DISAT Department of Applied Science and Technology

An Interactive Decision Support System for Energy Management in Process Industry

Ph.D. In “Metrology: Measuring Science And Technique” (XXIV Cycle).
Industrial safety and risk analysis

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Abstract

Industrial energy accounts for roughly one-third of total global energy consumption and is expected to continue with a similar share in the foreseeable future, therefore the efficient use of energy and energy saving are important issues for the industrial sectors. Energy Efficiency EE is a crucial factor for energy cost-benefits and waste reduction also environmental management, and can be improved by different approaches. Especially in this study the energy saving through management system will be illustrated. EE is achieved by use of an energy management system which presents various strategies, tools, methods, technologies, and effective measures to face energy saving and consumption issues, that also includes energy audits, monitoring, control and continuous improvement of the system. In particular in this work energy saving through maintenance (corrective and preventive) and operative procedures were addressed. Maintenance operations are fundamental in granting machineries and processes energy saving, given the capability of optimising them thanks to the predictive models. The major challenge of maintenance optimization is to implement a maintenance strategy, which maximizes availability and efficiency of the equipment, controls the rate of equipment deterioration, ensures the safe and environmentally friendly operation, and minimizes the total cost of the operation which means the both production and energy cost.

In this work, an energy efficiency analysis model was developed formed by integration of a deterministic and probabilistic model of the system, based on a balance of cost/benefits, to optimize maintenance interventions and operative procedures as the first aim of maximizing energy efficiency. In particular, as an element of novelty with respect to literature models, the maintenance influence has been explicitly modeled and used as an optimization parameter. The decision making model and data analysing were shown through application to a case study in an industrial production process in Bitumtec Ltd. plant, which produces bituminous materials for road paving. The motor-driven equipment accounts for approximately 60% of manufacturing final electricity use worldwide. A major barrier to effective policymaking, and to more global acceptance of the energy efficiency potential in industrial motor systems, is the lack of a transparent methodology for quantifying the magnitude and cost-effectiveness of these energy savings. Therefore the power consumption was analyzed, as an example, for the most critical system (the greater energy consumption system) or the three phases electric motor system (160 kW) “Siefer” which drives the homogenization mill during production. Bottom-up energy efficiency supply curve models is used to estimate the cost-effective

electricity efficiency potentials, also CO_2 emission reduction, for the motor system. Using a combination of expert opinions and available data, from our selected industrial case study, there was introduced an analysis approach where is used the concept of a "conservation supply curve CSC" to capture the cost effective as well as the technical potential for energy efficiency. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy. This approach is explained in details; further the results were illustrated and discussed.

The first step of this study was a literature review to develop a base line of information, through of research in the field of energy management systems, industrial energy efficiency technologies. That included general review of energy saving models, also optimization of energy consumption in industrial production process. Because of the importance of the maintenance activities and reliability of the systems, also was reviewed maintenance optimization models and their impacts on energy cost-effectiveness, productivity benefits and environments. A part of these studies are introduced in this work and illustrated as the theoretical parts.

Analysis has been emphasized, the importance of optimizing maintenance activities and operating procedures to increase the performance of the system. Energy efficiency was evaluated for three different base case scenarios; Low, Medium and High with their related potential energy recovery, performance and environmental benefits.

Maximizing efficiency of the system that is our goal is achieved through the use of this model, which also based on analysis of historical data, expert inputs and analysis of the economic impacts that was discussed and demonstrated by the results.

In this work the proposed framework with flowing steps are introduced:

- Identification of the Most Important System MIS

  Specially, in this study a motor-driven system in a production process of bituminous materials in Bitumtec Ltd. plant, is addressed.
- Identification of the most critical component MCC

  Particularly, in this study is addressed the electrical motor (160 kWh) that drives homogenization mill "Siefer" during production process of bituminous materials.
- Life time and energy consumption data collection and observation, also data related to maintenance activities (corrective and preventive) and failures data collection.

- Estimated costs of maintenance and the economic evaluation of maintenance policies (based on balanced cost and risk of inefficiency).
- Maintenance optimization (in terms of probability and consequences).
- Estimated operating costs of the system.
- Analysis of energy efficiency through maintenance optimization and operating procedures, by using of bottom-up energy efficiency supply curve analysis model, where it was introduced; Expert inputs (based on the information of the expert of the system), and data assumption.
- Definition of three base case scenarios

  In this case, were defined three efficiency base case scenarios; low, Medium and High, base case levels with related potential for recovery of electricity. Further, was proposed the related efficiency measures o adequate solutions (cost-effective) to increase the efficiency, based on the maintenance activities, operating procedures and the conditions of the system.
- Determination of the impact of these measures on the performance.

1 Industrial Energy Efficiency

Industrial energy accounts for roughly one-third of total global energy consumption and is expected to continue with a similar share in the foreseeable future, thus the improvements of energy efficiency and reduction of environmental impacts are one of the most important tasks for manufacturing industry. Energy efficiency is achieved not only through implementation of adequate equipment, process and operating practice, but also by implementation of energy efficiency management system, energy audits, definition and monitoring indicators as well as energy accounting or exergy and thermo-economic analysis, which was discussed by (Uson et al., 2010).

The Krakow Declaration for an EU initiative for improving Energy Efficiency in process industries presents four points to be considered: (i) Products of equipment's manufacturers; (ii) Process and system analysis; (iii) Procedures that includes efficiency monitoring and accounting, as well as accreditation of the achieved results; (iv) Promotion, which were recently illustrated by (Bunse et al., 2011).

In order to improve EE, it is evident the importance of monitoring, efficiency assessment and diagnosis techniques. The causes of efficiency reduction can be degradation of components and equipments (e.g. blade erosion in turbines), set points, maintenance operation and strategies, as well as fuel quality and environmental condition.

The importance of energy efficiency in manufacturing industries is to reduce energy cost and consumption thus, reducing of environmental impacts (CO_2 emissions, wastes).

The manufacturing industry, with its 31% of primary energy use and 36% of carbon dioxide emissions, is one of the main consumers of energy as well as one of the largest emitters of. The European Commission EC with the objective to reduce annual consumption of primary energy by 20% by 2020, for example, estimates that an energy saving potential for the manufacturing sector of 25% could be realized by measures such as implementing energy efficient motors, fans and lightings. From the manufacturing companies' point of view, there are three important drivers to introduce energy efficiency improvements: (i) Rising energy prices; (ii) New environmental regulations with their associated costs for CO_2 emissions; (iii) Customers changing their purchasing behavior with regard to "green" and energy efficient products and services. The above mentioned drivers make energy efficiency an important pillar contributing to all three aspects (triple bottom line) that are considered in sustainable manufacturing frameworks and are presented in Figure 1.1, which was showed by (Bunse et al., 2011).

Identifying most effective measures increase energy efficiency in manufacturing processes. Measuring energy efficiency is the basis for controlling energy consumption in the production processes, for deciding about improvement measures and for tracking changes and improvements in energy efficiency. Some examples of energy efficiency measures are: More energy efficient technology and machines; Energy recovery in the same process; future use of waste energy in different process; increase in energy conversion efficiency, and Optimization of production process.

