its life is being shortened, resulting in a more frequent replacement. This increased cost would not be experienced had the maintenance program been more proactive. Also, the labor costs associated with the repair will eventually be higher than normal because the failure will most likely require more extensive repairs than would have been required had the equipment not been run to failure [30].

Corrective Maintenance

Performed after the occurrence of a kind of failure that does not allow the furtherance of the equipment's activity, corrective maintenance is a type of maintenance planned to restore the equipment's ability to perform such activities. It can be performed without a delay after the fault has been detected or with a delay according to given maintenance rules [25].

This maintenance type is better suited when [29]:

- The equipment's operation is not crucial for the productive process;

- The cost of repair is low;
- There is no safety related problems.

Corrective maintenance can be divided in two different categories: deferred and remedial.

Deferred corrective maintenance is performed after the failure occurrence. It requires the cessation of equipment's activity and is performed to momentarily fix the equipment while waiting for the remedial maintenance activity, which will fix it correctly and permanently.

Remedial corrective maintenance has the objective of treating the cause of failure. It is preceded by a primary cause analysis with the purpose of verifying if there is forced or natural degradation, with a report being created after the registered occurrence.

Preventive Maintenance

Preventive Maintenance (PM) is performed in pre-determined periods or in accordance with approved criteria with the objective of reducing the probability of equipment failure [29].

An effective preventive maintenance plan should include planned replacement of components and diagnostic measures. By introducing the element of planning into the maintenance functions, the repair and manpower requirements can be reduced [31].

Preventive maintenance is an important ongoing accident prevention activity which should be integrated in the operations of the manufacturing processes. Some of the advantages of this type of maintenance are:

- Improved system reliability;
- Decreased costs of replacement;
- Decreased system downtime;
- Protection of assets;
- Prolongation of equipment's useful life.

Predictive Maintenance

Predictive maintenance attempts to detect the onset of a degradation mechanism with the goal of correcting that degradation prior to significant deterioration in the component or equipment. The diagnostic capabilities of predictive maintenance technologies have increased in recent years with advances in sensor technology, and more recently with a new IT concept known as IoT (Internet of Things) [32].

The field of predictive maintenance technology has become increasingly sophisticated and technology-driven, making critical the correct training of operators in order to properly use the tools it provides.

The increase in maintenance technology allowed companies to use Condition Monitoring software as a tool to provide more accurate Condition Based Maintenance (CBM), an essential component of predictive maintenance.

Condition Monitoring

Condition Monitoring is a process of continuously monitoring operational characteristics of a machine to predict the need for maintenance before a deterioration or breakdown occurs. Condition monitoring has the potential to improve operational efficiency by improving the reliability of operation and machine up-time. The monitoring can be done through non-intrusive techniques such as temperature monitoring, oil particulate analysis and ultrasonic analysis; as well as intrusive techniques, usually transducers mounted on the equipment that measure parameters such as vibration, temperature and pressure [33], [34].

Predictive maintenance strategies use continuous or periodic condition monitoring of plant and equipment to determine operating conditions and to identify early warning indicators of failure [34].

Improvement Maintenance

This type of maintenance is used when the re-establishment of the operating conditions can only be done through the modification of the equipment, or when the maintenance conditions, in the scope of a maintainability or reliability improvement, recommend that such modifications are done [29].

3.4 Availability

Availability is a performance criterion for repairable systems that accounts for both the reliability and maintainability properties of a system. It represents the duration of uptime for operations and is a measure of how often the system is running in satisfactory conditions. It is defined as "a percentage measure of the degree to which machinery and equipment is in an operable and committable state at the point in time when it is needed"[35]. It is often characterized as [36]:

$$\text{availability} = \frac{(\text{uptime})}{(\text{uptime} + \text{downtime})} \tag{2}$$

Where:

uptime - Capability to perform the task

downtime - No capability to perform the task

In order to have optimal availability, there are three main factors that need to be maximized [36]:

1. Increasing the time to failure;
2. Decreasing the downtime due to repairs or scheduled maintenance;
3. Accomplishing items 1 and 2 in a cost effective manner.

There are three frequently used types of availability terms: inherent availability, achieved availability and operational availability. These terms are explained below.

Inherent Availability (A_I)

Inherent availability represents the expected level of availability when considering exclusively the downtime for the performance of corrective maintenance. It assumes that spare parts and manpower are 100% available with no delays. It excludes logistics time, administrative downtime, and preventive maintenance downtime. Inherent availability fulfills the need to distinguish expected performance between planned shutdowns and is defined as [35]:

$$A_i = \frac{MTBF}{(MTBF + MTTR)} \tag{3}$$

Where:

MTBF - Mean Time Between Failures

MTTR - Mean Time to Repair

Achieved Availability (A_A)

Achieved availability is similar to inherent availability but counting additionally with preventive maintenance downtimes. It is the steady state availability when considering corrective and preventive downtime of the system. The achieved availability is often addressed as the availability seen by the maintenance department. It includes both corrective and preventive maintenance but does not include logistics time and administrative downtime and is defined below [35]:

$$A_A = \frac{MTBM}{(MTBM + \overline{M})} \tag{4}$$

Where:

MTBM - Mean Time Between Maintenance actions

$\overline{M}$ - Mean maintenance downtime

Operational Availability (A_O)

Operational availability is a measure of the average availability over a period of time and it includes all experienced sources of downtime. It is the probability that an item will operate satisfactorily at a given point in time when used in a realistic environment. It includes logistics time, readiness downtime, administrative downtime, preventive maintenance downtime, and corrective maintenance downtime. Contrarily to the previous availability terms, operation availability is an *a posteriori* availability based on actual events that happened to the system. It is the ratio between system uptime and system total time, as given below [35]:

$$A_o = \frac{\text{Uptime}}{\text{Operating Cycle}} \tag{5}$$

Where:

Operating Cycle - overall time period of operation

3.5 Other Approaches

Total Productive Maintenance

Born in Japan, Total Productive Maintenance (TPM) is considered the natural evolution from corrective maintenance to preventive maintenance. It incorporates efforts to avoid quality defects caused by wear and malfunction of equipment. The basic foundation is that people that use the respective equipment are more aware and have more knowledge about its problems and should contribute in the repairs and modifications of the equipment [37].

TPM is based in the following elements:

- Performance optimization of the equipment;
- Establishment of a structure to avoid losses associated with the equipment and work environment, such as: zero accidents, zero quality defects, and zero failures;

- Implementation of continuous improving activities involving all levels of organization;
- Form different teams to reduce defects and self-maintenance;
- Continuous training of employees;
- Costs reduction.

The major difference between TPM and other concepts is that the operators are also involved in the maintenance process. The concept of "I (Production Operators) operate, you (Maintenance Department) fix" is not followed.

The overall objective of TPM is to improve productivity. This can be achieved through the adoption of a life cycle approach for improving the overall performance of production equipment, by motivating workers with a more challenging position with increased job tasks and responsibilities (also called job enlargement), and by using small voluntary group activities to identify the cause of failure and possible plant and equipment modifications [38]. In Table 3.1 below, are identified the direct and indirect benefits of using TPM.

Table 3.1 Benefits of using TPM (adapted from [38])

Direct Benefits of TPM	▪ Increase the productivity and Overall Plant Efficiency (OPE) by 1,5 - 2 times; ▪ Rectify customer complaints; ▪ Reduce the manufacturing costs by 30%; ▪ Satisfy the customer needs by 100% (Delivering the right quantity at the right time, in the required quality); ▪ Reduce accidents;
Indirect Benefits of TPM	▪ Higher confidence level among the employees; ▪ Favorable change in the attitude of the operators; ▪ Achieve goals by working as a team; ▪ Horizontal deployment of a new concept in all areas of the organization; ▪ Share Knowledge and experience.

Reliability Centered Maintenance

Reliability Centered Maintenance (RCM) is the process of determining the most effective maintenance approach, in order to provide the stated function of the facility, with the required reliability and availability at the lowest cost. The concept employs several notions of maintenance, such as preventive maintenance, predictive maintenance, real-time monitoring, reactive maintenance, and proactive maintenance techniques in an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with minimum maintenance.

The primary RCM principles are [39]:

- RCM is **function oriented**: it seeks to preserve system or equipment function, not just operability;
- RCM is **system focused**: it is more concerned with maintaining the system function than individual component function;
- RCM is **reliability centered**: it treats failure statistics in an actuarial manner. Is seeks to know the conditional probability of failure at specific ages;
- RCM **acknowledges design limitations**: maintenance can, at best, only achieve and maintain the level of reliability for equipment which is provided for by design, although maintenance feedback can improve the original design;
- RCM is driven by **safety and economics**: safety must be ensured at any cost; thereafter, cost-effectiveness becomes the criterion;
- RCM defines failure as **any unsatisfactory condition**: failure can be either a loss of function or a loss of acceptable quality;
- RCM tasks must be **applicable**: the tasks must address the failure mode and consider the failure mode characteristics;
- RCM tasks must be **effective**: the tasks must reduce the probability of failure and be cost effective.

The RCM process can be divided in several different steps. The first step is to define the **functions** of each asset in its operating context, together with the associated desired standards of performance. This can be: primary functions (which summarize why the asset was acquired in the first place) and secondary functions (which recognize that every asset is expected to do more than simply fulfill its primary functions). Done properly, this step alone can take up a third of the time involved in the entire RCM analysis [40].

The second step is to identify the **functional failures**. RCM process does this at two levels: firstly, by identifying what circumstances amount to a failed state; secondly, by asking what events can cause the asset to get into a failed state. In RCM, failed states are known as functional failures because they occur when an asset is unable to fulfill a function to a standard of performance acceptable to the user.

The third step is to identify all the events which are reasonably likely to cause each failed state. This events are known as **failure modes**. Most traditional failure modes incorporate failures caused by deterioration or normal wear and tear, but should also incorporate failures caused by human error.

The fourth step in the RCM involves listing the **failure effects**, which describe what happens when each failure mode occurs. These descriptions should include all the information needed to support the evaluation of the consequences of the failure.

The fifth step is to analyze the **failure consequences**. RCM recognizes that the consequences of failure are more important than their technical characteristics. In fact, it recognizes that the reason for doing proactive maintenance is to avoid or at least reduce the consequences of failure.

The sixth and last step is to introduce **proactive tasks** specified for the required failures. RCM divides proactive tasks in three categories: scheduled restoration tasks, scheduled discard tasks and on-condition tasks.

Scheduled restoration tasks entails remanufacturing a component or overhauling an assembly at or before a specified age limit.

Similarly, scheduled discard tasks entails discarding an item at or before a specified age limit.

On-condition tasks are techniques used to detect potential failures so that action can be taken to avoid the consequences which could occur if they degenerate into functional failures.

4 Steam Systems Installation and Maintenance

4.1 Historical Evolution of Steam Systems

As soon as mankind was able to boil water to create steam, the necessity of a safety device became evident. As long as 2000 years ago, the Chinese were using cauldrons with hinged lids to allow (relatively) safer production of steam. At the beginning of the 14th century, chemists used conical plugs and later, compressed springs to act as safety devices on pressurized vessels.

Early in the 19th century, boiler explosions on ships and locomotives frequently resulted from faulty safety devices, which led to the development of the first safety relief valve [41].

In 1848, Charles Retchie invented the accumulation chamber, which increased the compression surface within the safety valve allowing it to open rapidly within a narrow overpressure margin. Today, most steam users are compelled by local health and safety regulations to ensure that their plant and processes incorporate safety devices and precautions, which ensure that dangerous conditions are prevented [42].

Steam heating was invented in the 1800s and improved in the 1900s. Originally running with coal, using very simple and dangerous concepts in the early days [43].

4.2 Introduction to Steam Systems

Steam is a very efficient, economic and easily controlled heat transfer medium provided from a clean and cheap resource: water. This heat transfer medium is most often used to transport the energy created by the heating source to various locations in the plant and is one of the most widely used media for doing so.

Steam is an essential part of today's existing industries. Without it a large scope of applications and a wide range of industries could not perform as they do. From the production of energy through steam turbine engines to food processing, steam is present in various sectors and in the production of numerous items. This items include: paper, plastics, building materials, beverages, food, chemicals, textiles, and pharmaceuticals. As well as processes that require the heat supplied by the steam such as: cleaning, heating and the production of energy [44], [45].

Not all steam is the same and different processes require different types of steam. There are three different steam conditions: sub-saturated water or wet steam, saturated steam and superheated steam. This conditions are used in the industry where different processes require different types of steam [46].

The initial pressure that makes the steam transportation possible is created inside the steam boiler by the burner coupled in the combustion chamber or by a heat recovery system integrated in the boiler, usually by using the hot combustion gases to transfer heat into the water. After this initial pressure is generated and all the system is at work conditions, the heat transportation is possible due to the tenuous difference in pressure originated by the heat transfer process. The heat flow occurs due to the temperature differential between the hot steam, created in the boiler, and the steam condensation present in the distribution lines and heat exchangers (condensate has a very small volume compared to the steam, which causes a pressure drop).

The proper insulation of the steam distribution lines is extremely important in order to minimize the heat transfer between hot steam and cold air and avoid the creation of condensate, maximizing the amount of steam available at the heat exchangers.

When steam arrives at the heat exchangers the procedure is completely different. Here the heat transfer is essential, and the purpose is to transfer as much heat as possible from the steam into the process that requires it [47].

A steam system can be split in four different groups: generation, distribution, end use and recovery. This four groups follow the path of steam from its creation to its condensate recovery. Figure 4.1 illustrates this path accordingly.

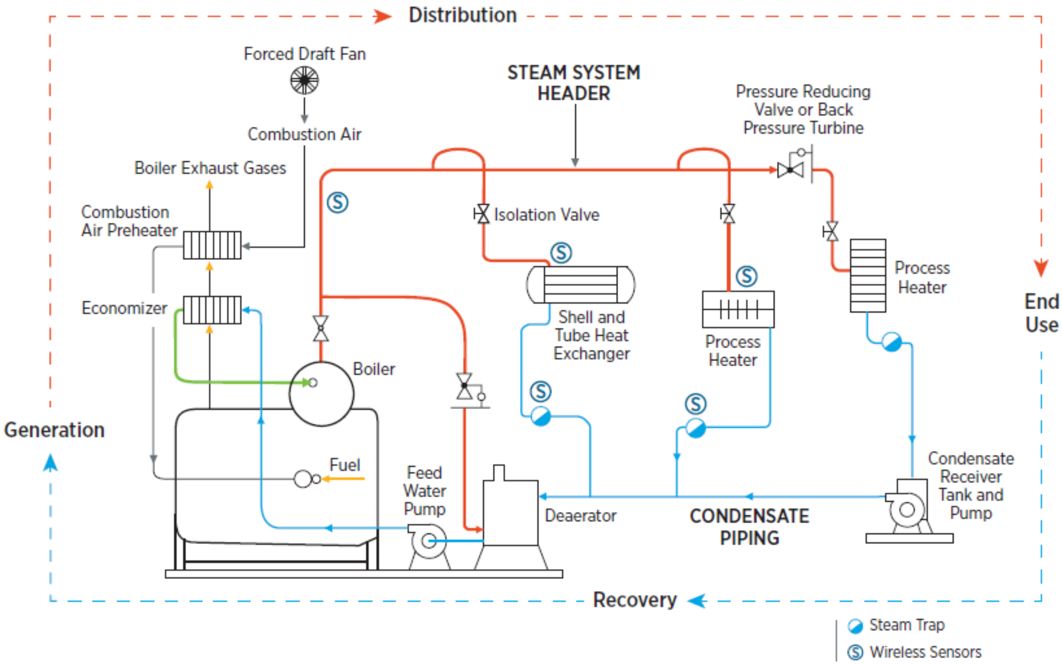


Figure 4.1 Steam System Scheme [48]

The process starts with the generation of steam in the steam boiler. Here steam is created by transferring heat from the burner combustion gases to the water present in the boiler. After the water is heated enough it shifts into steam. The steam pressure increases to a point where it flows to the distribution system [48].

The steam generated in the boiler must be conveyed to the point where its latent heat is required. The steam distribution system makes this possible. It is the connection between the steam generation system and the steam end use.

Distribution systems usually have lines operating at different pressures. The lines that carry steam from the generation system are called steam mains. The smaller lines, called branch lines, carry the steam from the mains to the end use process. The distribution lines are separated by various types of isolation and pressure-regulating valves. A properly performing distribution system delivers sufficient quantities of high-quality steam at the right pressures and temperatures to the end uses [47], [48].

The system end use is the process requiring the steam produced. The steam will be carried to the process using different equipment depending on the circumstances. End use equipment consists of heat exchangers, turbines, fractionating towers, strippers, and chemical reaction vessels. In some cases the process only requires heat from the steam, not steam itself, for example: when using heat exchangers to supply heat to the cooking process in the food industry. The consumption of the steam produced lowers the overall system efficiency and should be avoided when possible, using only its heat through heat exchangers makes the system much more efficient.

The desirable heat transfer from the steam to the substance heated turns a vast amount of steam into condensate. After this process is complete and the steam has given up its precious latent value, the hot condensate that was created must be promptly removed. The recovery system, also known as the condensate system, collects this condensate and the condensate formed during steam transportation and returns it to the feed water tank.

The recovery of condensate has several benefits: it increases the system efficiency, lowers the water consumption and reduces the water treatment module chemical consumption, since recovered condensate is already chemically treated and well suited to be introduced into the system.

4.3 Industrial Steam Boilers

Industrial boilers are designed to withstand enormous pressures. As so, these boilers are welded from thick steel plates that are up to 35 mm thickness, making pressures of 30 bar and more possible. A stable, robust design is also essential – if a boiler of this type were to blowup, enormous explosive forces would be released.

In case of Bosch Industrial Boilers [49], a capacity of up to 55000 kg per hour of steam is possible to be generated from a single boiler. A boiler of this type, filled with water and ready for operation, can weigh as much as 165 tons. A full capacity boiler of this size converts 3000 liters of fuel oil per hour, which is sufficient to heat more than 2000 houses.

The steam boiler design consists of an horizontal, cylindrical pressure vessel, which is fired through a burner and an internally situated reversing chamber that reverses the flue gases and leads them back in the second smoke tube pass. On the front of the boiler is an external reversing chamber, which again reverses the flue gases and lead them to the end of the boiler in the third smoke tube pass. Steam boiler vessels are filled with ¾ of water, leaving the upper quarter for the generation of steam [49].

Because of the huge volume of water and the multi-stage lead-through of the flue gases, these boilers are also called three-pass shell boilers. Figure 4.2 shows a sectional drawing of a representative image of a three pass shell boiler.

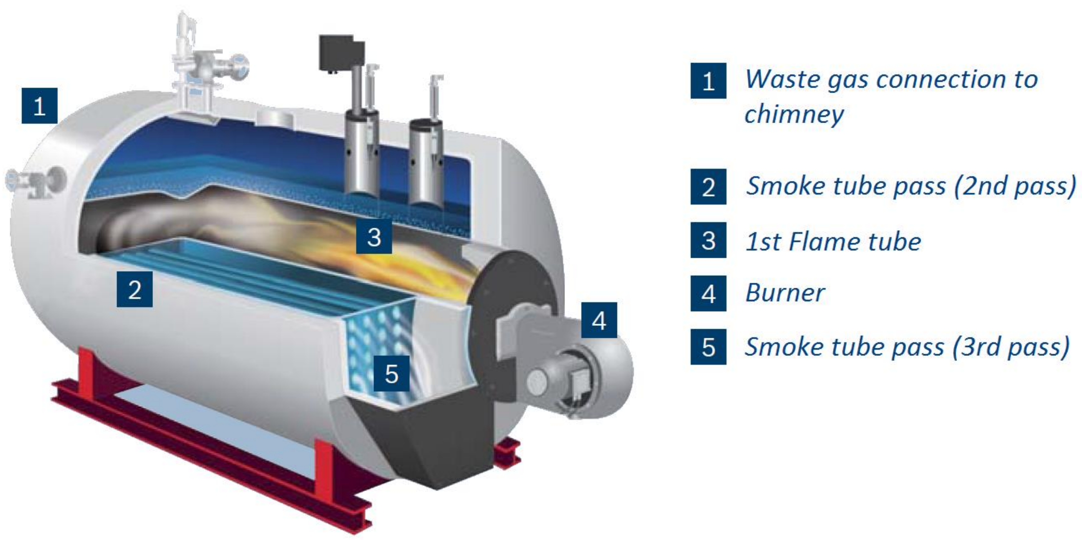


Figure 4.2 Sectional drawing of a three pass boiler [49]

4.4 Steam Distribution Systems

The Steam Distribution System is a bundle of several components that make the steam transportation efficient and safe from the steam generator to the steam end user, supplying steam of the highest reasonable quality. This bundle usually consists of: pipes (also called steam lines), drain points, branch lines, strainers, filters, separators, steam traps, air vents, insulation and the condensate recovery system [46]. Figure 4.3 shows a typical steam distribution system.

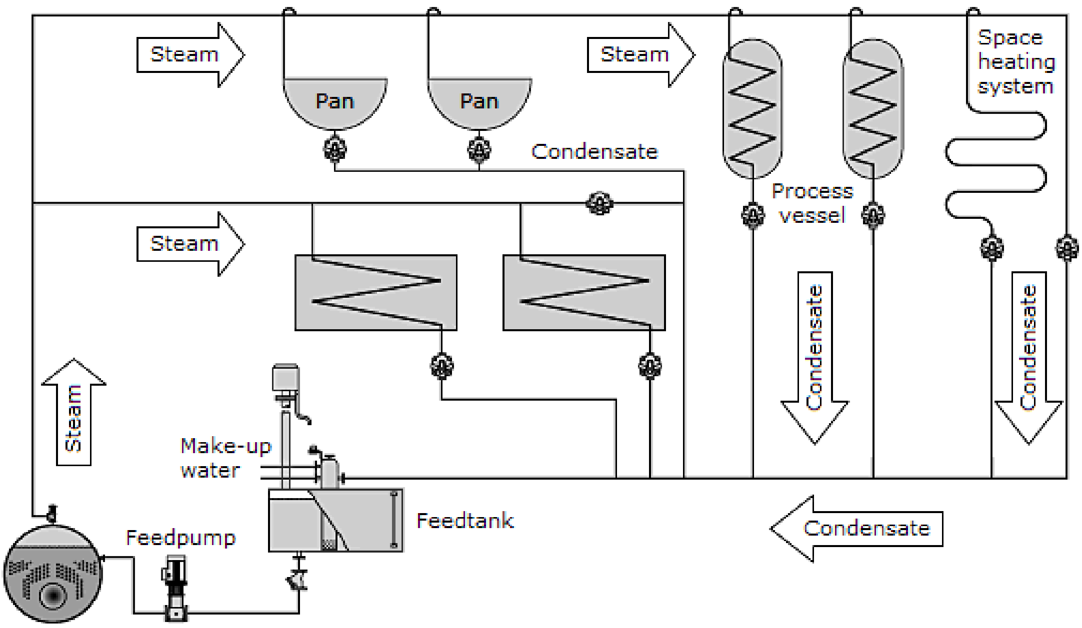


Figure 4.3 Steam Distribution System [47]

These systems regulate the delivery of steam and respond to changing temperature and pressure requirements. A proper performance of the distribution system requires careful design practices and effective maintenance. The piping should be properly sized, supported and insulated and should have the adequate flexibility. Devices such as pressure reducing valves and back pressure turbines should be used to regulate the pressure in the system and provide proper steam balance. The distribution system should be configured to allow adequate condensate drainage, with adequate drip leg capacity and proper selection and installation of steam traps.

Effective distribution system performance requires proper steam pressure balance, good condensate drainage, complete insulation with regular repair and maintenance, and effective pressure regulation. [48]

The Importance of Pressure in the Steam

A kilogram of steam at a higher pressure occupies less volume than at a lower pressure. If steam is generated and also distributed at a high pressure, the size of the distribution mains will be smaller than for a low-pressure system for the same heat load. Generating and distributing steam at a higher pressure has various advantages [48]:

- It increases the thermal storage capacity of the system;
- It reduces the steam distribution equipment costs due to smaller bore steam mains;
- It reduces the steam distribution insulation costs also due to smaller bore mains.

Although distributing steam at a higher pressure being advantageous, the steam pressure still needs to be reduced down to the maximum pressure required at the different points of use. The local pressure reduction brings another benefit to the steam produced: it makes it drier.

A common and reliable method used for centuries for reducing pressure at the point of use is to use a pressure reducing valve.

4.4.1 Condensate Recovery System

Condensate is the liquid formed when steam passes from the vapor to the liquid state and is the by-product of heat transfer in a steam system. It forms in the distribution system due to unavoidable radiation, and it also forms in the heating and process equipment as a result of desirable heat transfer from the steam to the substance heated. When initial conditions are present, pipes are still cold while the steam is extremely hot. This makes the steam to instantly condensate into water as soon as it begins to move. Due to the maximum temperature difference existent in start-up conditions, the condensing rate will be at its maximum in these conditions [44].

Once the steam has condensed and given up its valuable latent heat, the hot condensate must be removed immediately. Condensate formed in the distribution steam lines and in the process equipment contains the sensible energy from the steam vapor. It holds as much as 10% of the total steam energy content of a typical system, depending on the steam pressure and temperature. So it's still valuable hot water and should be returned to the boiler feed water. As fuel costs are taken more in consideration, it is one of the highest return on investments and should be imperative to focus on recovering condensate in every industrial steam operation [45], [50].

Condensate recovery is a process of reusing the water and sensible heat contained in the discharged condensate. Recovering condensate instead of throwing it away has several benefits [51], [52]:

- It increases the system efficiency (depending on the insulation and travel distance);
- Lowers the water consumption of the feed water tank;
- Reduces the water treatment module chemical consumption (recovered condensate is already chemically treated and well suited to be introduced into the system);
- Reduces sewer system disposal costs;
- Meets environmental regulations;
- Reduces energy losses due to boiler blowdown, considering the return of high purity condensate;
- Increased fuel savings, as most returned condensate is relatively hot (54 ºC to 107 ºC), reducing the amount of cold makeup water (10 ºC to 16 ºC) that must be heated.

The transport and recovery of condensate for reuse requires a positive pressure differential from the source to the destination, usually a condensate collection area. Sometimes the trap's inlet pressure is sufficient to overcome the system backpressure.

This is the cheapest method and usually the most reliable, since no special equipment is required.

However, many installations require a pump to transfer condensate to the recovery area due to negative differential pressure. In this case, a pumping system is required to transport and recover condensate once the system backpressure becomes higher than the lowest possible trap inlet pressure [53].

Steam traps, installed in proper condensate discharge locations, are the most effective and efficient method of draining condensate from a steam distribution system.

The resulting condensate falls to the bottom of the pipe and is carried along by the steam flow and assisted by gravity due to the gradient in the steam main that should be arranged to fall in the direction of steam flow. The condensate will then have to be drained from various strategic points in the steam main then channeled, collected and temporarily stored in a condensate tank, like the one represented in Figure 4.4 [54].

Figure 4.4 Bosch Condensate Service Module [54]

The discharge of condensate from the steam mains to the condensate lines is made through steam traps from a higher to a lower pressure. As a result of this drop in pressure, some of the condensate will then re-evaporate, and is referred to as flash steam. Around 10% to 15% of the proportion will flash off, although it differs according to the level of pressure reduction between the steam and condensate sides of the system, and about 50% of the energy content hold by condensate can be lost through flash steam. Therefore, Flash Steam Recovery is an essential part of achieving an energy efficient system [55].

4.5 Steam System Maintenance

Steam Lines

In order to maintain the efficiency of the steam lines, two major activities are required [56]:

1. Correction of steam leaks;
2. Repair of steam line insulation.

Both represent great losses in efficiency, which leads to a major increase in operation costs. However both problems are recurrently ignored.

In order to detect such problems, routinely surveys should be made. This surveys allow the identification of numerous problems such as:

- Steam leaks;
- Wet or damage insulation;
- Missing insulation.

Steam leaks are very costly to the system operation, however are often ignored due to their repair costs. A steam leak repair usually requires a system shutdown and the replacement or repair of the leaking component. The costs of this operation are often though as too high, but most times the benefits are worth the investment [56].

Unlike steam leaks, damaged and missing insulation is not readily detected, although it compromises the insulation value. Wet insulation gives almost no noticeable indications, and even areas where insulation is missing may not be obvious. Due to that, insulation frequently becomes damaged or is removed and never replaced during a steam system repair or maintenance [57].

The best way to identify this insulation problems is to survey the entire steam system. Through regular surveys, all leaks and insulation problems must be identified and scheduled for repair, and sources of moisture must be eliminated prior to insulation replacement. In some cases, repairs must be postponed until the system can be shut down for annual maintenance.

Steam Traps

Maintenance of steam traps is often ignored by maintenance workers due to operational components being usually enclosed and hidden from view. As a result, attention is only given to this piece of equipment once it starts to give problems, thus making the condensate system faulty [56].

Lack of proper maintenance on steam traps can lead to its failure and cause high losses of steam. Implementation of a comprehensive maintenance program can reduce energy losses due to failed traps, and increase the system efficiency by up to 10% [56].

The correct approach to ensure that steam traps are functioning properly is to implement a regular preventive maintenance program where traps are inspected frequently and, if needed, cleaned, repaired or replaced. The program starts with a survey to locate every trap within the steam system and catalogue their size, type, and model. It is wise to develop a mapped route that identifies the location of each trap and recommends a route to be followed in order to locate all traps [55].

In addition to the tracking of steam traps, the survey must also test their operation. There are three methods that can be used:

- Visual observation;
- Acoustic monitoring;
- Temperature measurement.

In order to minimize production downtime, it is advisable to hold a stock of spares for the most critical parts and a number of standby valves and traps which are on hand for use in an emergency [55].

Condensate Return Lines

Condensate return lines are particularly susceptive to corrosion due to the corrosive nature of condensate, which results in the need for frequent maintenance. An appropriate water treatment system that can separate out aggressive gases from the feed water, and provide a proper water softening, decarboning and desalting, can greatly reduce corrosion in condensate lines [56].

The main purpose of a condensate system maintenance program is to return as much good quality condensate as possible to the boiler. The system's operation must be continuously monitored. Condensate sample collection and chemical tests should be done daily to track changes in the clean condensate and to take action if needed. Any changes in the sample are indications that the water treatment is not operating properly or that there are leaks in the system [56].

In addition to daily testing, the complete condensate system should be inspected once a year. All sources of air and water leaks must be identified and corrected. Equipment connected to the system should be examined for leaks [56].

4.6 Installations Best Practices

Steam Distribution

When working with steam, it is essential that the steam arrives at the farthest heat exchanger. If the boiler is properly sized, the steam will reach it without all of itself turning into condensate. After the initial conditions, the pipes will warm up and highly reduce the amount of condensate generated in the distribution lines.

In order to carry the steam to the farthest process equipment and successfully complete the steam loop, the steam must be maintained at a predefined pressure which is limited by the maximum safe working pressure of the boiler and the minimum pressure required at the plant. As steam passes through the distribution lines, it will lose pressure due to friction resistance and condensation within the pipework. Consequently, when determining the initial pressure, allowance should be made for this pressure loss [44], [47].

Branch line connections shall be taken from the top in order to collect the driest possible steam. If connections were taken from the side, or from the bottom, there would be condensate and debris coming along with steam from the steam mains. The result would be a wet and dirty steam that could affect the performance of the end-use equipment. Figure 4.5 shows the proper installation of a branch line connection [47].

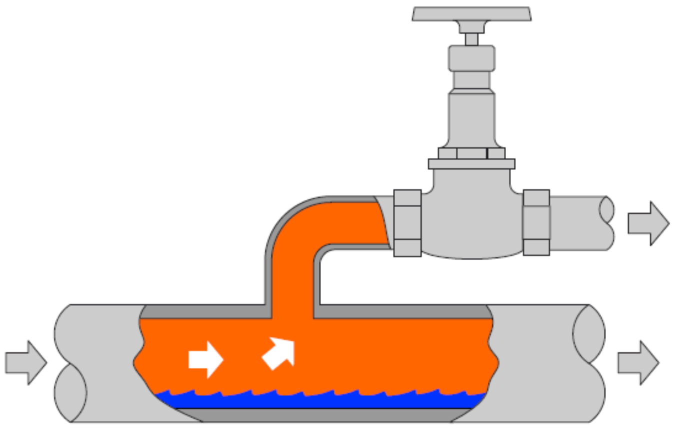


Figure 4.5 Correct steam off-take [35]

Drip legs and steam traps shall be installed at all low spots or natural drainage points such as:

- Ahead of risers;
- End of mains;
- Ahead of expansion joints or bends;
- Ahead of valves or regulators.

Drip legs are provided to let condensate escape by gravity from the fast-moving steam, and to store the condensate until the pressure differential can discharge it through the steam trap [58].

The use of thermostatic air vents will help remove the accumulating air from the steam mains. Air vents consist in thermostatically-actuated steam traps positioned in the system where air will gather. Proper installation of air vents require them to be located at high points, at the end of the steam main piping as seen in Figure 4.6, and on all heat exchange equipment [55].

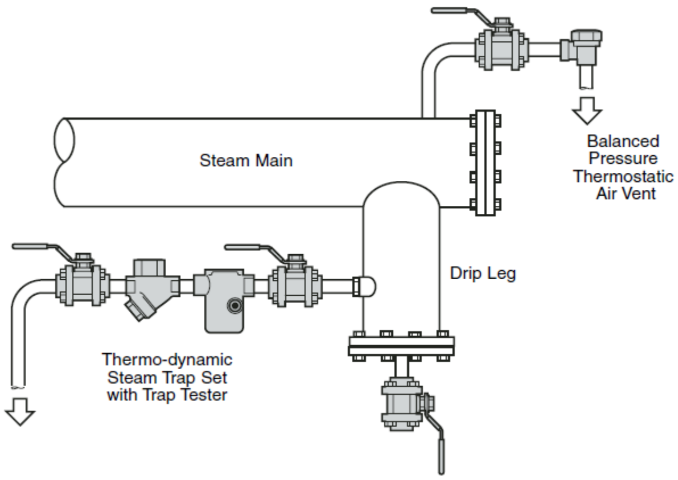


Figure 4.6 Air venting and steam trap at the end of a steam main [55]

Insulation

Important insulation properties include thermal conductivity, strength, abrasion resistance, workability and resistance to water absorption [48].

Removable insulating jackets are available for a wide range of fittings. The use of insulation jackets prevents the fitting surface from radiating heat, thus improving the efficiency of the system. Installation of this jackets should be done according to the fitting manufacturer's direction in order to maintain a proper equipment operation [57].

Pipe Sizing

When selecting the size of the piping, consideration should be given to the type of environment in which the steam lines will be located [48].