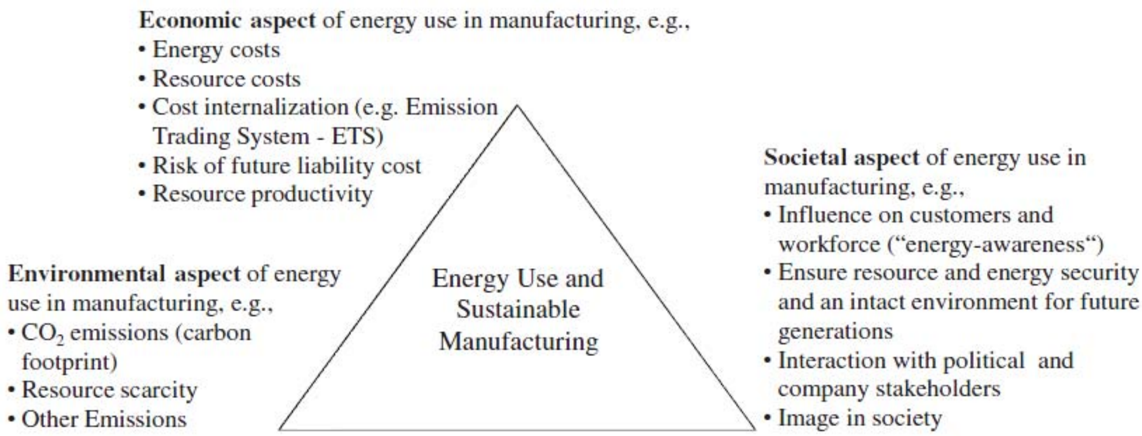

Figure 1.1. Contribution of energy efficiency to the tree main aspects of sustainable manufacturing.

Energy efficiency in industry plays key roles in improving energy security, environmental sustainability and economic performance. It is particularly important in strategies to mitigate climate change. The evidence of great potential for cost-effective efficiency derived reductions in industrial energy use and greenhouse gas emissions have prompted governments to implement numerous policies and measures aimed at improving their manufacturing industries' energy efficiency.

The sector's energy use is influenced by its many different technologies, processes and products, energy sources and prices, political, economic and business situations and managerial priorities and decision making paradigms. Further, energy efficiency can be improved by a wide variety of technical actions including:

- Maintaining, refurbishing and returning equipment to counter natural efficiency degradation and to reflect shifts in process parameters.

- Retrofitting, replacing and retiring obsolete equipment, process lines and facilities to new and state of art technologies.
- Using heat management to decrease heat loss and waste energy by, for example: proper use of insulation; utilization of exhausted heat and materials from one to other processes.
- Improving process control, for better energy and materials efficiency and general process productivity.
- Streamlining processes-eliminating processing steps and using new production concepts.
- Re-using and recycling products and materials.
- Increasing process productivity.
- Decreasing product rejects rates and increasing materials yields.

Policy facilitates those technical efforts. A policy of energy efficiency should also be able to exploit the potential in various fields, in particular in the industrial sector where efficiency means greater competitiveness and thus trigger a virtuous circle for the country's economy. The successful use of policy for energy efficiency improvement depends on how policy can finally give incentives for each possible technical improvement, directly or indirectly, to industry sector, which was recently discussed by (Tanaka, 2011).

1.1 Energy Efficiency Management System

A company can improve its Energy Efficiency using innovative tools such as energy audits, monitoring programs or standardization such as EN 16001, and ISO 50001 (2011) that is the new international standard for energy management systems, designed to support organizations and also in the continuous and necessary seeking to improve the energy efficiency of their processes. This International Standard is based on the Plan, Do, Check, Act continual improvement framework and incorporates energy management into every day organizational practices. The application of these tools can therefore reduce energy costs and emissions, thereby achieving optimum environmental performance within the limits of the law and future, contributing to the improvement of the company. A management system in an organization has tools, methods and technologies for quantification of the impact of energy consumption and addresses the issues of savings. For this reason, technology is a necessary step to put in place innovative and effective consumption monitoring and control systems and equipment in order to optimize its energy efficiency.

Innovative industrial technologies aim not only at reducing Energy use, but also to improve productivity, to reduce operational and capital cost, to improve reliability as well as to reduce emissions and improve working condition. To achieve these results, an Energetic Efficiency Management System EEMS is needed that will require a structure like all other industrial management systems (quality, environment and safety) which have a common frame, based on the four phases: Plan, Do, Check, and Act. An EEMS scheme is described in Figure 1.2.

Figure 1.2. An energy efficient management system scheme.

A further significant increase in efficiency of production systems is achieved by using innovative methodologies applied to predictive maintenance systems and electric motors that determine the prevailing share of energy consumption in the manufacturing sector.

1.1.1 Plan

Plan conduct the energy review and establish the baseline, energy performance indicators, objectives, targets and action plans necessary to deliver results in accordance with opportunities to improve energy performance and the organization's energy policy.

The design of an EEMS requires modeling of energetic system to perform data collection of the energy consumption in the site under study. Thus a preliminary auditing activity should be performed in order to identify where and why power or heat losses are present and/or where and how the measures for the enhancement of energy efficiency have to be adopted. On the basis of the above information a model of the system will be developed in order to represent the present behavior of the plant under study and to understand the specific energy consumption where will be required the intervention (maintenance, process optimization, etc.).

1.1.2 Do

Do phase implement the energy management action plans. This is the activation phase of the management system and it requires that the EEMS is implemented. During this phase the data needed to represent the effectiveness of the system have to be collected, in order to allow both the assessment of the system itself and the decision making about further technical and management measures to be introduced, if necessary. The operational control is one of the main aspects of any management system, and in this case an Integrated Decision Support System is proposed as a tool for the collection and analysis of operational data. The characteristics of this tool will be described in a dedicated paragraph.

1.1.3 Check

Check phase monitor and measure processes and the key characteristics of its operations that determine energy performance against the energy policy and objectives and report the results. The data collected in the previous phases are here analysed and used for further decision-making. Another element of novelty is here introduced: the use of risk based decision-making in the area of energy saving.

1.1.4 Act

Act means take actions to continually improve energy performance and the EEMS. In this phase of revision of the management system all the data analysed in the "check" phase are used for the EEMS improvement, the model alignment to the real plant situation and the definition of further measures to be implemented in the plant to enhance energy efficiency.

1.2 Energy Efficiency Measuring

Measuring energy efficiency is the basis for controlling energy consumption in the production processes, for deciding about improvement measures and for tracking changes and improvements in energy efficiency. Moreover, the Information and Communication Technology ICT and Standardization play important roles as enablers for energy efficient manufacturing. Measurement and control systems are integral parts of manufacturing systems. New energy management concepts form a basis for decisions on energy efficiency improvement measures. To develop new energy management concepts, attention has to be given to sensors and control devices, the key performance indicators KPIs, and the techno human interfaces. Energy efficiency should also be represented in ICT systems for production. Due to new options for enhanced collaboration, further energy savings can be realized in supply chains. In the context of energy management in production ICT and standardization play an enabling role for measurement, control and improvement of energy efficiency in manufacturing that was shown in the Figure 1.3, which was shown by (Bunse et al., 2011).