When determining pipe size, the following factors should be considered:

- Initial steam pressure: the output pressure at the boiler or at the main, depending on what type of lines are being designed (mains or branches);

- Allowable pressure drop: the total pressure drop, including losses on pipes and fittings, allowed from the source to the end of the system. The total pressure drop should be less than 20% of the boiler's maximum pressure;
- Flow rate: the amount of steam that must be supplied to the end use equipment;
- Steam velocity: problems such as erosion and system noise increase with velocity. Therefore, in process steam systems, steam velocity should be maintained between 30 m/s and 60 m/s;
- Future expansions: lines should be sized with conceivable future awareness. When in doubt, oversized lines usually present fewer problems than undersized lines.

Allowance must be given for the additional frictional resistance of the pipe fittings and heat losses from the main [47] [59].

Protection of the Steam System

Protective devices such as safety valves are extremely important in the protection of the system, making it possible to protect the equipment against overpressure conditions, reducing the overall damage to the system. This valves are designed to protect the system against excessive pressure by, according to the European standard EN ISO 4126 – 1, "automatically, without assistance of any energy other than that of the fluid concerned, discharge a quantity of the fluid so as to prevent a predetermined safe pressure being exceeded, and which is designed to re–close and prevent the further flow of fluid after normal pressure conditions of service have been restored", this reduces the excess pressure in a safe and controlled way.

The installation of this devices should be made wherever the maximum pressure existing at normal operating conditions of the system is expected to be exceeded. This pressure is denominated the Maximum Allowable Working Pressure - MAWP (sometimes called the Safe Working Pressure - SWP). Also, according to the EN ISO 4126: "All safety valves shall be sealed by the manufacturer, his representative or a responsible authority. Unauthorized interference with the load on the spring, after the safety has been adjusted, shall be prevented by: the fitting of a ferrule under the adjusting collar, or the fitting of a compression ring under the adjusting screw collar, or the locking of the adjusting screw. Alterations should only be made with the authority of the manufacturer and/or the inspecting authority”.

For steam boiler applications there are very specific requirements for safety valve performance, demanded by national standards and often, insurance companies. Approval by an independent authority is often necessary, such as the Association of Technical Supervision (TÜV) from Germany, Lloyd's Register from the United Kingdom and the National Board of Boiler and Pressure Vessel Inspectors (NB) representing the United Stated of America and Canada. The use of this devices in Europe also requires an additional accordance to the standards associated with the Pressure Equipment Directive (PED).

Condensate Recovery

Unfortunately, a large percentage of industrial plants are wasting the condensate from the steam system and are not taking a proactive step in returning condensate to the boiler plant. Condensate that is being returned is still losing the thermal energy due to uninsulated tanks, uninsulated condensate pipe, valves and fittings. The “Best Practice” for condensate is that all devices in the condensate system are insulated to prevent thermal energy losses [50].

Flash Steam Recovery

When high temperature condensate under pressure is exposed to a large pressure drop such as when exiting a steam trap, its temperature must drop very quickly to the boiling point for the lower pressure. The surplus heat energy contained in the high temperature condensate, which prevents it from remaining in liquid form at a lower pressure is then used as latent heat causing some of it to re-evaporate into steam.

If the flash steam is to be recovered from the condensate. This is best achieved by passing the mixture of flash steam and condensate through a Flash Steam Vessel, as shown in Figure 4.7 [55], [60].

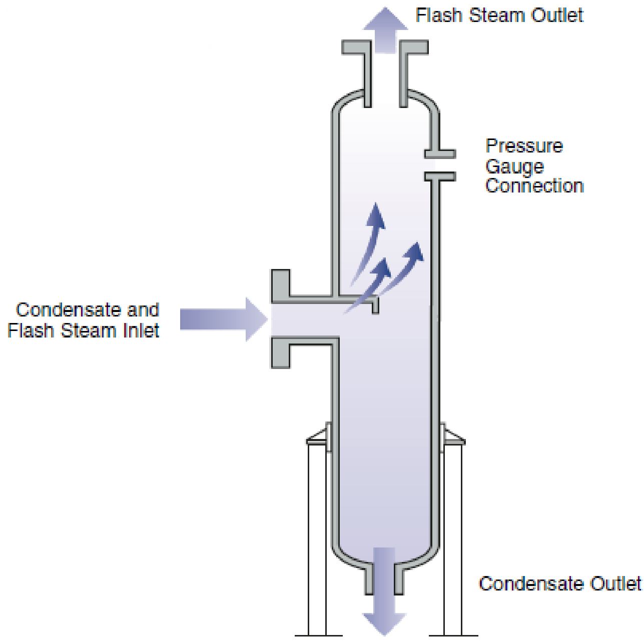


Figure 4.7 Flash Steam Vessel Operation [55]

In order to separate the flash steam and condensate adequately, the size of the vessel must be designed to allow for a reduced velocity. By doing so, the carry-over of condensate out into the flash steam recovery system is prevented.

4.7 Prominent Problems in Steam Systems

Many problems mistakenly thought of as inevitable in the operation of a typical steam system are avoidable. Occurrences such as pipe erosion, water hammers and reduced heat transfer are often reduced or even eliminated by proper sizing and placement of equipment. In the next paragraphs it will be discussed the leading problems encountered in steam systems [61].

Pipe Erosion-Corrosion

Pipe erosion can result in steam leaks. Most erosion is created when water, as entrained water in the steam flow and as non-discharged condensate, traveling at high speeds, is retained in the piping, which leads to a repeated impact in piping elbows. The impact, due to the water mass and high velocity, can cause gradual thinning of the pipe. This type of erosion is usually called Liquid Droplet Impingement (LDI) erosion.

The process of flash steam re-vaporization in condensate recovery piping can also be a source of erosion. This flash steam erosion is often called flashing erosion, and according to the steam expert company, TLV [62], it can often be worsened by two related factors:

- Undersized condensate return lines that cause high flash steam velocity;
- Corrosive elements such as carbonic acid associated with low temperature condensate.

Erosion and corrosion are usually interconnected. The erosion of inner piping leads to the elimination of its protective surface treatment, particularly when carbon steel material is used. This leads to an increase in electrochemical thinning of the pipes, also known as corrosion. A number of parameters are directly involved with the erosion-corrosion effect and influence the material loss behavior, such as [63]:

- Fluid velocity;
- Fluid pH level;
- Fluid oxygen content;
- Fluid temperature;
- Component geometry;
- Component chromium content;
- Component copper content;
- Component molybdenum content.

Many of this parameters can be controlled in order to mitigate erosion-corrosion effect. Factors such as the water pH, oxygen content and pipe material can be directly controlled by the plant owner.

Corrosion is one of the most common problems in steam systems. It can cause premature degradation of equipment and be responsible for production downtime. Oxygen that enters a steam system oxidizes and corrodes the system's equipment, creating small but deep holes in the metal, an effect called "pitting"[64].

Water Hammers

According to Peffel [51], a steam expert from Swagelok Company, a water hammer is "a high pressure surge or wave created by the kinetic energy of the moving liquid" which causes catastrophic effects in steam installations and is responsible for 67% of premature component failures in steam systems.

In by-phase systems, where liquid and vapor phases are both present, the water hammer effect is more propitious to happen. Meaning heat exchangers, tracer lines, steam mains, and condensate return lines, where condensate co-exists with steam, are more prominent for water hammer occurrence.

This kind of occurrence where condensate is the source of the water hammer, is often called Condensate-Induced Water Hammer (CIWH) and is usually caused by differential shock. Differential shock can occur when steam and condensate flow in the same line at different velocities. If condensate isn't promptly removed, its level rises, which increases steam velocity and turbulence. With steam flowing at a greater velocity than condensate, often 10 times higher, condensate waves develop. With condensate levels rising, eventually steam will not be able to flow through the condensate seal, as seen in Figure 4.8. When this happens, condensate will then be carried by steam at higher velocities, and will keep adding condensate to the slug as it is driven downstream. If this slug of condensate, with high momentum, is then required to change direction at a tee or an elbow, it can result in catastrophic damage [65] [66].

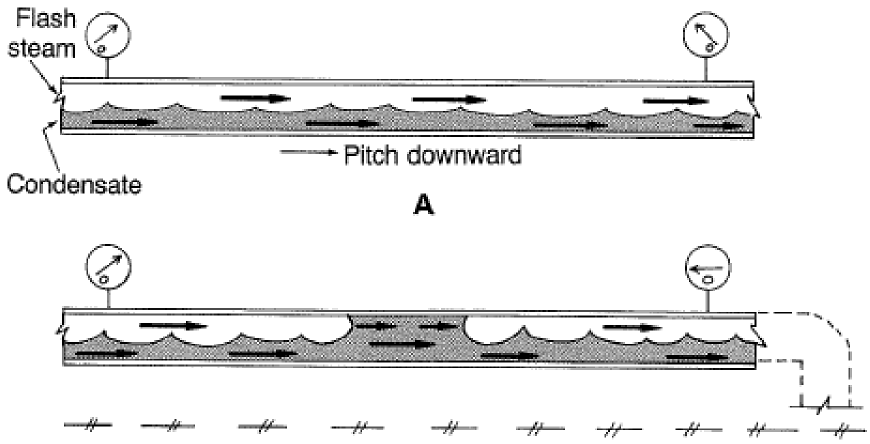


Figure 4.8 Formation of a condensate slug [66]

The pronounced force caused by water hammer can cause dangerous complications to the installation. Listed below are some of the most pertinent effects [66]:

- Collapse of thermostatic elements;
- Overstress of gauges;
- Bend of mechanisms;
- Crack and rupture of fittings and equipment;
- Expansion of piping.

Although this tremendous complications can happen with the occurrence of water hammers, it is possible for high pressure steam systems to function without this type of problem. Water hammer is not a normal effect, and with the properly design and operation of the system, it will not occur.

Overpressure

Excessive pressure in the steam lines can occur due to a number of different situations and can damage the steam system's equipment and final product while also representing a real treat to plant personnel. Listed below are typical situations which lead to overpressure [42]:

- Fluid flow rate imbalance due to inadvertently closed or opened isolation valves;

- Control instrumentation malfunction;
- Transient pressure surges;
- Heat exchanger tube failure;
- Ambient temperature changes;
- Industry driven problems such as uncontrollable exothermic reactions in chemical plants.

Overpressure protection of a system is usually achieved by the use of pressure relief devices, such as safety valves. This valves open suddenly, remain fully open, and reclose when the overpressure decreases [67].

Presence of Non-Condensable Gases

The presence of non-condensable gases, such as air, can have devastating effects in a steam system. This gases can increase corrosion and lower the system performance. The thermal conductivity of air (0,025 W/m ºC) is much lower compared with the conductivity of water (0,6 W/m ºC), making air a good insulator, which is the opposite of what is needed when heat transfer is required, Due to their insulate properties, if air and other non-condensable gases are not removed from the steam system, a reduction on heat transfer efficiencies of more than 20% is to be expected [68].

5 Analysis of Current Maintenance Services Offered by the Company in Africa

5.1 Company Description

One of the world's leading international providers of technology and services, Bosch is a global company with some 375 000 associates and four business sectors, represented in 150 countries.

With inventions such as:

- ESP (Electronic Stability Program), which prevents up to 80% of all skidding accidents with an antilock braking system that keeps the car stable when a loss of traction is detected;
- Direct injection, where the fuel is injected at high pressure, resulting in an optimum swirl effect which reduces fuel consumption by around 15%;
- Bosch IXO, a cordless screwdriver which is the world's best-selling power tool, with more than 15 million units sold.

It has invested more than 24 billion euros over the past five years in research and development with the objective of developing innovative, useful, and exciting products and solutions to enhance quality of life.

Its four business sectors are:

- **Mobility Solutions**: one of the world's largest suppliers of automotive technology;
- **Industrial Technology**: leading in drive and control technology, packaging, and process technology;
- **Energy and Building Technology**: Leading manufacturer of security technology, and global market leader of energy-efficient heating products and hot-water solutions, managed by Bosch Thermotechnology division, where Bosch Industrial Boilers subsidiary is integrated;
- **Consumer Goods**: Leading supplier of power tools and accessories, and leading supplier of household appliances.

5.1.1 Company History

Bosch Industrial Boilers, officially Bosch Industriekessel GmbH, is a company with 150 years of existence, originally known as LOOS, it was acquired by Bosch in 2009, becoming a subsidiary of Bosch Thermotechnology division.

It is a world-renowned specialist for boiler systems of all sizes and performance classes with a systematic focus on environmental protection and saving of resources. It has sold more than 120 000 boiler plants in 140 countries.

Bosch boiler systems are standing out by reliability and long lifetime. With a design and equipment of each product tailored to individual customer specifications with many different options and variants, modular solutions are offered for easy installation.

In Africa, there are more than 700 installed Bosch boiler systems. The Industrial Boiler team responsible for Africa was first created in 2012 with 1 person responsible for its development. The team was created to increase the availability of services and to boost the installed base of boiler systems in the continent.

Currently there are 11 persons fully dedicated for boilers in Africa, including 6 service engineers ready to provide after sales service in the continent.

5.1.2 Main Products

Bosch Industrial offers shell boiler systems for all applications. Not only used in industrial businesses, but also in smaller businesses, service companies, office buildings and residential blocks.

In order to cover the wide range of applications, Bosch developed a diverse product portfolio prepared to offer different type of products depending on the necessities of the customers.

Figure 5.1 shows Bosch product portfolio for boilers.

Figure 5.1 Bosch boilers portfolio [69]

To complement the steam boiler portfolio and to offer a complete solution for steam systems, Bosch developed modules that allow for the design of steam systems according to each customer's requirements. They ensure maximum operating safety as well as long service life and high level of efficiency under specific operation conditions.

This portfolio can be seen on Table 5.1.

Table 5.1 Bosch product portfolio for boiler house components [54]

WSM-V / WSM-T	CSM / CHP	WA / WTM	EHB / BEM / EHM	GRM
 Water service modules	 Condensate service modules	 Water treatment & analysis	 Waste water: expansion, blow-down, cooling, heat recovery	 Gas regulation module
PM	**SP / RP**	**RTS**	**SD**	**OCM / OSM / OPM / ORM**
 Pump module	 Supply / Return flow	 Return flow temperature safeguard	 Steam distributor	 Fuel supply oil

5.2 Maintenance Services and Activities

In order to maintain a steam system working properly it is particularly important to have a planned maintenance program. The program, planned to be executed in predetermined periods or in accordance with approved criteria will significantly help reduce equipment failure probability.

Using a planned maintenance program allows for planned diagnostic procedures and deliberate replacement of components, acting preemptively instead of reactively. As a result, system reliability is increased, and system downtime is decreased, bringing substantial benefits for the company.

In case of Bosch it is of great importance to provide predictive maintenance tools as well as guidelines that customers can follow for a proper preventive maintenance plan in order to maximize product reliability and life time.

In order to deliver solutions to the customers regarding preventive and predictive maintenance, Bosch already has three supplementary services: maintenance contracts, condition monitoring and remote service.

The maintenance contracts provide a reliable maintenance program adapted to customer necessities with bundled features, providing the exact solution that each customer is looking for.

Condition monitoring is done through CMbasic, which is a program that allows the monitoring of multiple operating parameters through an installed control system on the equipment, giving the opportunity to monitor the efficiency and proper operation of the equipment. It analyses and evaluates system data and displays it in a transparent way in order to produce significant forecasts promoting a consistently high level of system efficiency and availability. Using CMbasic, customers are able to detect operating anomalies before failure, allowing to act preemptively.

Remote service is provided through MEC remote. It allows the execution of predictive maintenance actions through remote access to the control system; offers the possibility for the service engineer to pre-check the equipment plant in case of planned visit on site; allows the adjustment of parameters remotely; and provides the possibility to send periodic reports of equipment operating conditions.

Figure 5.2 shows an example of the Bosch Management System where CMbasic and MEC Remote are used.

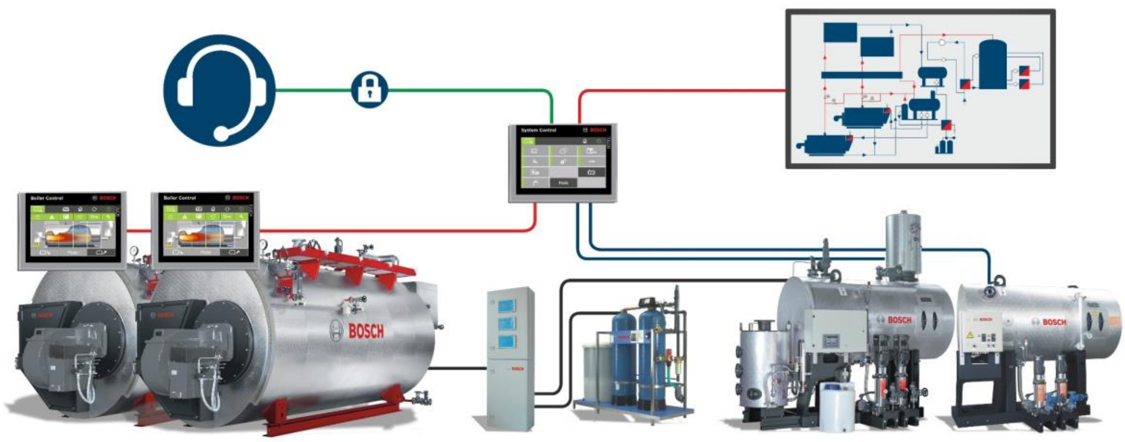


Figure 5.2 Bosch Management System for the control of steam systems [70]

5.2.1 Identified Improvement Aspects

After a profound analysis of the current solutions that are available to be delivered to African customers, the ones that had more improvement potential were selected in order to provide suggestions that will allow those solutions to become more competitive in the market.