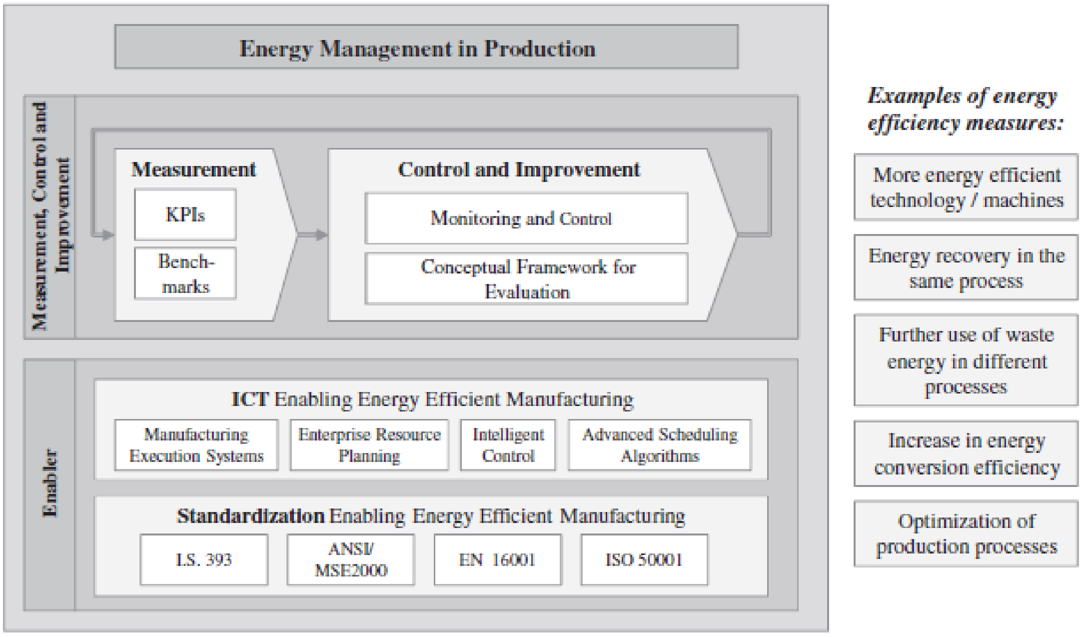

Figure 1.3. The role of ICT and Standardization for measurement, control and improvement of energy efficiency in manufacturing.

1.2.1 Key performance indicators

Measuring and controlling the energy efficiency in production processes is the first step for evaluating and implementing improvement measures. By establishing production information Systems towards energy efficiency, decision makers will be provided with relevant information on impacts on energy performance resulting from production planning and business decisions. In the interviews and the workshops with industry representatives it became evident, that there is a need for energy efficiency KPIs to track the changes and improvements on both process and on plant level. Industry seems to lack the means and appropriate KPIs to compare energy usage profiles of machines and processes and to compare their energy efficiency performance to other companies.

Key needs expressed by the interviewees in the area of measurement of energy efficiency include KPIs, this argument was recently illustrated by (Bunse et al., 2011):

- Energy efficiency manufacturing metrics to identify inefficiencies within a plant's energy usage, e.g. energy consumption profiles;
- Measurement standards for energy efficiency and carbon emission;
- Standardization of environmental performance metrics including energy efficiency KPIs;
- KPIs to facilitate tracking changes and improvements in energy efficiency;
- Measurement of energy efficiency directly in monetary values to communicate directly, where money can be saved;
- Development of processes to map energy usage for better understanding input, output, and measurement points for each manufacturing process.

1.2.2 Energy efficiency indicators and application

The Energy Efficiency Indicator system EEI is used to evaluate industrial energy efficiency. A popular approach used in analyzing EEI structure is the decomposition method. In this approach the indicator is decomposed into a group of components using a mathematical chain rule; each of the components is analyzed independently and the results are multiplied together to re-obtain the indicator.

In a typical industrial process there are many factors affecting the Energy Consumption per Unit of the Product ECPU, and these factors include: process equipment, operation method, energy category, raw material, system management, energy saving activity, and utilization of production capability.

By quantifying these factors into variables, and simplifying them, ECPU can be approximated in a function of two variables. Mathematically these two variables can be defined as follows: (i) variable α defined by the utilization index of process production capacity, and (ii) variable β defined by the variation index of process utilization. Function f is used to represent ECPU. These results were shown by (Wu et al., 2007), and can be expressed as:

$$f = \mathrm{f}(\alpha, \beta), \tag{1.1}$$

Where;

$$\alpha \equiv \frac{Q_r}{Q_d} \tag{1.2}$$

$$\beta \equiv \frac{E_d - E_r}{E_d} \tag{1.3}$$

Where Q_d = designed annual productivity of the process; Q_r = real annual productivity of the process; E_d = designed annual energy consumption of the process; and E_r = real annual energy consumption of the process. Because of Q_r and E_r, the variables α and β are time dependent too. According to the definitions given above, when $\alpha < 1$, the process has less productivity than the designed value ($\alpha=1$) and when $\beta>0$ the process is consuming more energy than designed.

By the structure model of the ECPU, the energy efficiency analysis of the process is possible. If design values Q_d and E_d are chosen as two base line data ($\alpha_0=1$, $\beta_0=0$) and the f is assumed high-order differentiable, the function can be expand as a Taylor series. Furthermore the f can be linearly approximated as Equation 1.4.

$$\frac{E_r}{Q_r} \cong \frac{E_d}{Q_d} + \Delta\alpha \frac{\partial f}{\partial \alpha} + \Delta\beta \frac{\partial f}{\partial \beta} \tag{1.4}$$

From differential operation, two partial terms can be expressed as Equations 1.5 and 1.6.

$$\frac{\partial f}{\partial \alpha} = \frac{\partial (E_r / Q_r)}{\partial (Q_r / Q_d)} = -Q_d \frac{E_r}{Q_r^2} = -\frac{1}{\alpha} \frac{E_r}{Q_r} \tag{1.5}$$

$$\frac{\partial f}{\partial \beta} = \frac{\partial (E_r / Q_r)}{\partial (E_d - E_r / E_d)} = -\frac{E_d}{Q_r} \tag{1.6}$$

Then, Equation 1.4 becomes:

$$\frac{E_r}{Q_r} \cong \frac{1}{2 - \frac{1}{\alpha}{}_d} \frac{E_d}{Q_d} + \frac{-\beta}{2 - \frac{1}{\alpha}} \frac{E_d}{Q_r} \tag{1.7}$$

Equation 1.7 is the model for EEI at the process level. According to this equation ECPU consist of two terms, the first one contains only variable α that means this term depends on equipment utilization only and is not energy-related. The second one contains α and β, which means this term, depends on both energy utilization and equipment utilization and is therefore energy related.

For the case $E_r/Q_r > E_d/Q_d$, the process, on average is consuming more energy in production than the designed value, and then it should be considered insufficient energy efficiency; which also was discussed by (Wu et al., 2007). The way of assessing the rules involved will depend on the dimension and on the energy policy of the company in which the system is implemented.

1.3 Planning and Operating Energy Efficient Systems

Decisions in planning and operating production systems are mainly based on traditional metrics such as cost, quality and flexibility and rarely consider energy consumption. High energy availability, low prices and a lack of knowledge on the systems' energy consumption structure are the main reasons for this. On the other hand planning and operating energy-efficient production systems require detailed knowledge on the energy consumption behaviour of their components, energy consumption of production processes, and methods to evaluate design variants.

In order to systematically exploit new technological potentials, a detailed system-wide prediction of energy consumption and the introduction of analytical energy management methods are required. These will enable factory managers to answer accurately the questions of how much energy is required at which time and place and thus support their decisions with respect to dynamic changes in production programs, changing energy prices and availability, and environmental impact. Decisions that have an impact on the energy consumption of a

Production system is part of all phases of a factory's life cycle; from production system planning to operation. Thus process energy consumption data have to be made available in a consistent, generic form already from the system design phases.

In this section, the Energy Blocks methodology for accurate energy consumption prediction is introduced. The proposed Energy Blocks planning methodology has been developed to integrate criteria of energy efficiency and effectiveness in manufacturing planning and scheduling on different levels of aggregation from single machine components to value creation networks. The methodology is based on the representation of production operations as segments of specific energy consumption for each operating state of the production equipment. Modelling any process chain is possible by arranging the segments according to the production program; this argument was recently discussed by (Weinert et al., 2011).