Bosch Conditioning Monitoring was one of those identified solutions, it offers a sophisticated predictive maintenance solution that allows the monitoring of multiple operating parameters through an installed control system on the equipment, however due to the lack of highly qualified operators in Africa, such data might not be analyzed to a fully extent by the operator.

As a solution for this matter, MEC Remote could be used, which would allow for a qualified Bosch technician to analyze equipment operating parameters through remote access to the control system. However, this solution is only available if the customer has MEC Remote installed on the equipment's system and if he has acquired the annual software subscription. For this reason, there is a necessity to keep track of which customers do or do not have access to MEC Remote. For those who don't have access, the benefits of this tool should be enlightened.

In addition, the development of supplementary services that could be provided remotely would be an added value due to the considerable lack of availability for service, spare parts and qualified technicians in Africa.

Another identified solution was Bosch maintenance contract, which is a preventive maintenance solution that helps reducing equipment failure probability and can increase its system's lifetime. The maintenance contract is well prepared for the European requirements, however, they require adaptations in order to meet African necessities.

Due to the lack of availability of spare parts and qualified workforce in Africa, systems can be down for even longer periods of time, for instance, a service action that would take days or even hours to be provided in Europe, could require weeks in advance to be prepared for Africa. These longer delivery periods can incur in enormous production losses for the companies. For this reason, it is even more important to deliver an adapted maintenance contract that provides reliable system downtime prevention.

Another matter that needs to be improved is customer awareness towards redundant solutions. Supplying solutions with lack of redundancy, for instance solutions without supplementary stand-by equipment, is a problem for the customer and a concern for the supplier. Systems without redundancy increase dramatically the probability of an availability issue.

Looking at the example of a fuel pump, a critical device for the operation of the boiler, if a failure occurs with this device and a second pump is not readily available to continue the operation, the complete system will be shut-downed. The customer will not be satisfied and will look for answers with the supplier that did not offered a redundant solution.

However, what frequently happens is that a redundant solution is initially offered to the customer, but then due to cost constrains, the customer requests a cheaper option. To meet customer cost requirements, the offer is adapted and redundancy is removed. For example, imagining the above scenario of the fuel pump, the initial offer quoted to the customer could have a two-pump fuel station, but the customer requested to reduce the offer price, so the final offer was reduced to include only a single-pump station, thus losing the so valuable stand-by equipment.

Below are pictures of a real case situation, where the customer didn't have supplementary stand-by equipment and all the production had to be stopped because of a problem with the fuel pump that supplies the steam boiler. After a diagnostic performed by the service engineer, it was concluded that the customer did not performed any significant preventive maintenance actions in the system. The figures below show some parts before and after the service engineer intervention. It becomes evident the degree of griminess that the equipment was acquiring due to lack of attention given to it.

Figure 5.3 shows the burner mixing head completely covered in unburnt fuel. It is evident that it is not in an acceptable condition to perform a reliable operation.

Figure 5.3 Burner mixing head without proper maintenance

Figure 5.4 shows the burner mixing head after being cleaned during maintenance work from the service engineer that was requested to be on site.

Figure 5.4 Burner mixing head after maintenance work

Figure 5.5 below shows the flame tubes from the steam boiler also in an unacceptable condition. It is possible to see in the picture the high degree of obstruction due to the soot accumulation in the tubes. The source of this problem was the combination of using a different quality fuel with a burner that was not adjusted to use a fuel with those properties.

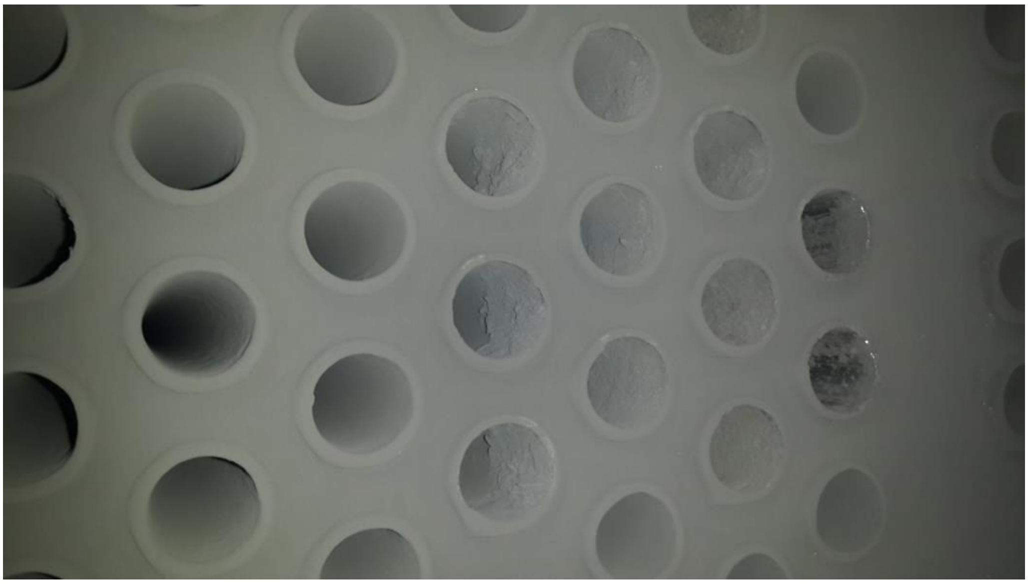


Figure 5.5 Flame tubes without proper maintenance

Figure 5.6 shows the same flame tubes after being cleaned during maintenance work from the service engineer that was requested to be on site.

Figure 5.6 Flame tubes after maintenance work

As could be seen in this case, improper maintenance of the steam system, as well as lack of redundancy of the system led to the breakdown of the entire production of the factory. In Africa, this is an extremely important matter due to the lack of availability of service and spare parts. Customers, during the planning of steam systems should be well informed about the advantages of the increased availability that the use of supplementary stand-by equipment offers, and should be encouraged on acquiring such solutions. Preventive maintenance solutions such as maintenance contracts should also be implemented to provide a higher degree of downtime prevention.

6 Development of Improvement Proposals

6.1 Remote Predictive Maintenance Solution

It is found that usually in Africa most companies do not apply proper predictive and preventive maintenance actions. An exception can be seen when looking at multinational companies which normally follow the operation procedures used globally by the company.

Predictive maintenance is less frequently seen in Africa due to the lack of availability of technologies needed for these procedures, which are often very sophisticated and technology driven, requiring highly qualified operators. For that reason, it is necessary to find other approaches that can help fulfil this need without requiring the need of sophisticated tools.

TRIZ methodology can be applied with the objective of finding what other innovative solutions can be developed in order to provide further predictive and preventive maintenance actions in Africa.

With the purpose of creating proposals to further improve the tools used by the company in Africa, and with the objective of obtaining a method to perform additional actions remotely, which is one of the most efficient ways to provide a specialized service to a very large region, one of TRIZ tools can be used, namely, the Contradiction Matrix.

In order to use this tool to obtain a remote solution, improving and worsening features must be identified. In this case improving feature 35 (adaptability or versatility) and worsening feature 37 (difficulty of detecting and measuring) were selected. Improving feature 35 was selected because, in the case study, the company is operating in the whole African continent. As a consequence of the vast territory it has to cover, new solutions must be found. This solutions must be versatile and allow to keep control of operations even at a distance.

With the versatility that is needed, there is a worsening feature, which is the difficulty of obtaining information remotely (difficulty of detecting and measuring).

Using the Contradiction Matrix, as shown in Figure 6.1, it is possible to find the inventive principle that may solve the problem: inventive principle 1 (segmentation).

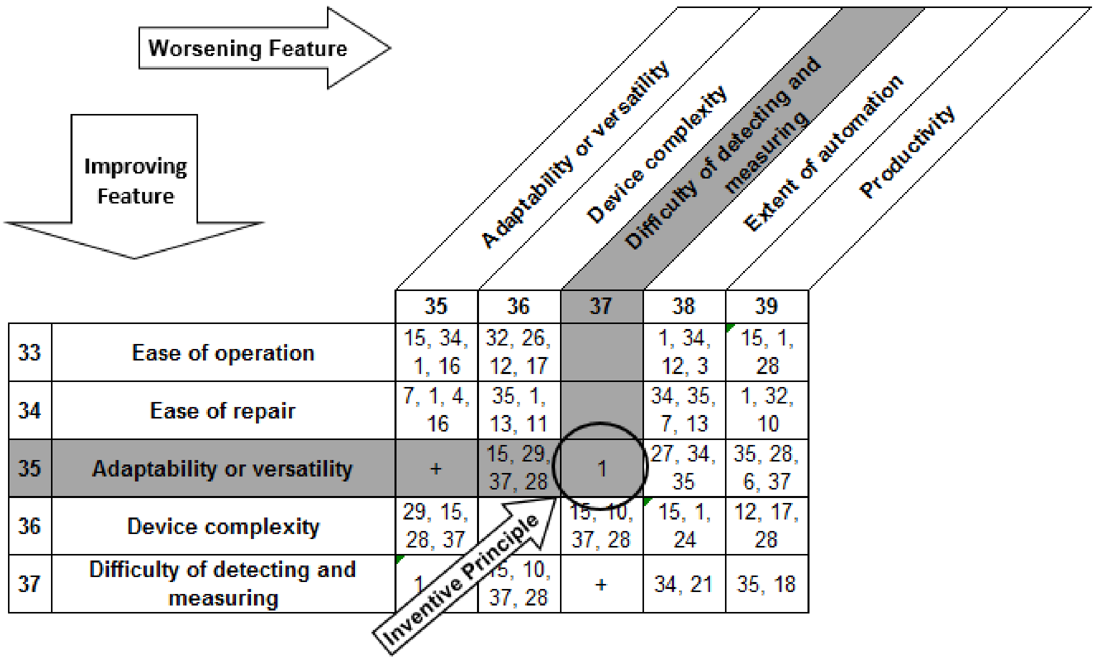


Figure 6.1 Contradiction matrix for case A

Through inventive principle 1, segmentation, it becomes clear that a solution to be found must segment the information in order to provide a versatile solution without making the gathering of information too complicated.

To solve this problem, a tool already developed by Bosch, a Customer Relationship Management (CRM) tool, adapted to the industrial business needs in Africa, could be used and adapted to provide segmented information about maintenance actions that can be offered. This segmentation will allow Bosch to offer suitable predictive and preventive maintenance solutions in accordance to the customer needs.

The existing CRM tool offers the possibility to track every installed boiler system sold by the company in Africa, including: equipment model, capacity and age information. With this information, Service Engineers have the possibility to perform high value actions, such as:

- Contact customers in order to schedule a check-up visit to customer facilities;
- Offer a maintenance contract adapted to customer needs;
- Advise the customer about the advantages of acquiring a MEC Remote service;
- Evaluate the boiler age, giving recommendations accordingly.

Figure 6.2 shows the main menu of the CRM tool that is currently being used by the company in Africa.

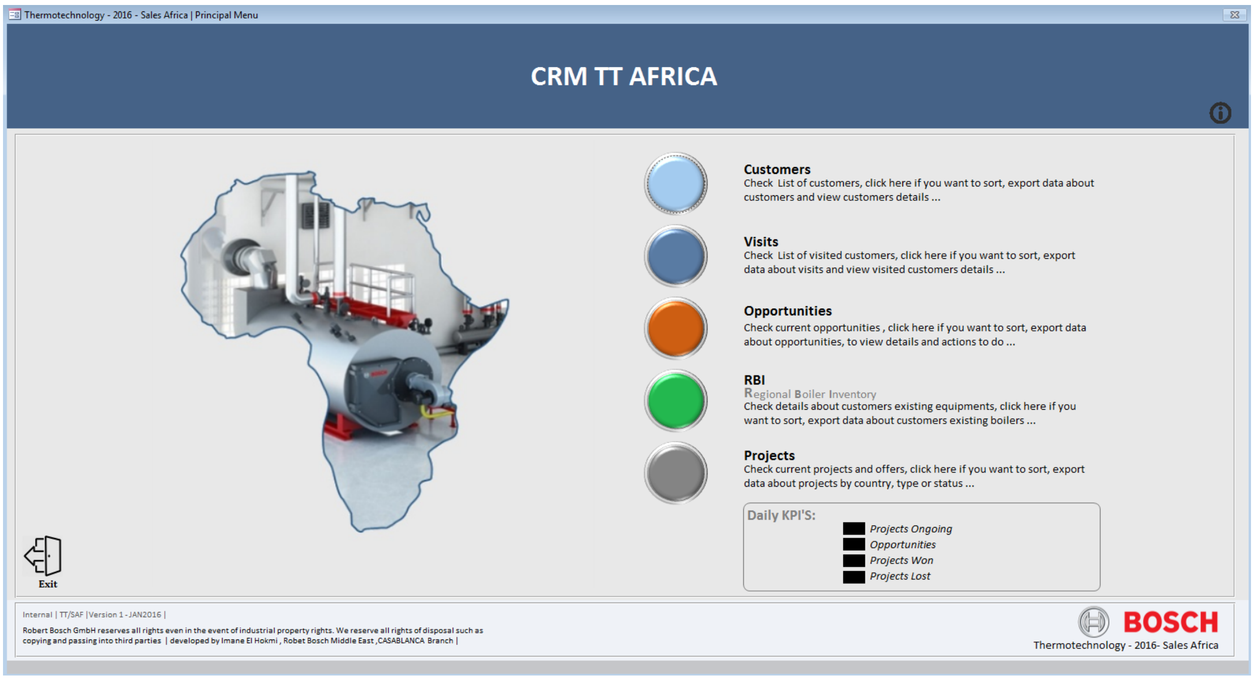
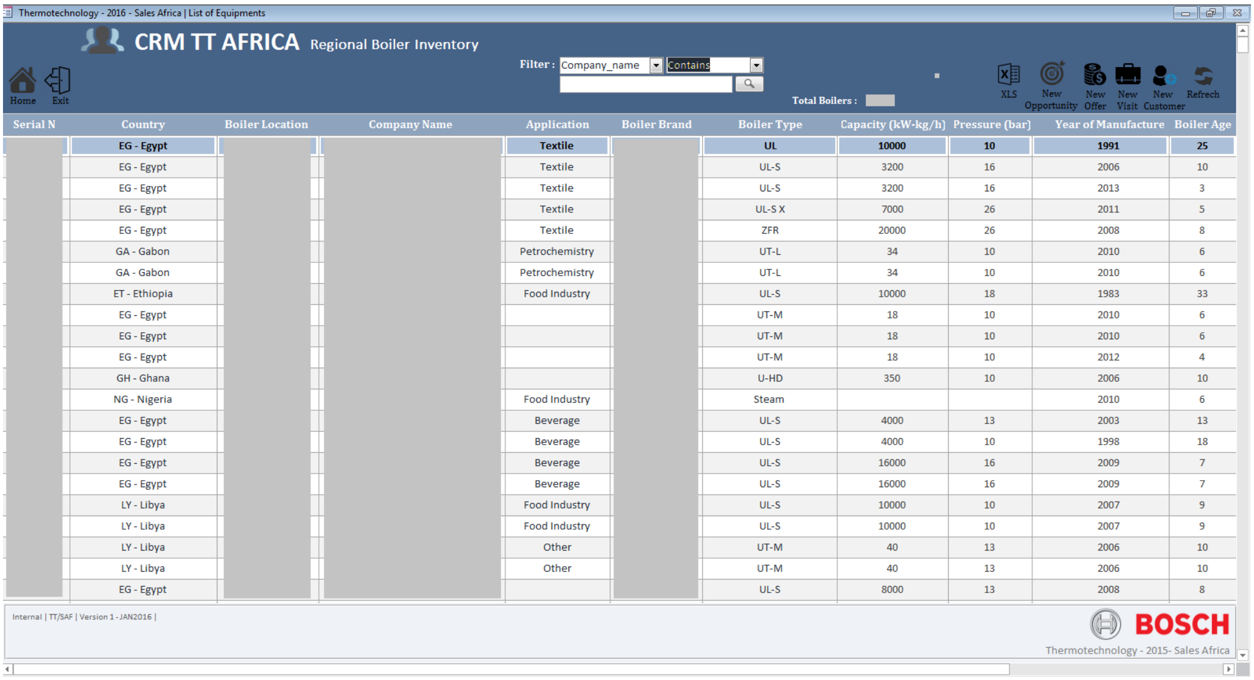


Figure 6.2 Main menu of the existing CRM [71]

Figure 6.3 shows the Boiler Inventory section of the CRM where it is possible to check for key information such as equipment model, capacity, age, location, and which industry application uses the equipment.