1.3.1 Information requirements

Planning a production system starts with the definition of production processes and the selection of available technologies. Defining each process step imposes technological limitations on succeeding steps. In order to design energy efficient systems, besides each single process step, the consumption of the whole process chain has to be taken into account. In addition, exploiting energy regeneration and recovery cycles requires a detailed understanding of the consumption behavior of the involved processes.

After selecting processes and technologies, appropriate equipment and the layout of the planned system are determined in an iterative process of defining, evaluating and selecting alternative designs. Here, energy efficiency objectives such as minimizing total consumption or energy recovery have to be integrated into the evaluation and decision processes. Scheduling assigns products and processes to available production equipment and influences the energy consumption behavior of the whole system. By integrating energy efficiency criteria into scheduling, a reduction of energy costs is to be expected. Such criteria and metrics are for instance peak shaving, adapting the production program to external conditions such as energy prices or renewable energy availability and automatically turning equipment off when stand-by time thresholds are reached and scheduling constraints are fulfilled.

A prerequisite for the integration of energy efficiency criteria in planning activities is a detailed prediction of the energy consumption. This prediction has to be carried out on a machine level, i.e., the energy consumption of each machine and product has to be calculated. Moreover, approaches such as load leveling and peak shaving require high time domain resolution of energy consumption; the different operating states of the machines have to be taken into account. In such ways system-wide consumption and cost estimations as well as comparison of alternative equipment during system design can be based on analytical models. Aggregating the predicted consumptions for different levels of a factory’s organizational structure allows for a centralized energy cost management.

1.3.2 Energy blocks planning methodology

The methodology, shown in Figure 1.4, is based on describing the energy consumption of production equipment e.g., machining centers or handling and transport systems according to their operating states. Each type of equipment has various operating states that exhibit different energy consumption patterns that can be identified in its power profile. Operating states are e.g. turned off, start-up, warm-up, stand-by, processing or stopping. Especially during the operating state "processing" different consumption behaviors result from different process parameters, as was shown by (Weinert et al., 2011).

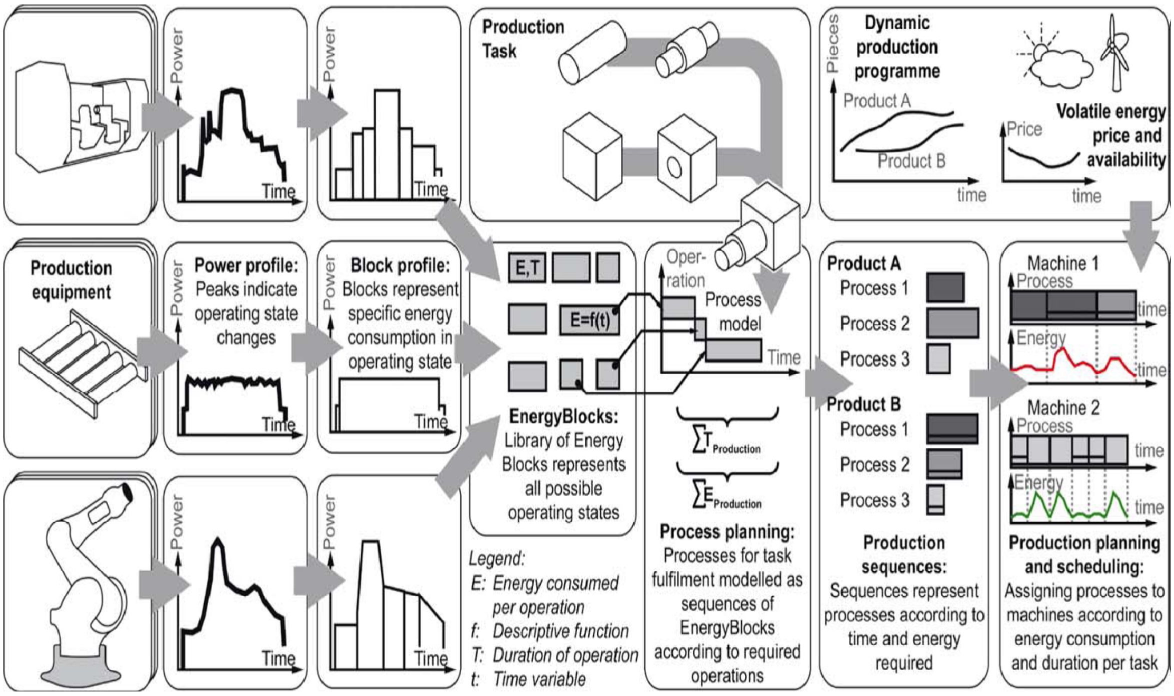

Figure 1.4. Energy Blocks methodology.

However, for a given set of process parameters the energy consumption behavior is unique and can be reproduced. The duration of an operating state can be fixed or variable. For example, the time necessary for processing will differ from product to product. The time required for starting controls and machines will be approximately the same for all items.

The amount of energy required in a specific operating state can be constant or variable with respect to its duration. An example is given in Figure 1.5, where different operating states of a laser for welding plastics are depicted. While the energy required during stand-by is rather constant, in start-up as well as the processing/welding it depends on the time the laser is in the respective operating state.

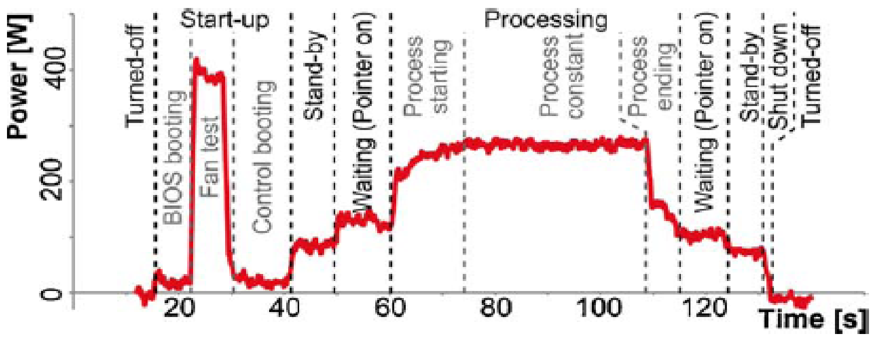

Figure 1.5. Power profile of a laser for plastics welding.

A matching of energy consumption to operating state and thus time is possible, and each operating state is defined as an Energy Block, representing the duration as well as the energy required in this operating state. A production process comprises of a sequence of operating states. Hence, every production process can be described as a sequence of Energy Blocks.

A database of Energy Blocks allows any process chain to be modelled. The base data can be generated, aside from directly measuring the energy consumption per part and process, from any reference process showing similar process parameters and machine specifications. It is also possible to generate consumption data by simulation or estimation; this would influence modelling accuracy as was recently discussed by (Weinert et al., 2011).

1.3.3 Application of energy blocks

The results of modeling the energy consumption of a production system using Energy Blocks provide three different views, as shown in Figure 1.6. Each process is described as an Energy Blocks sequence. For each machine, a series of sequences describes the machine's production program and thus the energy consumption of the machine throughout the whole production can be determined. Related indicators, like machine specific energy costs, become available. Further, the time-based modeling eases the integration of the Energy Blocks methodology in existing scheduling tools. Based on the aggregation of all machine consumptions, a prediction of how much energy is required at which time becomes possible.

From the product perspective, by evaluating all product specific work processes, the embodied energy for each product can be calculated. Not only primary production processes are considered, but also secondary operations like loading and set-up. Further, not only theoretical processing energies are considered, but all part specific consumptions of all subsystems. Thus, the overall consumption calculation is more accurate than e.g. dividing the total energy consumed in secondary operations by the number of produced parts or elapsed production times.