Serial N	Country	Boiler Location	Company Name	Application	Boiler Brand	Boiler Type	Capacity (kW-kg/h)	Pressure (bar)	Year of Manufacture	Boiler Age
	EG - Egypt			Textile		UL	10000	10	1991	25
	EG - Egypt			Textile		UL-S	3200	16	2006	10
	EG - Egypt			Textile		UL-S	3200	16	2013	3
	EG - Egypt			Textile		UL-S X	7000	26	2011	5
	EG - Egypt			Textile		ZFR	20000	26	2008	8
	GA - Gabon			Petrochemistry		UT-L	34	10	2010	6
	GA - Gabon			Petrochemistry		UT-L	34	10	2010	6
	ET - Ethiopia			Food Industry		UL-S	10000	18	1983	33
	EG - Egypt					UT-M	18	10	2010	6
	EG - Egypt					UT-M	18	10	2010	6
	EG - Egypt					UT-M	18	10	2012	4
	GH - Ghana					U-HD	350	10	2006	10
	NG - Nigeria			Food Industry		Steam			2010	6
	EG - Egypt			Beverage		UL-S	4000	13	2003	13
	EG - Egypt			Beverage		UL-S	4000	10	1998	18
	EG - Egypt			Beverage		UL-S	16000	16	2009	7
	EG - Egypt			Beverage		UL-S	16000	16	2009	7
	LY - Libya			Food Industry		UL-S	10000	10	2007	9
	LY - Libya			Food Industry		UL-S	10000	10	2007	9
	LY - Libya			Other		UT-M	40	13	2006	10
	LY - Libya			Other		UT-M	40	13	2006	10
	EG - Egypt					UL-S	8000	13	2008	8

Figure 6.3 Boiler inventory section of the existing CRM [71]

Figure 6.4 shows the Visits Report section of CRM. Here it is possible to keep a record of the visits made by the Sales Engineers to the customers. Information such as date of the visit, minutes of the meetings and opportunities that were identified during the visit can be introduced for each registered customer.

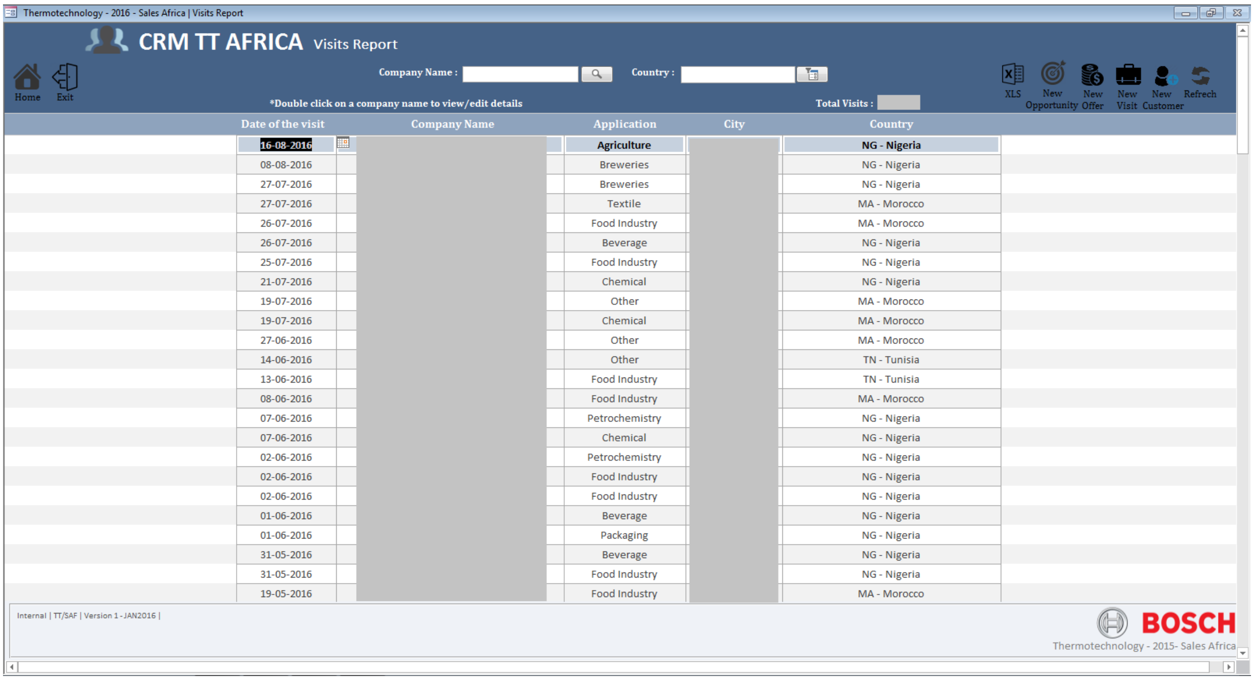


Figure 6.4 Visits report section of the existing CRM [71]

In order to improve the existing CRM to serve this new service solution adjustments must be made to provide segmented information about maintenance actions that can be offered; some additional features would need to be developed for the present tool. Below are the identified features:

1) The creation of a section for Service and Maintenance tracking where the user would be able to record and keep track of contacts made to the customer where he could posteriorly identify opportunities for maintenance activities;

2) A register log to record service activities that were provided to the customer in order to contact the customer when such activities need to be performed again. This activities include: maintenance contracts, periodic maintenances, and MEC remote subscription periods;

3) New columns in the boiler inventory section to keep track of Maintenance Contract and MEC Remote subscription expiration dates for each equipment installed;

4) A warning message to pop-up when a boiler has exceeded a predetermined lifetime, which can be a sign that the boiler needs special maintenance attention;

5) A warning message to pop-up in the system when a new opportunity appears. For instance when a customer maintenance contract or a MEC Remote subscription that was registered in CRM expires.

Figure 6.5 shows the improvement that was suggested in point 1) above. A new section named "Service Tracking" was added to the main menu which can be seen inside the red rectangle. In this section the user would be able to record and keep track of contacts made to the customer and posteriorly identify opportunities for maintenance activities.

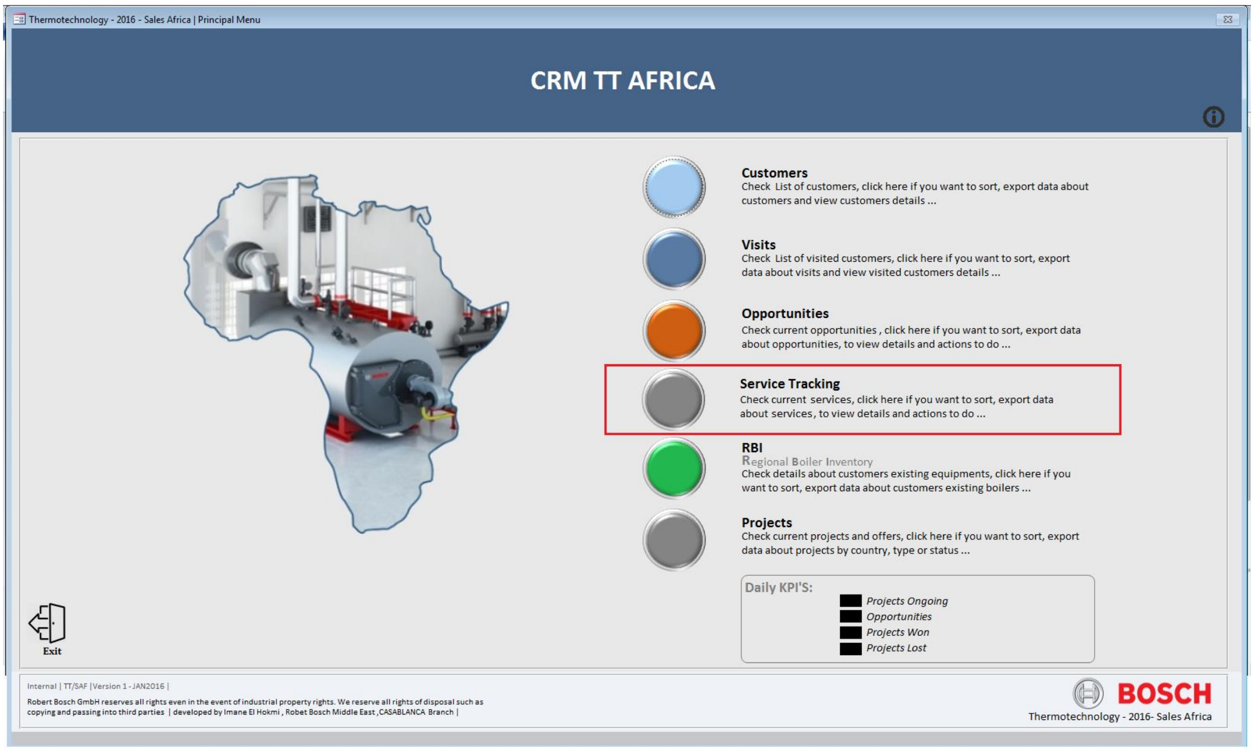


Figure 6.5 Improvement suggestion for the main menu of the CRM [71]

Figure 6.6 shows the improvement that was suggested in point 2). A new button named "New Service" was added to the visits report section which can be seen inside the red rectangle. This new button opens a register log where service activities that were provided to the customer can be recorded in order to contact the customer when such activities need to be performed again.

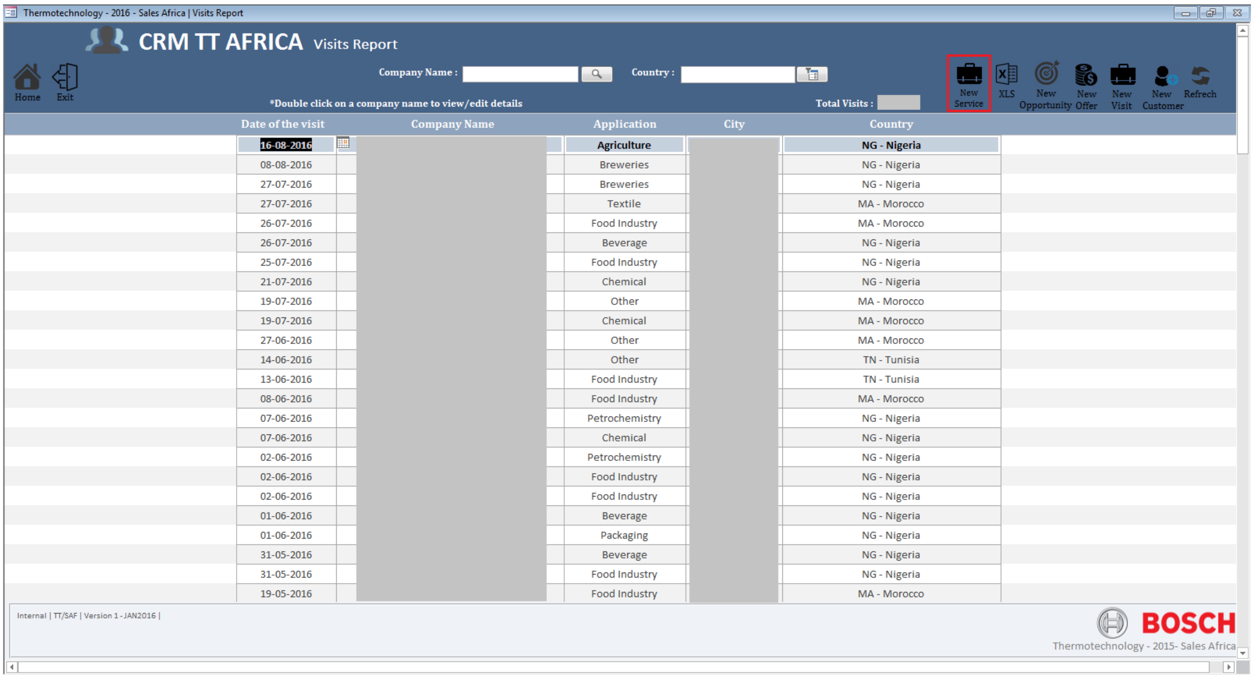
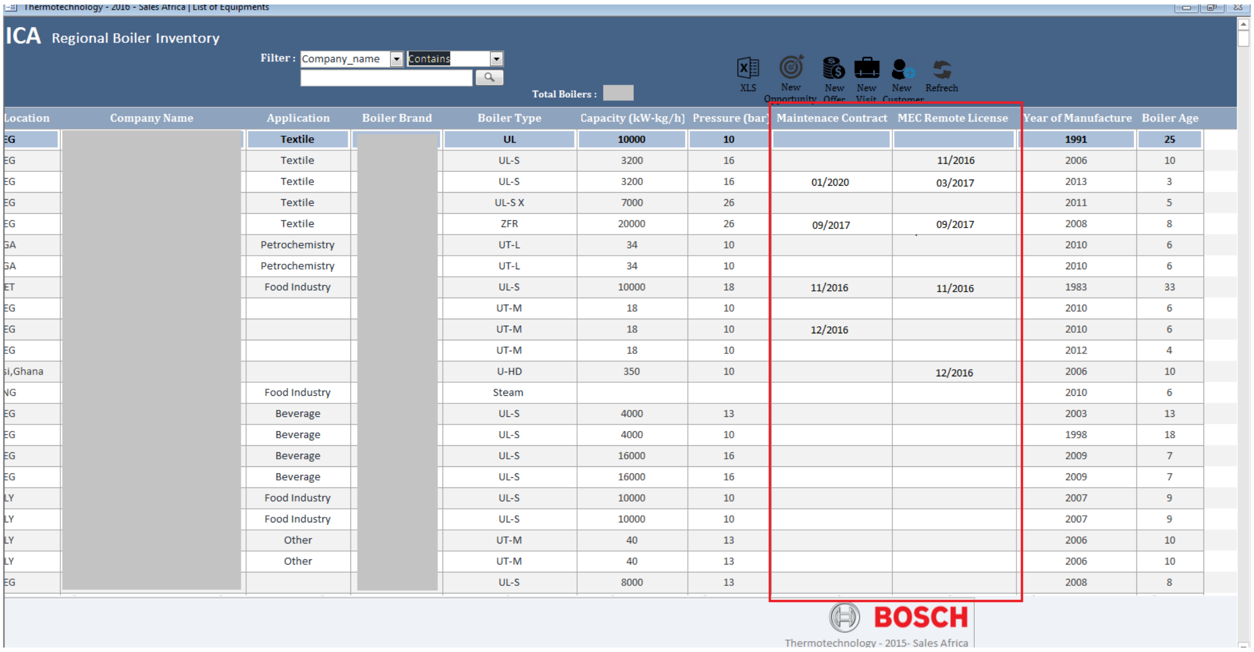


Figure 6.6 Improvement suggestion for the visits section of the CRM [71]

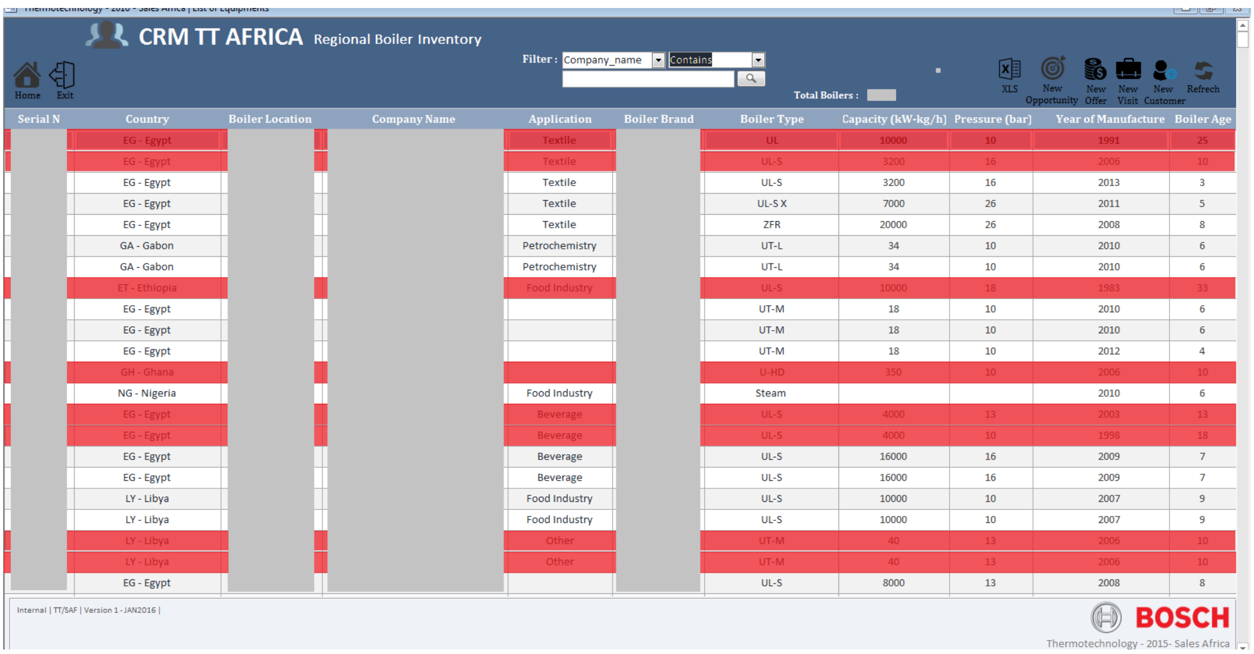
Figure 6.7 shows the improvements that were suggested in point 4). New columns were added in the boiler inventory section to keep track of Maintenance Contract and MEC Remote subscription expiration dates for each equipment installed. This columns can be seen inside the red rectangle.



Location	Company Name	Application	Boiler Brand	Boiler Type	Capacity (kW-kg/h)	Pressure (bar)	Maintenace Contract	MEC Remote License	Year of Manufacture	Boiler Age
EG		Textile		UL	10000	10			1991	25
EG		Textile		UL-S	3200	16		11/2016	2006	10
EG		Textile		UL-S	3200	16	01/2020	03/2017	2013	3
EG		Textile		UL-S X	7000	26			2011	5
EG		Textile		ZFR	20000	26	09/2017	09/2017	2008	8
GA		Petrochemistry		UT-L	34	10			2010	6
GA		Petrochemistry		UT-L	34	10			2010	6
ET		Food Industry		UL-S	10000	18	11/2016	11/2016	1983	33
EG				UT-M	18	10			2010	6
EG				UT-M	18	10	12/2016		2010	6
EG				UT-M	18	10			2012	4
i,Ghana				U-HD	350	10		12/2016	2006	10
NG		Food Industry		Steam					2010	6
EG		Beverage		UL-S	4000	13			2003	13
EG		Beverage		UL-S	4000	10			1998	18
EG		Beverage		UL-S	16000	16			2009	7
EG		Beverage		UL-S	16000	16			2009	7
LY		Food Industry		UL-S	10000	10			2007	9
LY		Food Industry		UL-S	10000	10			2007	9
LY		Other		UT-M	40	13			2006	10
LY		Other		UT-M	40	13			2006	10
EG				UL-S	8000	13			2008	8

Figure 6.7 Improvement suggestion for the boiler inventory section of the CRM [71]

Figure 6.8 shows the improvement that was suggested in point 4). The lines of the equipment that have exceeded a predetermined lifetime (in this case ten or more years) are highlighted in red. With this information the Service Engineer knows that the equipment might need special maintenance actions.



Serial N	Country	Boiler Location	Company Name	Application	Boiler Brand	Boiler Type	Capacity (kW-kg/h)	Pressure (bar)	Year of Manufacture	Boiler Age
	EG - Egypt			Textile		UL	10000	10	1991	25
	EG - Egypt			Textile		UL-S	3200	16	2006	10
	EG - Egypt			Textile		UL-S	3200	16	2013	3
	EG - Egypt			Textile		UL-S X	7000	26	2011	5
	EG - Egypt			Textile		ZFR	20000	26	2008	8
	GA - Gabon			Petrochemistry		UT-L	34	10	2010	6
	GA - Gabon			Petrochemistry		UT-L	34	10	2010	6
	ET - Ethiopia			Food Industry		UL-S	10000	18	1983	33
	EG - Egypt					UT-M	18	10	2010	6
	EG - Egypt					UT-M	18	10	2010	6
	EG - Egypt					UT-M	18	10	2012	4
	GH - Ghana					U-HD	350	10	2006	10
	NG - Nigeria			Food Industry		Steam			2010	6
	EG - Egypt			Beverage		UL-S	4000	13	2003	13
	EG - Egypt			Beverage		UL-S	4000	10	1998	18
	EG - Egypt			Beverage		UL-S	16000	16	2009	7
	EG - Egypt			Beverage		UL-S	16000	16	2009	7
	LY - Libya			Food Industry		UL-S	10000	10	2007	9
	LY - Libya			Food Industry		UL-S	10000	10	2007	9
	LY - Libya			Other		UT-M	40	13	2006	10
	LY - Libya			Other		UT-M	40	13	2006	10
	EG - Egypt					UL-S	8000	13	2008	8

Figure 6.8 Lines highlighted when a predetermined lifetime is reached [71]

The improvement that was suggested in point 5) follows the same principle as the one indicated in point 4). In this case the lines of the equipment that have a maintenance contract or MEC Remote subscription near the expiration date would be highlighted in red.

6.2 Maintenance Contract Improvement

One of the most demanding challenges companies face is equipment failure. Without a reliable maintenance program, this failure can become a reality that incurs high costs to the company.

Due to the lack of availability of spare parts and qualified workforce in Africa, systems can be down for even longer periods of time so it is important to deliver solutions adapted to this reality.

Substance-Field analysis can be used in order to identify problematic situations existent in the current maintenance contract and create specific solutions by analyzing the general solutions for those problematic situations.

A manufacturing facility that has a production line using steam is a great example of the importance of the proper operation of the steam boiler. If this production line is fully dependent on steam, and if the boiler has a problem and shuts-down, that can represent large production losses for the company. For that reason, it is very important to maximize the availability and reliably of the steam system. One of the best ways of doing so is to have the right maintenance program adapted for that particular system.

Looking at the situation where a maintenance contract adapted for the European market is used, where spare parts and qualified service are quickly available, one can conclude that those contracts are not as effective for the African market as they are for Europe. In this scenario, Problematic Situation 3 (insufficient or inefficient impact) occurs.

Figure 6.9 shows the Problematic Situation 3.

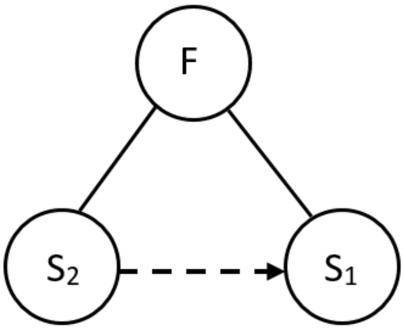


Figure 6.9 Problematic Situation 3 – insufficient or inefficient impact between the substances

In chapter 2.3.1 it was referred that the 76 pattern solutions could be condensed and generalized in seven general solutions. In this case the Substance-Field Model is complete, however the interaction between the substances is insufficient. This problematic situation can be solved using General Solution 4.

General Solution 4 consists of changing the existing field to reduce or eliminate harmful impact. Changing the existing field while keeping the same substances may be a choice to reduce or remove the harmful impact. The existing field can be increased, decreased, or completely removed and replaced by another.

Figure 6.10 shows General Solution 4.

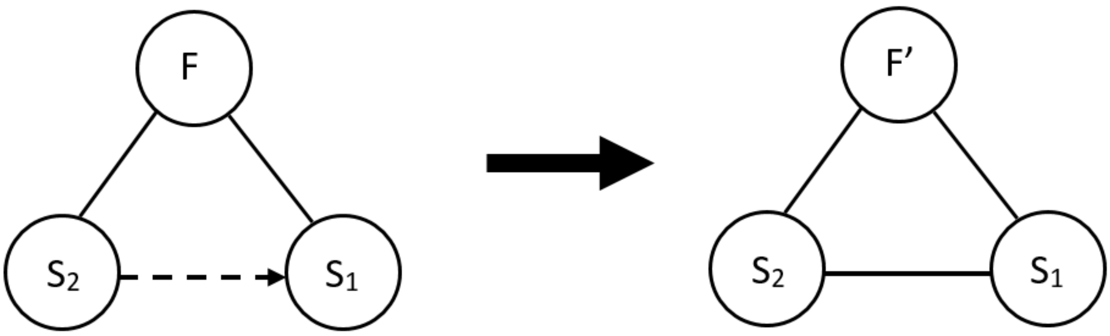


Figure 6.10 General Solution 4 for Problematic Situation 3

In this case the field F represents the maintenance contract, and this field needs to be improved in order to allow for the steam system (S_2) to perform a more reliable supply of steam to the process dependent on steam (S_1).

A possible specific solution would be the adaptation of the maintenance contracts to the African market by including a bigger package of spare parts to avoid the long delivery periods; by increasing qualified personnel availability, for instance by using a 24 hours service hot line directed specifically for African countries; and also by including MEC Remote subscription fee so that the customer can have remote support in case of necessity.

The development of this improved maintenance contract was accomplished during the trainee program and an excerpt of the final result can be seen in Appendix C.

6.3 System Availability Improvement

Service actions in Africa have shown that most problems aroused in installed steam systems could have been minimized or even avoided if a better planning of installations would have been made.

During planning of steam systems in Africa, it is necessary to take into account that lead times required to supply service and spare parts in African countries is much higher than usual due to the lack of local availability of such commodities. For that reason, it is necessary to plan and design a system that is able to comply with production needs even when a problem appears in the system. The failure to do so can incur in extremely high losses to the company.

Looking at the scenario of the fuel pump failure mentioned in chapter 5.2, where a failure occurs and a second pump is not readily available to continue the operation of the steam system, leading to the breakdown of the complete system; Substance-Field analysis can be applied in order to show how the system availability can be improved with the addition of redundancy.

In the above scenario, problematic situation 2 (harmful interactions between the substances) takes place.

Figure 6.11 shows the problematic situation.

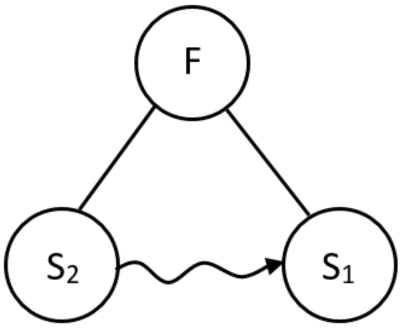


Figure 6.11 Problematic situation 2 – harmful interaction between the substances

In Problematic Situation 2, the Substance-Field Model is complete, however the interaction between the substances is harmful. This problematic situation can be solved using General Solution 6.

For this situation, the field F represents the single fuel pump station, which is causing a harmful interaction between the substances S_2, defective steam system, and $S_{1,}$ process dependent on steam. An additional field needs to be added in order to solve this problem.

General Solution 6 suggests the introduction of field F_x^+ that will work with the existing field F in order to increase the useful effect and reduce the negative effect of the existing system without modifying all other elements. Figure 6.12 shows General Solution 6.

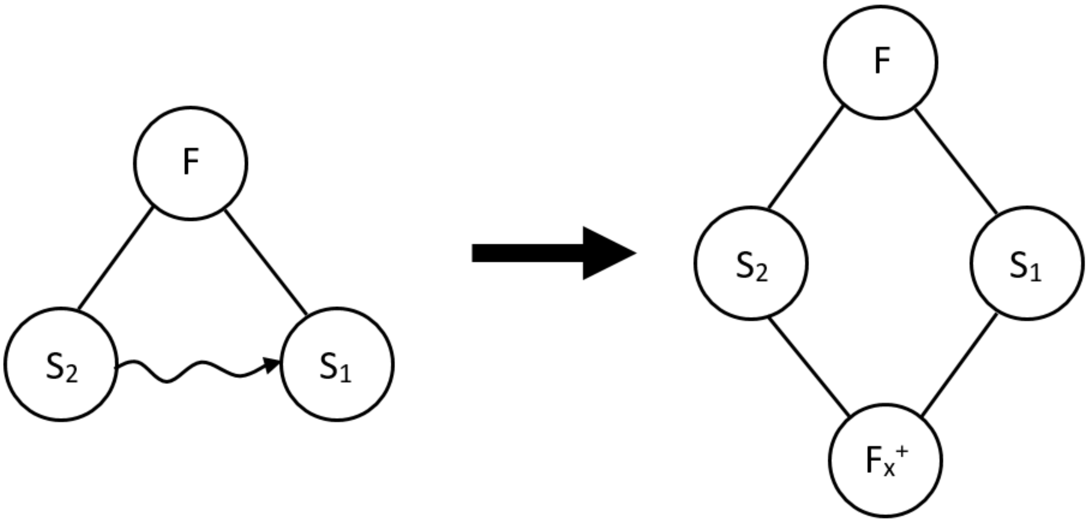


Figure 6.12 General Solution 6 for the problematic situation

A possible specific solution would be the installation of a second fuel pump to be used as a supplementary stand-by equipment. With this action a positive effect would be added to the system. The useful effect of the second pump would be the redundancy of the system, and the negative effect existing in the system (lack of redundancy) would be reduced.

6.4 System Efficiency Improvement

Sometimes in Africa, when acquiring new equipment for the plants, managers opt for cheaper products based only on price decision instead of making a deep life cycle cost analysis of the long term benefits of the more expensive solutions.

Taking into consideration what was mention above, the following scenario was studied: a manager acquired a low efficient system without proper insulation and no condensate recovery. After realizing that the cheapest solution that he had acquired had significant energy losses he wanted to implement energy efficiency improvements on the system.

Substance-Field analysis can be used in order to identify problematic situations existent in the current steam system and create specific solutions by analyzing the general solutions for those problematic situations.

Looking at the problem, Problematic Situation 3 can be identified, where insufficient or inefficient impact occurs (as seen previously in Figure 6.9), thus making the substance-field model insufficient.

For this situation, field F represents the insulation of the system, and this field needs to be improved in order to allow for the steam system (S_2) to perform a more efficient supply of steam to the steam process (S_1).

This problematic situation can be solved by using General Solution 4, also used in chapter 6.2 and can be seen below in Figure 6.13.

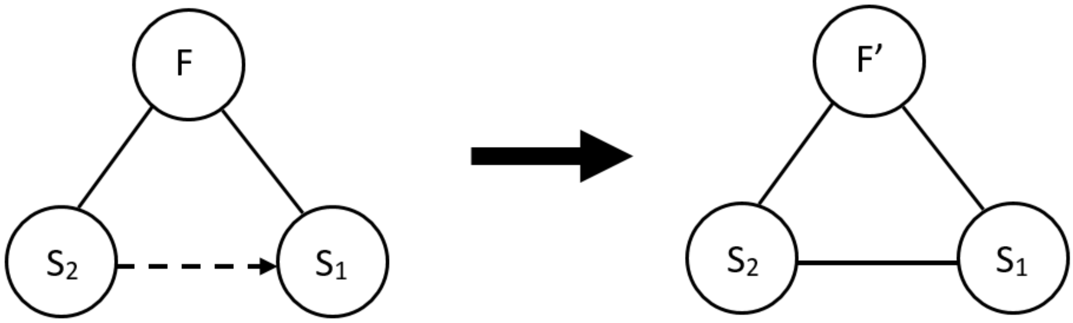


Figure 6.13 General Solution 4 for the problematic situation

A possible specific solution would be to increase the amount and quality of the insulation, proper insulation can reduce energy losses by up to 90% and help ensure proper steam pressure at the plant.

If the objective is to improve even further the energy efficiency of the system, Problematic Situation 3 can be applied again. This problematic situation can be solved by using General Solution 7.

General Solution 7 consists on expanding the existing Substance-Field model to a chain by introducing a new substance S_3 to the system.

Figure 6.14 shows General Solution 7.

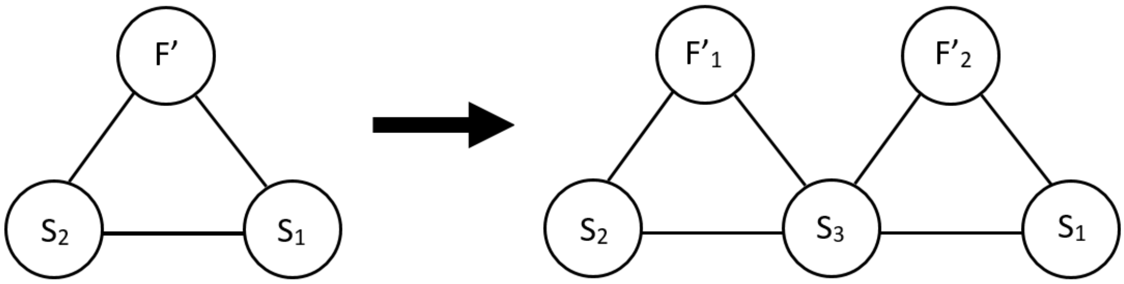


Figure 6.14 General Solution 7 for Problematic Situation 3

In this case, field F'_1 and F'_2 represent the improved insulation of the system, and a new substance (S3) needs to be introduced in order to allow for the steam system (S_2) to perform an even more efficient supply of steam to the steam process (S_1). With this solution the Substance-Field model becomes a chain.

A possible specific solution for this situation would be the installation of a condensate recovery system to recover the condensate. This measure would improve considerably the efficiency of the system by reducing heat losses and water consumption.

7 Conclusions and Future Developments

Throughout the experience of one year trainee program in Bosch, it was perceptible that certain maintenance services provided by the company to Africa could be modified to meet even further the needs of the market. After investigating the issues of equipment availability in Africa, it was clear the importance of redundant solutions to increase inherent availability of the systems in a continent where frequently spare parts and qualified workforce are scarce.

Systems without stand-by equipment greatly increase the probability of an availability problem. In Africa, due to logistic difficulties on the acquisition of spare parts and qualified workforce, systems can be down for long periods of time so it is important to deliver solutions adapted to this reality. Nevertheless to achieve the advised availability customers must be willing to acquire such redundant solutions.

The work developed in this dissertation had the objective of developing improvement proposals for the problems identified throughout the trainee program in Bosch. TRIZ methodology being a reliable and innovative approach that can be used repeatedly and consistently to quicken the ability of teams to solve problems is the right methodology for the development of this proposals.

TRIZ methodology offers several tools that can be used to create improvement solutions. As such, Contradiction Matrix was one of the tools used to develop these proposals. With the objective of increasing the aptitude of Bosch to actuate efficiently in the vast regions of Africa, a method to perform additional actions remotely was proposed.

This solution allows the implementation of preventive and predictive maintenance actions remotely, which is one of the most efficient ways to provide a specialized service to areas with very difficult access.

Substance-Field analysis, another tool of TRIZ methodology, was also used with the objective of solving the problematic situations identified in several improvement points discussed in chapter 5.2.

Three different proposals were created using Substance-Field analysis:

First, the adaptation of the existing maintenance contract, which was designed to the European market, to the African market. This was accomplished by identifying the problematic situation existent in the maintenance contract and creating specific solutions by analyzing the general solutions for those problems. The specific solutions proposed were the inclusion of a bigger package of spare parts to avoid the long delivery periods; the increase of qualified personnel availability, by creating a 24 hours service hot line targeted specifically to African countries; and also by including MEC Remote subscription fee so that customers can have remote support.

The new maintenance contract to the African market was created during the trainee program in Bosch and an excerpt of the final result can be seen in Appendix C.

Second, the use of supplementary stand-by equipment in order to improve system availability. Bad installation planning by the customer was the problematic situation identified, more specifically, the lack of an additional fuel pump to be used as a stand-by equipment. Substance-Field analysis was then used to show how equipment inherent availability could be improved with the addition of such supplementary equipment that provides a higher degree of redundancy to the system.