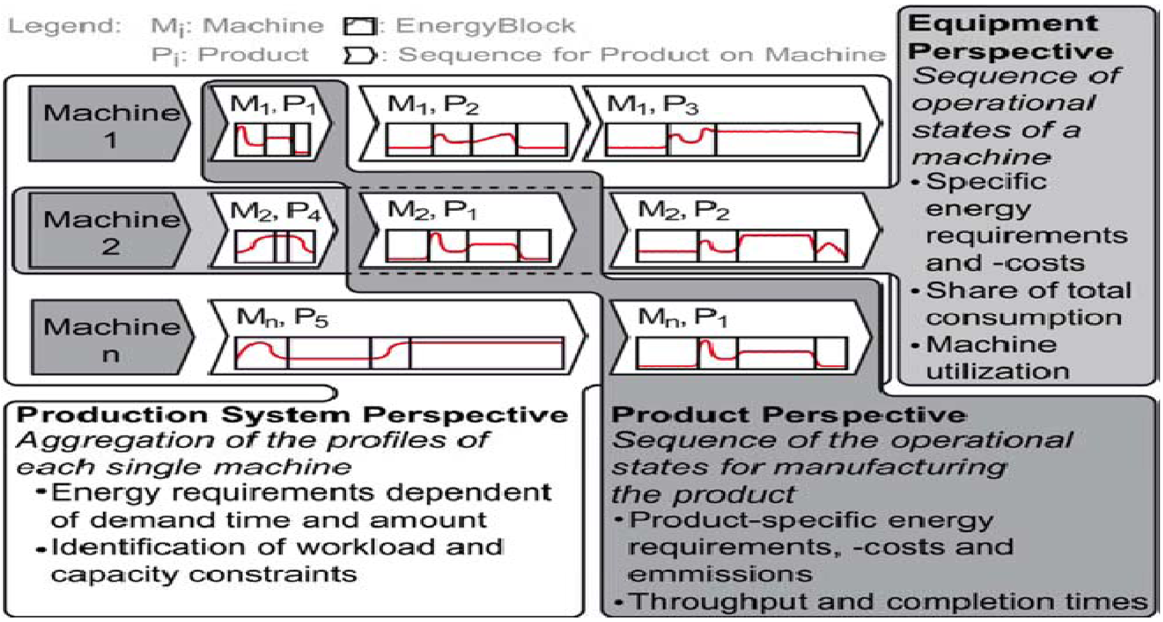

Figure 1.6. Results types of the energy blocks planning methodology.

Besides the energy consumption of the machines directly involved in the production process, secondary consumers like systems for pressurized air supply, heating, ventilating and air conditioning HVAC can be considered. When these represent a significant part of the overall consumption, they should be considered as part of the production chain and modeled according to the Energy Blocks approach, which was illustrated by (Weinert et al., 2011).

1.4 Productivity Benefits of Industrial Energy Efficiency Technologies

Productivity is generally a primary driver as much as energy efficiency in industrial decision making. Industry is also interested in approaches whose impact on profit is more apparent, such as productivity enhancements. Whether one’s perspective is that energy efficiency is a byproduct of productivity gains, or that productivity gains are a byproduct of energy efficiency, for this some often the productivity gains that will motivate industry to take action. Regardless of whether energy efficiency is the driver or the byproduct of a project, management must understand all of the costs and benefits associated with an investment in efficiency in order to make decisions that enhance shareholder value.

Improvements can come in a variety of ways, including lower capital costs and operating costs, increased yields, and reductions in resource and energy use. Any industrial technology development will incorporate one or more of these improvements. Some innovations may primarily be aimed at one goal, but also generally include beneficial impacts on other aspects of a production process. Certain technologies that are identified as being 'energy-efficient' because they reduce the use of energy will bring a number of additional enhancements to the production process. These improvements o non energy benefits beyond energy savings potential including:

- Increased productivity,
- Reduced costs of environmental compliance,
- Reduced production costs (including labour, raw materials),
- Reduced operations and maintenance,
- Reduced waste disposal costs as much as reduced waste and emission,
- Improved product quality (reduced scrap/rework costs, improved customer satisfaction),
- Improved capacity utilization,
- Improved reliability,
- Improved worker safety (resulting in reduced lost work and insurance costs).

While estimating energy and non-energy benefits, it is also critical to estimate all incremental costs, including indirect costs. For example, many projects will require process line shutdown during implementation, causing production losses. Focusing on productivity benefits these non energy benefits are also reassumed in Table 1.1, which was showed by (Worrel et al., 2003).

Table 1.1. Non energy benefits from efficiency improvements (Worrel et al., 2003).

Waste	Emissions	Operation and maintenance
Use of waste fuels, heat, gas	Reduced dust emissions	Reduced need for engineering controls
Reduced product waste	Reduced CO, CO2, NOx, SOx emissions	Lowered cooling requirements
Reduced waste water		Increased facility reliability
Reduced hazardous waste		Reduced wear and tear on equipment/machinery
Materials reduction		Reductions in labor requirements
Production	**Working environment**	**Other**
Increased product output/yields	Reduced need for personal protective equipment	Decreased liability
Improved equipment performance	Improved lighting	Improved public image
Shorter process cycle times	Reduced noise levels	Delaying or Reducing capital expenditures
Improved product quality/purity	Improved temperature control	Additional space
Increased reliability in production	Improved air quality	Improved worker morale

2 Maintenance, an Energy Saving Opportunities

Many different energy efficiency technologies and measures are practiced and applied in the grate energy consuming industry such as petrochemical, cement, iron and steel, pulp and paper, and chemistry. Many of these energy efficiency measures consist of improving productivity and purchasing, maintenance practices and procedures. These measures often have positive implications other than just energy savings. They can also reduce maintenance costs and increase the productivity benefits of the site, and vice versa. Likewise, with control of consumption and applying management system maintenance in the life cycle of a plant you can get energy efficiency.

The major challenge of maintenance optimization is to implement a maintenance strategy, which maximizes availability and efficiency of the equipment, controls the rate of equipment deterioration, ensures the safe and environmentally friendly operation, and minimizes the total cost of the operation which means the both production and energy cost. For example; industrial compressed air systems require periodic maintenance to operate at peak efficiency and minimize unscheduled downtime. Inadequate maintenance can increase energy consumption via lower compression efficiency, air leakage, or pressure variability. It also can lead to high operating temperatures, poor moisture control, excessive contamination, and unsafe working environments. Most issues are minor and can be corrected with simple adjustments, cleaning, part replacement, or elimination of adverse conditions which means preventive maintenance.

Maintenance is defined as 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. In the same standard, Maintenance Management is defined as all the activities of the management or priorities such as availability and cost reduction, strategies like management method in order to achieve maintenance objectives and responsibilities, and implement them by means such as maintenance planning, maintenance control and supervision, and several improving methods, including economic aspects in the organization which was shown in (Crespo & Gupta, 2006).

2.1 Maintenance Operation

A maintenance function is need to make decisions and determine the optimal interval of maintenance or control, and when it is necessary to replace or which and how many savings to be kept, in order to achieve a certain reliability that involves the performance or other benefit. To ensure that the plant achieved the desired performance it needs a track performance on maintenance operations and maintenance results. In addition it needs the relationship between the inputs of the maintenance process and the outcomes in terms of total contribution to manufacturing performance and objectives. Deterioration of manufacturing systems' condition, and hence its capability, begins to take place as soon as the system is commissioned. In addition to normal wear and deterioration, other failures may occur especially when the equipments are pushed beyond their design limits or due to operational errors. As a result, equipment downtime, quality problems, speed losses, safety hazards or environmental pollution become the obvious outcomes. All these outcomes have the potential to impact negatively the operating cost, profitability, customers' demand satisfaction, and productivity among other important performance requirements.

Once the maintenance objectives are outlined, maintenance strategy formulation is necessary to help decide which type of maintenance needs to be done, when to do it, and how often it can be done. Then a maintenance decision making can be broadly explained in terms of maintenance actions like basic elementary work, maintenance policies and maintenance concepts. Maintenance policies are the rules or set of rules describing the triggering mechanism for the different maintenance actions. Examples of these policies are Failure Based Maintenance FBM, Use Based or Time Based Maintenance UBM/TBM, Condition Based Maintenance CBM, Design Out Maintenance DOM and etc. A maintenance concept entails the general decision structure for both maintenance actions and policies. Some examples are Reliability Centered Maintenance RCM, Total Productive Maintenance TPM, Life Cycle Costing LCC and Business Centered Maintenance BCM among others. Some maintenance decision elements are carried out at the operational level, for example the basic maintenance interventions done by technicians. Other decision elements, for example the maintenance policies and concepts, apply to strategic level. Once the objectives and strategies have been established, the success of the maintenance function is dependent on the maintenance work management. The maintenance work management cycle, like all management systems consists of work identification, planning, scheduling, execution and closing the job. Maintenance work is identified from the Preventive, Predictive and Failure finding work orders that are usually generated by Proactive maintenance. Repair work arises as a result of failure. At the heart of the maintenance function are work planning and scheduling, which defines what gets done and when. To complete the work cycle, effective work execution is vital in ensuring that required equipment condition and performance is attained.

2.1.1 Maintenance objectives

To ensure the plant operates at the required condition while meeting its production targets at an optimal cost, maintenance management has to make conscious decisions regarding the maintenance objectives and strategies that need to be pursued. Good maintenance assumes that maintenance objectives and strategies are not determined in isolation, but are in some way derived from factors such as company policy, manufacturing policy and other potentially conflicting demands. So maintenance objectives are related to attainment of production target (through high availability) at required quality, and within the constraints of the system condition and safety. Further, maintenance resources are utilized so that the manufacturing equipments are in good condition, the plant achieves its design life, the safety standards are met, and the energy use and raw material consumption are optimized among other factors.

The maintenance objectives are summarized under five headings below as was shown by (Muchiri et al., 2010):

- Ensuring the plant functionality (availability, reliability, desired output, operability, product quality etc),
- Ensuring the plant achieves its design life,
- Ensuring plant and environmental safety,
- Ensuring cost effectiveness in maintenance,
- Ensuring effective use of resources (energy and raw materials).

We assume that the maintenance objectives pursued at a given plant influences the kind of performance indicators used.

2.1.2 Maintenance performance indicators

Maintenance objectives, maintenance decision making and work management, are essential ingredients for developing maintenance performance measurement system and indicators. Likewise, they form a potential basis for performance evaluation.

The maintenance leading indicators monitor whether the tasks are being performed well so that the desired production results can be attained. The maintenance process is addressed through: work identification (based on maintenance objectives and performance gaps), work planning, work scheduling, and work execution. Key performance indicators for each process are proposed to measure if requirements of each process are satisfied. Below are proposed some examples of indicators from literature that may be relevant to the proposed framework. For work identification, maintenance should identify potential failures, and immediately attend to most of the preventable causes of failure. Precautionary maintenance work is known to mitigate adverse failure consequences like high downtime, maintenance cost, safety and environmental hazards. Among the key performance indicators for work identification are the percentage man hours dedicated to precautionary work over a specified period.

There are many classifications for maintenance performance. Someone is classified measures of maintenance performance in three categories. These categories are (i) measures of equipment performance, (ii) measures of cost performance and (iii) measures of process performance. Also the European standard for maintenance key performance indicators (EN: 15341, 2007) provides three main categories of indicators namely Economic indicators Technical indicators and Organizational indicators. For each category, a list of indicators is given to choose from. The other commonly used classification is leading and lagging indicators. Leading indicators monitor if the tasks are being performed that will 'lead' to results. On the other hand, lagging indicators monitor whether the results or outcomes that have been achieved.

The results of the maintenance process can be summarized as reliability, reliability and operability of the technical systems. These are the core elements that maintenance seeks to address and thus, give measures of maintenance process success. Since maintenance seeks to meet its objectives at an optimal cost, it is imperative to measure the cost effectiveness of the maintenance activities. The lagging indicators are therefore used to measure maintenance results in terms of equipment performance and maintenance cost. A summary of the commonly used lagging maintenance indicators are shown in Table 2.1, which was illustrated by (Muchiri et al., 2010).

Both leading and lagging indicators are therefore important for managing the performance of the maintenance function. Moreover, the leading indicators are even more important than lagging indicators because they have the potential to avoid unfavorable situations from occurring.

2.1.3 Maintenance costs

Maintenance cost is in many instances influenced by the effectiveness and efficiency in which maintenance is performed. Maintenance cost and related indicators are therefore important measures of maintenance performance. Maintenance effectiveness is demonstrated by proactively identifying the right work and doing it at the right time. This in turn eliminates chances of secondary damage, safety and environmental consequences and thus minimizes the maintenance cost. Maintenance efficiency in planning and scheduling resources and manpower can potentially minimize the maintenance cost. Some of the important cost performance indicators are summarized as shown in Table 2.1. The cost and equipment performance indicators are instrumental in doing performance analysis of the maintenance function and identifying the performance gaps that would trigger management actions. They provide a good basis of conducting a root cause analysis for establishing the reasons for performance gaps, which leads to learning and improvement of the maintenance function as was illustrated by (Muchiri et al., 2010).

Table 2.1. A summary of lagging maintenance performance indicators (Muchiri et al., 2010).

CATEGORY	MEASURES / INDICATORS	UNITS	DESCRIPTION
Measures of Equipment Performance	No. of Failures	No.	No. of Failures classified by their consequences: Operational, Non-operational, safety etc
	Failure / Breakdown Frequency	No./ Unit Time	No. of failures per unit time (A measure of Reliability)
	MTBF	Hours	Mean Time Between Failure (A measure of Reliability)
	Availability	%	MTBF/(MTBF + MTTR) = Uptime/(Uptime + downtime)
	OEE	%	Availability * Performance Rate * Quality rate
Measures of Cost Performance	Direct Maintenance Cost	$	Total corrective and Preventive Maint. cost
	Breakdown Severity	%	Breakdown cost / Direct Maint. Cost
	Maintenance Intensity	$ / Unit production	% of Maint. Cost per unit of products produced in a period
	% Maint. Cost component over Manufacturing cost	%	% Maint. Cost / Total Manufacturing cost
	ERV (Equipment Replacement Value)	%	Maint. Cost / New condition Value
	Maintenance Stock turnover	No.	Ratio of cost of materials used from stock within a period
	Percentage Cost of Personnel	%	Staff Cost / Total Maintenance Cost
	Percentage Cost of subcontractors	%	Expenditure of Subcontracting / Total Maintenance cost
	Percentage cost of Supplies	%	Cost of Supplies / Total Maintenance Cost

2.2 Maintenance Policy Evolution

All manufacturing companies define their business strategies and competitive priorities based on several factors related to their production systems, like flexibility, productivity and quality. As e consequence maintenance plays a crucial role in guaranteeing availability and reliability of production facilities; hence designing proper maintenance policies allows companies reach their goals, and guarantees production plants efficiency in terms of quality and availability. For this reason the concept of maintenance has evolved significantly over time. As a consequence several maintenance policies have been introduced and maintenance management techniques have been experienced a major metamorphosis through of efficiency process over recent years. As it can be seen in Figure 2.1, that maintenance models have experienced several phases, from breakdown maintenance, preventive maintenance, predictive maintenance, risk-based maintenance towards maintenance and safety integrity management, and there actually exists a close relationship between maintenance efficiency and such maintenance model. Reliability, availability, maintainability and safety are the key indicators of maintenance efficiency, which are critical in optimizing maintenance model that was recently discussed by (Qingfeng et al., 2011).