Third, the efficiency increase of a steam system in order to reduce energy losses. With the problematic situation identified (high energy losses of the system), general situations were analyzed and specific solutions were created for that particular scenario. The specific proposals for the efficiency increase of the system were the addition of more quantity of insulation and the installation of a condensate recovery system.

The implementation of the improvement proposals mentioned above, represent great benefits, and a financial opportunity for Bosch and for customers. The introduction of the improvement proposals in the current CRM and the use of the improved maintenance contract, fitter to Africa would allow the company to strengthen the relationships and trust of customers. Customers would feel confidant using Bosch solutions knowing that service would always be available no matter where they are.

The use of more redundant solutions by the customer means more equipment inherent availability, and in the long term, by adding that with the reliability and efficiency of solutions offered by Bosch, as well as with the service activities that the company is able to provide in Africa, means that the amount of system downtime can be expressively lowered.

Analyzing the proposals created and described in this dissertation, and looking at the benefits they offer, it is possible to conclude that future developments could be performed in accordance with these proposals. As such, the next steps to be accomplished would be the implementation of the referred proposals to further increase the presence and attractiveness of Bosch in Africa.

The education of the market for the importance of actions already vastly accepted and implemented in Europe remains a challenge in Africa. The addition of the most important concepts discussed in this dissertation, such as the advantages of availability, efficiency, and the importance of preventive and predictive maintenance, into to the training program used by Bosch Service Engineers when training operators in Africa.

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ANSI/NB-23 National Board of Boiler and Pressure Vessel Inspections, National Board Inspection Code

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Appendix

Appendix A

Table A.1 Contradiction Matrix [72]

	Worsening engineer feature												
Improving engineer features	1	2	3	4	5	6	7	8	9	10	11	12	13
1		-	15, 8, 29,34	-	29, 17, 38, 34	-	29, 2, 40, 28	-	2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39
2	-		-	10, 1, 29, 35	-	35, 30, 13, 2	-	5, 35, 14, 2	-	8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40
3	8, 15, 29, 34	-		-	15, 17, 4	-	7, 17, 4, 35	-	13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34
4	-	35, 28, 40, 29	-		-	17, 7, 10, 40	-	35, 8, 2,14	-	28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35
5	2, 17, 29, 4	-	14, 15, 18, 4	-		-	7, 14, 17, 4	-	29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39
6	-	30, 2, 14, 18	-	26, 7, 9, 39	-		-	-	-	1, 18, 35, 36	10, 15, 36, 37	-	2, 38
7	2, 26, 29, 40	-	1, 7, 4, 35	-	1, 7, 4, 17	-		-	29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39
8	-	35, 10, 19, 14	19, 14	35, 8, 2, 14	-	-	-		-	2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40
9	2, 28, 13, 38	-	13, 14, 8	-	29, 30, 34	-	7, 29, 34	-		13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18
10	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12		18, 21, 11	10, 35, 40, 34	35, 10, 21
11	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21		35, 4, 15, 10	35, 33, 2, 40
12	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10	-	14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14		33, 1, 18, 4
13	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4	
14	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 18, 3, 14	10, 3, 18, 40	10, 30, 35, 40	13, 17, 35
15	19, 5, 34, 31	-	2, 19, 9	-	3, 17, 19	-	10, 2, 19, 30	-	3, 35, 5	19, 2, 16	19, 3, 27	14, 26, 28, 25	13, 3, 35
16	-	6, 27, 19, 16	-	1, 40, 35	-	-	-	35, 34, 38	-	-	-	-	39, 3, 35, 23
17	36,22, 6, 38	22, 35, 32	15, 19, 9	15, 19, 9	3, 35, 39, 18	35, 38	34, 39, 40, 18	35, 6, 4	2, 28, 36, 30	35, 10, 3, 21	35, 39, 19, 2	14, 22, 19, 32	1, 35, 32
18	19, 1, 32	2, 35, 32	19, 32, 16	-	19, 32, 26	-	2, 13, 10	-	10, 13, 19	26, 19, 6	-	32, 30	32, 3, 27
19	12,18, 28,31	-	12, 28	-	15, 19, 25	-	35, 13, 18	-	8, 35, 35	16, 26, 21, 2	23, 14, 25	12, 2, 29	19, 13, 17, 24
20	-	19, 9, 6, 27	-	-	-	-	-	-	-	36, 37	-	-	27, 4, 29, 18
21	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37	-	19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	15, 35, 2	26, 2, 36, 35	22, 10, 35	29, 14, 2, 40	35, 32, 15, 31
22	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	16, 35, 38	36, 38	-	-	14, 2, 39, 6
23	35, 6, 23, 40	35, 6, 22, 32	14, 29, 10, 39	10, 28,24	35, 2, 10, 31	10, 18, 39, 31	1, 29, 30, 36	3, 39, 18, 31	10, 13, 28, 38	14, 15, 18, 40	3, 36, 37, 10	29, 35, 3, 5	2, 14, 30, 40
24	10, 24, 35	10, 35, 5	1, 26	26	30, 26	30, 16	-	2, 22	26, 32	-	-	-	-
25	10, 20, 37, 35	10, 20, 26, 5	15, 2, 29	30, 24, 14, 5	26, 4, 5, 16	10, 35, 17, 4	2, 5, 34, 10	35, 16, 32, 18	-	10, 37, 36,5	37, 36,4	4, 10, 34, 17	35, 3, 22, 5
26	35, 6, 18, 31	27, 26, 18, 35	29, 14, 35, 18	-	15, 14, 29	2, 18, 40, 4	15, 20, 29	-	35, 29, 34, 28	35, 14, 3	10, 36, 14, 3	35, 14	15, 2, 17, 40
27	3, 8, 10, 40	3, 10, 8, 28	15, 9, 14, 4	15, 29, 28, 11	17, 10, 14, 16	32, 35, 40, 4	3, 10, 14, 24	2, 35, 24	21, 35, 11, 28	8, 28, 10, 3	10, 24, 35, 19	35, 1, 16, 11	-
28	32, 35, 26, 28	28, 35, 25, 26	28, 26, 5, 16	32, 28, 3, 16	26, 28, 32, 3	26, 28, 32, 3	32, 13, 6	-	28, 13, 32, 24	32, 2	6, 28, 32	6, 28, 32	32, 35, 13
29	28, 32, 13, 18	28, 35, 27, 9	10, 28, 29, 37	2, 32, 10	28, 33, 29, 32	2, 29, 18, 36	32, 23, 2	25, 10, 35	10, 28, 32	28, 19, 34, 36	3, 35	32, 30, 40	30, 18
30	22, 21, 27, 39	2, 22, 13, 24	17, 1, 39, 4	1, 18	22, 1, 33, 28	27, 2, 39, 35	22, 23, 37, 35	34, 39, 19, 27	21, 22, 35, 28	13, 35, 39, 18	22, 2, 37	22, 1, 3, 35	35, 24, 30, 18
31	19, 22, 15, 39	35, 22, 1, 39	17, 15, 16, 22	-	17, 2, 18, 39	22, 1, 40	17, 2, 40	30, 18, 35, 4	35, 28, 3, 23	35, 28, 1, 40	2, 33, 27, 18	35, 1	35, 40, 27, 39
32	28, 29, 15, 16	1, 27, 36, 13	1, 29, 13, 17	15, 17, 27	13, 1, 26, 12	16, 40	13, 29, 1, 40	35	35, 13, 8, 1	35, 12	35, 19, 1, 37	1, 28, 13, 27	11, 13, 1
33	25, 2, 13, 15	6, 13, 1, 25	1, 17, 13, 12	-	1, 17, 13, 16	18, 16, 15, 39	1, 16, 35, 15	4, 18, 39, 31	18, 13, 34	28, 13 35	2, 32, 12	15, 34, 29, 28	32, 35, 30
34	2, 27 35, 11	2, 27, 35, 11	1, 28, 10, 25	3, 18, 31	15, 13, 32	16, 25	25, 2, 35, 11	1	34, 9	1, 11, 10	13	1, 13, 2, 4	2, 35
35	1, 6, 15, 8	19, 15, 29, 16	35, 1, 29, 2	1, 35, 16	35, 30, 29, 7	15, 16	15, 35, 29	-	35, 10, 14	15, 17, 20	35, 16	15, 37, 1, 8	35, 30, 14
36	26, 30, 34, 36	2, 26, 35, 39	1, 19, 26, 24	26	14, 1, 13, 16	6, 36	34, 26, 6	1, 16	34, 10, 28	26, 16	19, 1, 35	29, 13, 28, 15	2, 22, 17, 19
37	27, 26, 28, 13	6, 13, 28, 1	16, 17, 26, 24	26	2, 13, 18, 17	2, 39, 30, 16	29, 1, 4, 16	2, 18, 26, 31	3, 4, 16, 35	30, 28, 40, 19	35, 36, 37, 32	27, 13, 1, 39	11, 22, 39, 30
38	28, 26, 18, 35	28, 26, 35, 10	14, 13, 17, 28	23	17, 14, 13	-	35, 13, 16	-	28, 10	2, 35	13, 35	15, 32, 1, 13	18, 1
39	35, 26, 24, 37	28, 27, 15, 3	18, 4, 28, 38	30, 7, 14, 26	10, 26, 34, 31	10, 35, 17, 7	2, 6, 34, 10	35, 37, 10, 2	-	28, 15, 10, 36	10, 37, 14	14, 10, 34, 40	35, 3, 22, 39

Table A.1 Contradiction Matrix (continuation) [72]

Improving engineer features	Worsening engineer feature												
	14	15	16	17	18	19	20	21	22	23	24	25	26
1	28, 27, 18, 40	5, 34, 31, 35	-	6, 29, 4, 38	19, 1, 32	35, 12, 34, 31	-	12, 36, 18, 31	6, 2, 34, 19	5, 35, 3, 31	10, 24, 35	10, 35, 20, 28	3, 26, 18, 31
2	28, 2, 10, 27	-	2, 27, 19, 6	28, 19, 32, 22	19, 32, 35	-	18, 19, 28, 1	15, 19, 18, 22	18, 19, 28, 15	5, 8, 13, 30	10, 15, 35	10, 20, 35, 26	19, 6, 18, 26
3	8, 35, 29, 34	19	-	10, 15, 19	32	8, 35, 24	-	1, 35	7, 2, 35, 39	4, 29, 23, 10	1, 24	15, 2, 29	29, 35
4	15, 14, 28, 26	-	1, 10, 35	3, 35, 38, 18	3, 25	-	-	12, 8	6, 28	10, 28, 24, 35	24, 26,	30, 29, 14	-
5	3, 15, 40, 14	6, 3	-	2, 15, 16	15, 32, 19, 13	19, 32	-	19, 10, 32, 18	15, 17, 30, 26	10, 35, 2, 39	30, 26	26, 4	29, 30, 6, 13
6	40	-	2, 10, 19, 30	35, 39, 38	-	-	-	17, 32	17, 7, 30	10, 14, 18, 39	30, 16	10, 35, 4, 18	2, 18, 40, 4
7	9, 14, 15, 7	6, 35, 4	-	34, 39, 10, 18	2, 13, 10	35	-	35, 6, 13, 18	7, 15, 13, 16	36, 39, 34, 10	2, 22	2, 6, 34, 10	29, 30, 7
8	9, 14, 17, 15	-	35, 34, 38	35, 6, 4	-	-	-	30, 6	-	10, 39, 35, 34	-	35, 16, 32 18	35, 3
9	8, 3, 26, 14	3, 19, 35, 5	-	28, 30, 36, 2	10, 13, 19	8, 15, 35, 38	-	19, 35, 38, 2	14, 20, 19, 35	10, 13, 28, 38	13, 26	-	10, 19, 29, 38
10	35, 10, 14, 27	19, 2	-	35, 10, 21	-	19, 17, 10	1, 16, 36, 37	19, 35, 18, 37	14, 15	8, 35, 40, 5	-	10, 37, 36	14, 29, 18, 36
11	9, 18, 3, 40	19, 3, 27	-	35, 39, 19, 2	-	14, 24, 10, 37	-	10, 35, 14	2, 36, 25	10, 36, 3, 37	-	37, 36, 4	10, 14, 36
12	30, 14, 10, 40	14, 26, 9, 25	-	22, 14, 19, 32	13, 15, 32	2, 6, 34, 14	-	4, 6, 2	14	35, 29, 3, 5	-	14, 10, 34, 17	36, 22
13	17, 9, 15	13, 27, 10, 35	39, 3, 35, 23	35, 1, 32	32, 3, 27, 16	13, 19	27, 4, 29, 18	32, 35, 27, 31	14, 2, 39, 6	2, 14, 30, 40	-	35, 27	15, 32, 35
14		27, 3, 26	-	30, 10, 40	35, 19	19, 35, 10	35	10, 26, 35, 28	35	35, 28, 31, 40	-	29, 3, 28, 10	29, 10, 27
15	27, 3, 10		-	19, 35, 39	2, 19, 4, 35	28, 6, 35, 18	-	19, 10, 35, 38	-	28, 27, 3, 18	10	20, 10, 28, 18	3, 35, 10, 40
16	-	-		19, 18, 36, 40	-	-	-	16	-	27, 16, 18, 38	10	28, 20, 10, 16	3, 35, 31
17	10, 30, 22, 40	19, 13, 39	19, 18, 36, 40		32, 30, 21, 16	19, 15, 3, 17	-	2, 14, 17, 25	21, 17, 35, 38	21, 36, 29, 31	-	35, 28, 21, 18	3, 17, 30, 39
18	35, 19	2, 19, 6	-	32, 35, 19		32, 1, 19	32, 35, 1, 15	32	13, 16, 1, 6	13, 1	1, 6	19, 1, 26, 17	1, 19
19	5, 19, 9, 35	28, 35, 6, 18	-	19, 24, 3, 14	2, 15, 19		-	6, 19, 37, 18	12, 22, 15, 24	35, 24, 18, 5		35, 38, 19, 18	34, 23, 16, 18
20	35	-	-	-	19, 2, 35, 32	-		-	-	28, 27, 18, 31	-	-	3, 35, 31
21	26, 10, 28	19, 35, 10, 38	16	2, 14, 17, 25	16, 6, 19	16, 6, 19, 37	-		10, 35, 38	28, 27, 18, 38	10, 19	35, 20, 10, 6	4, 34, 19
22	26	-	-	19, 38, 7	1, 13, 32, 15	-	-	3, 38		35, 27, 2, 37	19, 10	10, 18, 32, 7	7, 18, 25
23	35, 28, 31, 40	28, 27, 3, 18	27, 16, 18, 38	21, 36, 39, 31	1, 6, 13	35, 18, 24, 5	28, 27, 12, 31	28, 27, 18, 38	35, 27, 2, 31		-	15, 18, 35, 10	6, 3, 10, 24
24	-	10	10	-	19	-	-	10, 19	19, 10	-		24, 26, 28, 32	24, 28, 35
25	29, 3, 28, 18	20, 10, 28, 18	28, 20, 10, 16	35, 29, 21, 18	1, 19, 26, 17	35, 38, 19, 18	1	35, 20, 10, 6	10, 5, 18, 32	35, 18, 10, 39	24, 26, 28, 32		35, 38, 18, 16
26	14, 35, 34, 10	3, 35, 10, 40	3, 35, 31	3, 17, 39	-	34, 29, 16, 18	3, 35, 31	35	7, 18, 25	6, 3, 10, 24	24, 28, 35	35, 38, 18, 16	
27	11, 28	2, 35, 3, 25	34, 27, 6, 40	3, 35, 10	11, 32, 13	21, 11, 27, 19	36, 23	21, 11, 26, 31	10, 11, 35	10, 35, 29, 39	10, 28	10, 30, 4	21, 28, 40, 3
28	28, 6, 32	28, 6, 32	10, 26, 24	6, 19, 28, 24	6, 1, 32	3, 6, 32	-	3, 6, 32	26, 32, 27	10, 16, 31, 28	-	24, 34, 28, 32	2, 6, 32
29	3, 27	3, 27, 40	-	19, 26	3, 32	32, 2	-	32, 2	13, 32, 2	35, 31, 10, 24	-	32, 26, 28, 18	32, 30
30	18, 35, 37, 1	22, 15, 33, 28	17, 1, 40, 33	22, 33, 35, 2	1, 19, 32, 13	1, 24, 6, 27	10, 2, 22, 37	19, 22, 31, 2	21, 22, 35, 2	33, 22, 19, 40	22, 10, 2	35, 18, 34	35, 33, 29, 31
31	15, 35, 22, 2	15, 22, 33, 31	21, 39, 16, 22	22, 35, 2, 24	19, 24, 39, 32	2, 35, 6	19, 22, 18	2, 35, 18	21, 35, 2, 22	10, 1, 34	10, 21, 29	1, 22	3, 24, 39, 1
32	1, 3, 10, 32	27, 1, 4	35, 16	27, 26, 18	28, 24, 27, 1	28, 26, 27, 1	1, 4	27, 1, 12, 24	19, 35	15, 34, 33	32, 24, 18, 16	35, 28, 34, 4	35, 23, 1, 24
33	32, 40, 3, 28	29, 3, 8, 25	1, 16, 25	26, 27, 13	13, 17, 1, 24	1, 13, 24	-	35, 34, 2, 10	2, 19, 13	28, 32, 2, 24	4, 10, 27, 22	4, 28, 10, 34	12, 35
34	11, 1, 2, 9	11, 29, 28, 27	1	4, 10	15, 1, 13	15, 1, 28, 16	-	15, 10, 32, 2	15, 1, 32, 19	2, 35, 34, 27	-	32, 1, 10, 25	2, 28, 10, 25
35	35, 3, 32, 6	13, 1, 35	2, 16	27, 2, 3, 35	6, 22, 26, 1	19, 35, 29, 13	-	19, 1, 29	18, 15, 1	15, 10, 2, 13	-	35, 28	3, 35, 15
36	2, 13, 28	10, 4, 28, 15	-	2, 17, 13	24, 17, 13	27, 2, 29, 28	-	20, 19, 30, 34	10, 35, 13, 2	35, 10, 28, 29	-	6, 29	13, 3, 27, 10
37	27, 3, 15, 28	19, 29, 39, 25	25, 34, 6, 35	3, 27, 35, 16	2, 24, 26	35, 38	19, 35, 16	18, 1, 16, 10	35, 3, 15, 19	1, 18, 10, 24	35, 33, 27, 22	18, 28, 32, 9	3, 27, 29, 18
38	25, 13	6, 9	-	26, 2, 19	8, 32, 19	2, 32, 13	-	28, 2, 27	23, 28	35, 10, 18, 5	35, 33	24, 28, 35, 30	35, 13
39	29, 28, 10, 18	35, 10, 2, 18	20, 10, 16, 38	35, 21, 28, 10	26, 17, 19, 1	35, 10, 38, 19	1	35, 20, 10	28, 10, 29, 35	28, 10, 35, 23	13, 15, 23	-	35, 38