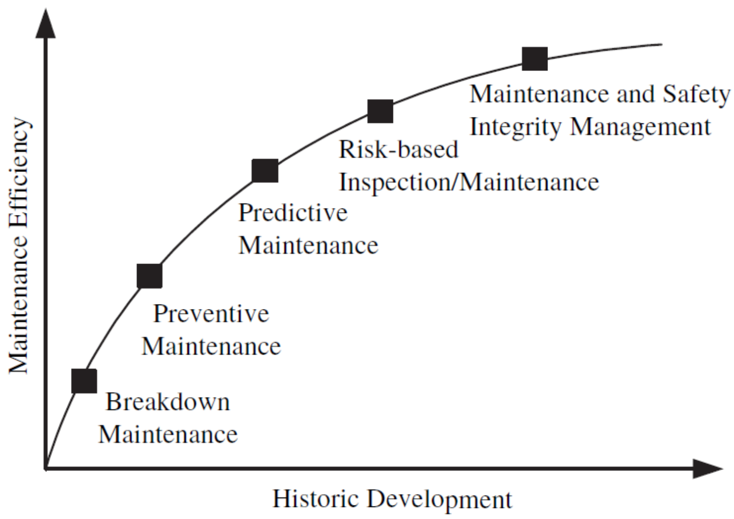

Figure 2.1. Maintenance models and their corresponding maintenance efficiency.

There are two basic maintenance strategies for interventions: Corrective maintenance and Preventive maintenance.

Under the Corrective Maintenance strategy, the components are operated until failure then repair or renovation actions are performed as shown in Figure 2.2. This is the oldest approach to maintenance and is nowadays still adopted in some industries, especially for equipment which is neither safety-critical nor crucial for the production performance where capital costs are small, consequences of failure are slight, no safety risk are immediate and quick failure identification and rapid failure repair are possible, so whose spare parts are easily available and not expensive.

Preventive Maintenance is carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or degradation of functioning of an item (see SS-EN 13306). Preventive maintenance is divided into two types: predetermined maintenance and Condition-based maintenance CBM. According to the way these two basic interventions are applied, maintenance policies can be distinguished.

Nowadays industrial plant's policies to perform maintenance can be grouped into main categories below which are also shown in Figure 2.2, that argument was recently discussed by (Zio & Compare, 2013).

- Reactive or Break down Maintenance;

Simply equipment is used until the fault occurs and no longer able to function properly and then repairs are made. Break down maintenance cannot be the most effective of the typical maintenance programs.

- Preventive maintenance;

The goal of preventive maintenance is to prevent possible problems, by nature; it's very expensive and typically requires intensive labour, more inspection of and repair, to ensure that failures do not occur.

- Predictive maintenance;

Predictive maintenance should be done to predict when a failure will occur and (presumably) make the necessary repairs before the failure, or at least be prepared for failure. Predictive maintenance can be expensive because the substantial data must be collected over a long period to determine the frequencies and modes of failure (e.g. Condition Based Maintenance CBM).

- Ameliorative which consists of identifying the causes of failure and redesign to remove them.

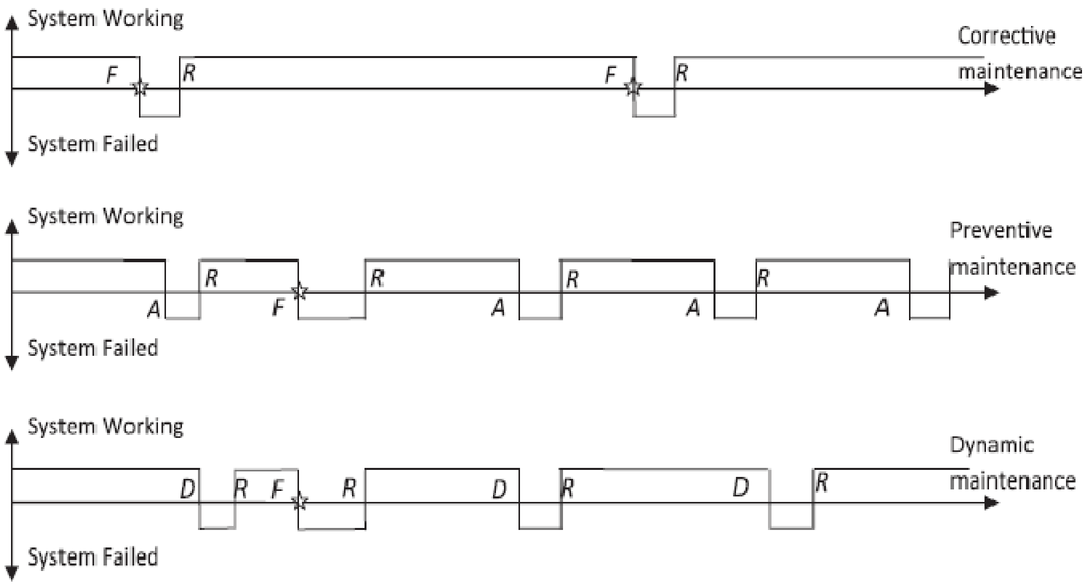

Figure 2.2. Synoptic of the maintenance policies.

Most facilities should consider a combination of the approaches described above because one approach does not economically. If a maintenance program is successful or not, can be evaluated in terms of what is able to prevent the equipment breakdowns, thus determining an increase of the availability of the same, as well as safety. The maintenance activity, its cost, its effectiveness in any type of system depends on the proper integration of these activities, in contrast to what happened historically, and unfortunately often happens today in many companies, where the only policy adopted and reactive maintenance.

2.3 Modern Approaches to Maintenance

Over the last few decades, maintenance functions have drastically devolved with the growth of technology.

In the industry, application of the PM strategy can be generally performed through either experience or Original Equipment Manufacturer OEM recommendations, and is based on a scientific approach. The application of PM through experience is a conventional PM practice. In most cases, it is performed at regular time intervals, T. But PM intervals based on OEM recommendations may not be optimal because actual operating conditions may be very different from those considered by the OEM. As such, actual outcomes may not satisfy company requirements.

According to (Ahmad & Kamaruddin, 2012) maintenance concept development forms the framework from which installation-specific maintenance techniques are developed and is the embodiment of the way a company thinks about the role of maintenance as an operational function. Some examples of maintenance concepts for industrial management maintenance concept development framework are Reliability-Centred Maintenance RCM, Business-Centred Maintenance BCM, Risk-Based Maintenance RBM, Total-Productive Maintenance TPM. The Specific-Based Technique, as its name implies, is a specific maintenance technique that has unique principles for solving maintenance problems. Examples of specific-based technique are Time-Based Maintenance TBM and Condition-Based Maintenance CBM.