Table A.1 Contradiction Matrix (continuation) [72]

Improving engineer features	Worsening engineer feature: 27	28	29	30	31	32	33	34	35	36	37	38	39
1	1, 3, 11, 27	28, 27, 35, 26	28, 35, 26, 18	22, 21, 18, 27	22, 35, 31, 39	27, 28, 1, 36	35, 3, 2, 24	2, 27, 28, 11	29, 5, 15, 8	26, 30, 36, 34	28, 29, 26, 32	26, 35 18, 19	35, 3, 24, 37
2	10, 28, 8, 3	18, 26, 28	10, 1, 35, 17	2, 19, 22, 37	35, 22, 1, 39	28, 1, 9	6, 13, 1, 32	2, 27, 28, 11	19, 15, 29	1, 10, 26, 39	25, 28, 17, 15	2, 26, 35	1, 28, 15, 35
3	10, 14, 29, 40	28, 32, 4	10, 28, 29, 37	1, 15, 17, 24	17, 15	1, 29, 17	15, 29, 35, 4	1, 28, 10	14, 15, 1, 16	1, 19, 26, 24	35, 1, 26, 24	17, 24, 26, 16	14, 4, 28, 29
4	15, 29, 28	32, 28, 3	2, 32, 10	1, 18	-	15, 17, 27	2, 25	3	1, 35	1, 26	26	-	30, 14, 7, 26
5	29, 9	26, 28, 32, 3	2, 32	22, 33, 28, 1	17, 2, 18, 39	13, 1, 26, 24	15, 17, 13, 16	15, 13, 10, 1	15, 30	14, 1, 13	2, 36, 26, 18	14, 30, 28, 23	10, 26, 34, 2
6	32, 35, 40, 4	26, 28, 32, 3	2, 29, 18, 36	27, 2, 39, 35	22, 1, 40	40, 16	16, 4	16	15, 16	1, 18, 36	2, 35, 30, 18	23	10, 15, 17, 7
7	14, 1, 40, 11	25, 26, 28	25, 28, 2, 16	22, 21, 27, 35	17, 2, 40, 1	29, 1, 40	15, 13, 30, 12	10	15, 29	26, 1	29, 26, 4	35, 34, 16, 24	10, 6, 2, 34
8	2, 35, 16	-	35, 10, 25	34, 39, 19, 27	30, 18, 35, 4	35	-	1	-	1, 31	2, 17, 26	-	35, 37, 10, 2
9	11, 35, 27, 28	28, 32, 1, 24	10, 28, 32, 25	1, 28, 35, 23	2, 24, 35, 21	35, 13, 8, 1	32, 28, 13, 12	34, 2, 28, 27	15, 10, 26	10, 28, 4, 34	3, 34, 27, 16	10, 18	-
10	3, 35, 13, 21	35, 10, 23, 24	28, 29, 37, 36	1, 35, 40, 18	13, 3, 36, 24	15, 37, 18, 1	1, 28, 3, 25	15, 1, 11	15, 17, 18, 20	26, 35, 10, 18	36, 37, 10, 19	2, 35	3, 28, 35, 37
11	10, 13, 19, 35	6, 28, 25	3, 35	22, 2, 37	2, 33, 27, 18	1, 35, 16	11	2	35	19, 1, 35	2, 36, 37	35, 24	10, 14, 35, 37
12	10, 40, 16	28, 32, 1	32, 30, 40	22, 1, 2, 35	35, 1	1, 32, 17, 28	32, 15, 26	2, 13, 1	1, 15, 29	16, 29, 1, 28	15, 13, 39	15, 1, 32	17, 26, 34, 10
13	-	13	18	35, 24, 30, 18	35, 40, 27, 39	35, 19	32, 35, 30	2, 35, 10, 16	35, 30, 34, 2	2, 35, 22, 26	35, 22, 39, 23	1, 8, 35	23, 35, 40, 3
14	11, 3	3, 27, 16	3, 27	18, 35, 37, 1	15, 35, 22, 2	11, 3, 10, 32	32, 40, 25, 2	27, 11, 3	15, 3, 32	2, 13, 25, 28	27, 3, 15, 40	15	29, 35, 10, 14
15	11, 2, 13	3	3, 27, 16, 40	22, 15, 33, 28	21, 39, 16, 22	27, 1, 4	12, 27	29, 10, 27	1, 35, 13	10, 4, 29, 15	19, 29, 39, 35	6, 10	35, 17, 14, 19
16	34, 27, 6, 40	10, 26, 24	-	17, 1, 40, 33	22	35, 10	1	1	2	-	25, 34, 6, 35	1	20, 10, 16, 38
17	19, 35, 3, 10	32, 19, 24	24	22, 33, 35, 2	22, 35, 2, 24	26, 27	26, 27	4, 10, 16	2, 18, 27	2, 17, 16	3, 27, 35, 31	26, 2, 19, 16	15, 28, 35
18	-	11, 15, 32	3, 32	15, 19	35, 19, 32, 39	19, 35, 28, 26	28, 26, 19	15, 17, 13, 16	15, 1, 19	6, 32, 13	32, 15	2, 26, 10	2, 25, 16
19	19, 21, 11, 27	3, 1, 32	-	1, 35, 6, 27	2, 35, 6	28, 26, 30	19, 35	1, 15, 17, 28	15, 17, 13, 16	2, 29, 27, 28	35, 38	32, 2	12, 28, 35
20	10, 36, 23	-	-	10, 2, 22, 37	19, 22, 18	1, 4	-	-	-	-	19, 35, 16, 25	-	1, 6
21	19, 24, 26, 31	32, 15, 2	32, 2	19, 22, 31, 2	2, 35, 18	26, 10, 34	26, 35, 10	35, 2, 10, 34	19, 17, 34	20, 19, 30, 34	19, 35, 16	28, 2, 17	28, 35, 34
22	11, 10, 35	32	-	21, 22, 35, 2	21, 35, 2, 22	-	35, 32, 1	2, 19	-	7, 23	35, 3, 15, 23	2	28, 10, 29, 35
23	10, 29, 39, 35	16, 34, 31, 28	35, 10, 24, 31	33, 22, 30, 40	10, 1, 34, 29	15, 34, 33	32, 28, 2, 24	2, 35, 34, 27	15, 10, 2	35, 10, 28, 24	35, 18, 10, 13	35, 10, 18	28, 35, 10, 23
24	10, 28, 23	-	-	22, 10, 1	10, 21, 22	32	27, 22	-	-	-	35, 33	35	13, 23, 15
25	10, 30, 4	24, 34, 28, 32	24, 26, 28, 18	35, 18, 34	35, 22, 18, 39	35, 28, 34, 4	4, 28, 10, 34	32, 1, 10	35, 28	6, 29	18, 28, 32, 10	24, 28, 35, 30	-
26	18, 3, 28, 40	13, 2, 28	33, 30	35, 33, 29, 31	3, 35, 40, 39	29, 1, 35, 27	35, 29, 25, 10	2, 32, 10, 25	15, 3, 29	3, 13, 27, 10	3, 27, 29, 18	8, 35	13, 29, 3, 27
27		32, 3, 11, 23	11, 32, 1	27, 35, 2, 40	35, 2, 40, 26	-	27, 17, 40	1, 11	13, 35, 8, 24	13, 35, 1	27, 40, 28	11, 13, 27	1, 35, 29, 38
28	5, 11, 1, 23		-	28, 24, 22, 26	3, 33, 39, 10	6, 35, 25, 18	1, 13, 17, 34	1, 32, 13, 11	13, 35, 2	27, 35, 10, 34	26, 24, 32, 28	28, 2, 10, 34	10, 34, 28, 32
29	11, 32, 1	-		26, 28, 10, 36	4, 17, 34, 26	-	1, 32, 35, 23	25, 10	-	26, 2, 18	-	26, 28, 18, 23	10, 18, 32, 39
30	27, 24, 2, 40	28, 33, 23, 26	26, 28, 10, 18		-	24, 35, 2	2, 25, 28, 39	35, 10, 2	35, 11, 22, 31	22, 19, 29, 40	22, 19, 29, 40	33, 3, 34	22, 35, 13, 24
31	24, 2, 40, 39	3, 33, 26	4, 17, 34, 26	-		-	-	-	-	19, 1, 31	2, 21, 27, 1	2	22, 35, 18, 39
32	-	1, 35, 12, 18	-	24, 2	-		2, 5, 13, 16	35, 1, 11, 9	2, 13, 15	27, 26, 1	6, 28, 11, 1	8, 28, 1	35, 1, 10, 28
33	17, 27, 8, 40	25, 13, 2, 34	1, 32, 35, 23	2, 25, 28, 39	-	2, 5, 12		12, 26, 1, 32	15, 34, 1, 16	32, 26, 12, 17	-	1, 34, 12, 3	15, 1, 28
34	11, 10, 1, 16	10, 2, 13	25, 10	35, 10, 2, 16	-	1, 35, 11, 10	1, 12, 26, 15		7, 1, 4, 16	35, 1, 13, 11	-	34, 35, 7, 13	1, 32, 10
35	35, 13, 8, 24	35, 5, 1, 10	-	35, 11, 32, 31	-	1, 13, 31	15, 34, 1, 16	1, 16, 7, 4		15, 29, 37, 28	1	27, 34, 35	35, 28, 6, 37
36	13, 35, 1	2, 26, 10, 34	26, 24, 32	22, 19, 29, 40	19, 1	27, 26, 1, 13	27, 9, 26, 24	1, 13	29, 15, 28, 37		15, 10, 37, 28	15, 1, 24	12, 17, 28
37	27, 40, 28, 8	26, 24, 32, 28	-	22, 19, 29, 28	2, 21	5, 28, 11, 29	2, 5	12, 26	1, 15	15, 10, 37, 28		34, 21	35, 18
38	11, 27, 32	28, 26, 10, 34	28, 26, 18, 23	2, 33	2	1, 26, 13	1, 12, 34, 3	1, 35, 13	27, 4, 1, 35	15, 24, 10	34, 27, 25		5, 12, 35, 26
39	1, 35, 10, 38	1, 10, 34, 28	18, 10, 32, 1	22, 35, 13, 24	35, 22, 18, 39	35, 28, 2, 24	1, 28, 7, 10	1, 32, 10, 25	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	5, 12, 35, 26	

Appendix B

Table B.1 Mapping the 76 standard solutions onto the 40 inventive principles in TRIZ [10]

1	Segmentation	5.1.2 2.2.2 2.2.4 3.2.1	Divide the element into smaller units Use particles instead of the whole object Divide the object into parts, then make it flexible by linking the parts Transition to the micro-level
2	Take out		
3	Local Quality	1.1.8.2 1.2.5 2.2.6 5.1.1.5	Protect certain regions from the full impact of an action Turn a magnetic field on or off according to the local need. Change from uniform structure to a structure that is specific to the situation Concentrate an additive in one location
4	Asymmetry	2.2.6	Change from uniform structure to a structure that is specific to the situation
5	Merging	1.1.2-1.1.5 3.1.4	Additive, temporary or permanent, internal or external, from the environment or from changing the environment Simplification of Bi- and Poly-systems
6	Universality		
7	Nested Doll		
8	Anti-weight		
9	Preliminary anti-action		
10	Preliminary action		
11	Cushion in advance	1.1.8.1	Use a substance to protect a weaker substance from a potentially harmful occurrence.
12	Equipotentiality		
13	Other way around	2.4.6	Introduce magnetic materials in the environment, instead of into the object
14	Spheroidality or use of curves		
15	Dynamism	2.2.4. 2.4.8	Make the system flexible Use dynamic magnetic fields
16	Partial/excessive action	1.1.6 5.1.4	Control small quantities by applying and removing a surplus Simulate the introduction of more than is acceptable

Table B.1 Mapping the 76 standard solutions onto the 40 inventive principles in TRIZ (continuation) [10]

17	Another dimension		
18	Mechanical Vibration	2.3.1. 2.4.10 4.3.2	Match the natural frequencies of the field with the substance Use vibration in conjunction with magnetic fields Measure changes in a system by means of changes in its resonant frequency.
19	Periodic action	2.2.5 2.4.10	Replace an uncontrolled field with a structured one. Use magnetic field resonance
20 21	Continuity of action Skipping (do fast)	2.3.3.	Do one operation during the downtime of another
22	Blessing in disguise	1.2.2	Eliminate harmful effects (also others in 1.2)
23	Feedback	5.4.1	Self-controlled changes
		2.4.8	Use dynamic magnetic fields
24	Intermediary	1.1.7 2.4.9 2.4.5 1.1.2-1.1.5 5.1.1.6 4.1.2	Use one object to make the actions of another possible. Create structures by use of magnetic particles Introduce a ferromagnetic additive, temporarily Use a temporary additive, internal or external Introduce an additive temporarily Measure a copy
25	Self-service	5.4.1 2.4.8	Self-controlled changes Use dynamic magnetic fields
26	Copying	4.1.2 5.1.1.7	Measure a copy Apply additives to a copy instead of the original
27	Cheap short life		
28	Replace mechanical system with fields	2.2.1 2.4(all) 2.4.11 4.2 (all) 5.1.1.2	Replace or supplement a poorly controlled field with a more easily controlled field Use of ferromagnetism and ferromagnetic materials Use electric current instead of magnetic particles Create a field that can be detected or measured Use a field instead of a substance

Table B.1 Mapping the 76 standard solutions onto the 40 inventive principles in TRIZ (continuation) [10]

29	Pneumatic/hydraulic	2.4.3 5.1.1.1 5.1.4	Use magnetic liquids Use "nothing" Use "nothing" to simulate structures
30	Flexible shell, films	2.2.6	Change from a uniform structure to a structure that is specific to the situation
31	Porous materials	2.2.3 2.2.6 2.4.4	Use porous or capillary materials Change a uniform structure to a non-uniform one Use capillary or porous structures in a magnetic material, or to contain magnetic fluid
32	Change color	4.1.3 4.3.1	Use detection instead of measurement Measure the system by means of natural phenomena
33	Homogeneity		
34	Discard/recover	5.1.3	The additive disappears after use
35	Change parameters	5.3.1 1.1.2-1.1.5 2.4.12	Phase change Additive, temporary or permanent, internal or external, from the environment or changing the environment Use rheological liquids
36	Use phase transition	5.3.2,4,5 2.4.7 4.1.1 4.3.1	Use the accompanying effects from phase changes Use the physical effects of magnetic transitions Control a system by means of a phase transition, instead of measuring temperature, pressure, magnetic field, etc. Measure the system by means of natural phenomena
37	Use thermal expansion	4.1.1 4.3.1	Control a system by means of thermal expansion, instead of measuring temperature Measure expansion instead of temperature
38	Strong Oxidants	5.5 5.1.1.4	Getting needed ions, molecules, etc. Includes 5.51, 5.52, and 5.53 Use small amounts of very active additives
39	Inert Atmosphere	1.1.3 1.1.5	Additive, temporary or permanent, external Change the environment of the system
40	Composite materials	5.1.1.1	Add "nothing"—foam, honeycomb, etc.

Appendix C

BOSCH

MAINTENANCE SERVICE CONTRACT

This contract is concluded between
[redacted]
as Contractor and

Contract No.
[redacted]

Company name:
[redacted]
as Customer

Plant location:
[redacted]

Start of Maintenance
[redacted]

Order No.
[redacted]

Boiler No.
[redacted]

Boiler Model
UL-S

Burner Model
Saacke: SKV-A 124-37

Water Treatment Manufacturer
Bosch

Service Summary

Position	Description	Quantity
I	Boiler safety maintenance	4
II	Burner safety maintenance	4
III	Water supply safety maintenance	4
IV	Spare parts package	1
V	MEC remote annual subscription fee	1
VI	24 hour premium telephone support	-
VII	Emergency maintenance assistance visit (2 hour fee included)	1

Scope of maintenance: trimestrial
Duration of maintenance: 1 year

Amount (plus statutory VAT)
total fee of: [redacted] **EUR**

[redacted]
Date: [redacted]

Name: ____________________
Designation: ____________________

(contractor's signature)

Name: ____________________
Designation: ____________________

(client's signature)

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Figure C.1 Main page of the improved maintenance contract adapted to Africa. This page is only an excerpt that summarizes the contents of the contract. The full contract has 11 pages.