In process industries, to improve safety, reliability and availability of the plants and their equipments are tried to implement risk-based maintenance programs. On the other hand reliability, availability and safety of equipment are difficult to control and guarantee due to the existing maintenance deficiencies, maintenance surplus, risk of potential danger and possible accidents. In order to ensure stable production and reduce operation cost, equipment Maintenance and Safety Integrity management system MSI is established that can provide dynamic risk rank data, predictive maintenance data and Risk and Maintenance RAM decision-making data, through which the personnel at all levels can grasp the risk state of equipment timely and accurately and optimize maintenance schedules to support the decision-making. The result of an engineering case shows that the system can improve reliability, availability, and safety, lower failure frequency, decrease failure consequences and make full use of maintenance resources, thus achieving the reasonable and positive result.

2.3.1 Equipment integrity management system

Equipment integrity management system has created a program that collects reliability data and maintenance data through the management workflow. The probabilistic analysis, failure consequence analysis, quantitative risk analysis, failure prediction, failure prevention, maintenance task optimization and quantitative indicators of performance monitoring heavily depend on reliability data and maintenance data.

Equipment integrity management system can be divided into four aspects: (i) Work execution and review; (ii) Proactive maintenance; (iii) Risk-based management, as well as (iv) Maintenance and Safety Integrity Management MSI as is shown in Figure 2.3, which was shown by (Qingfeng et al., 2011).

In process industries, are trying to implement risk-based maintenance programs to improve safety, reliability and availability of the plants and their equipments. Risk-based management which utilizes RBI, Reliability Centered Maintenance RCM and Safety Integrity Level SIL evaluation tools to identify and classify key equipments is the core content and the technical support for the system. Risk-based Evaluation can be used to determine the risk rank of equipment, formulate optimal maintenance tasks, allocate maintenance resources reasonably and avoid maintenance deficiencies/surplus, thus ensuring the reliability of equipment. Preventive maintenance, predictive maintenance and Root Case Analysis RCA are all proactive maintenance modes which are applied by the integrity management. Predictive maintenance information, risk rank of equipment and Reliability data and Maintenance evaluation RAM indicators are the basis to make inspection/maintenance strategies. In every stage of the life cycle of equipment, purposeful preventive maintenance and failure eradication plans are needed, especially for high-risk equipment.

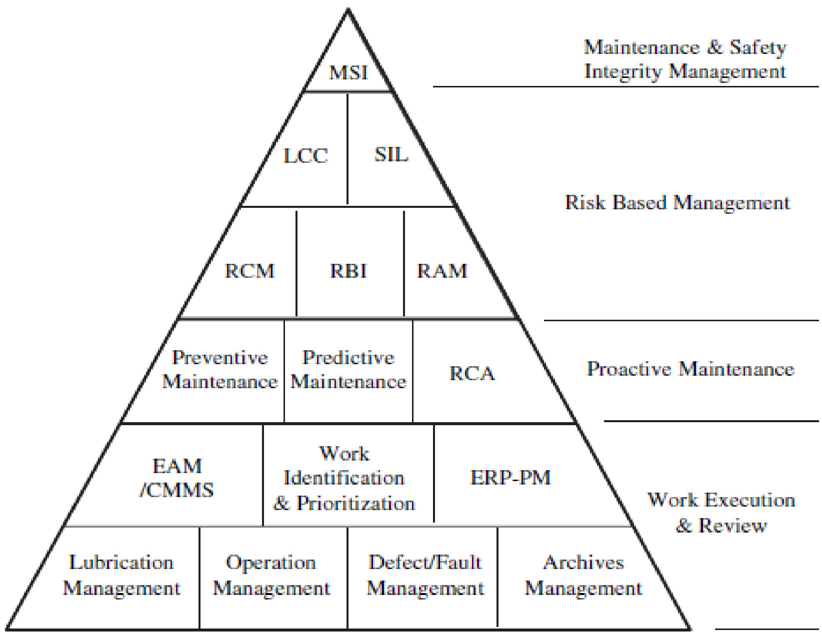

Figure 2.3. Equipment integrity management pyramid structure in process industry.

During the work execution and review process, optimal maintenance tasks are executed through Enterprise Asset management EAM, computerized maintenance and Management System CMMS or Enterprise Resource Planning ERP systems, while failure data and maintenance data are recorded according to certain standards. In the meantime, working tasks are confirmed and optimized through professional management programs in terms of lubrication management, operation management, abnormality management like defect and fault, and archives management, thus ensuring the quality of the workflow. Abnormality management, which can be divided into preventive management and predictive management, is also important in the integrity management system, which was recently discussed by (Qingfeng et al., 2011).

Some contents of preventive management coincide with those of intrinsic safety design. In order to avoid failures which are usually un obvious, safety protection devices are set up during the reliability design process, which needs planned inspection, planned testing and planned checking to formulate failure-pinpointing tasks. To achieve the goal of intrinsic safety, the most important thing is to prevent incipient failure in advance, and through self-diagnosis or self recovery, equipment can re operate in an orderly and stable state.

Effective preventive management can generally ensure the safety of individual equipment, but can't ensure the integral safety of one unit or one system, while predictive management can fulfill this task. It utilizes predictive maintenance technology in combination of vibration, temperature, pressure, flow, liquid level, current, corrosion rate and other features to perform incipient failure diagnosis by vibration analysis, thermograph analysis, ultrasonic analysis and lubrication oil analysis. By doing so, uncertainty of maintenance, failure frequency and failure consequence can be reduced, thus minimizing maintenance cost while improving operational safety.

In process industries, reliability data usually includes the failure mode, failure cause, failure description, failure position, failure consequences (e.g. safety consequence, economic consequence, environmental consequences) and failure detection method, while maintenance data mainly refers to the time when potential failure is detected, when failure starts, when downtime begins, when maintenance begins and when maintenance ends.

2.3.2 Reliability, availability, and maintainability indicators

Both reliability data and maintenance data are often used in probabilistic analysis, RCA, Weibull plot, Monte Carlo simulation, Markov model and so on to perform failure prediction, reliability prediction and maintainability prediction.

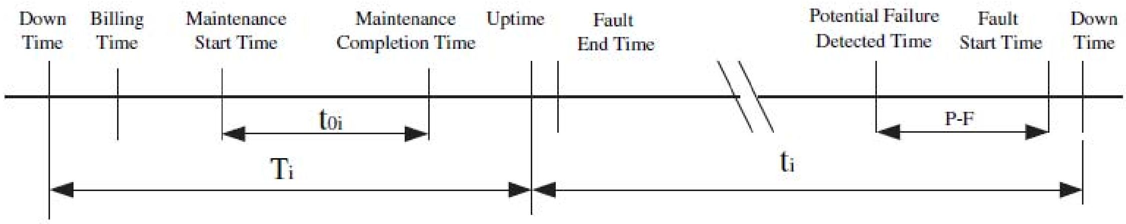

Figure 2.3. Reliability and maintenance data for equipment (Qingfeng et al., 2011).

As Figure 2.3 shows, t_i represents operation time, t_{0i} represents repair time, and T_i represents breakdown time. Have been provided that there occur N_0 failures during operation and the equipment can continue to be used as new one after repair. Mean Time Between failures MTBF, Mean Time to Repair MTTR and Mean Time between Outage MTBO can be calculated by Equations 2.1, 2.2 and 2.3 below respectively, which was recently illustrated by (Qingfeng et al., 2011).

$$MTBF = {}^{1}/_{N} \sum_{i=1}^{N0} t_i \tag{2.1}$$

$$MTTR = {}^{1}/_{N} \sum_{i=1}^{N0} t_{0i} \tag{2.2}$$

$$MTBO = {}^{1}/_{N} \sum_{i=0}^{N0} T_i \tag{2.3}$$

MTBF is related to availability, reliability and failure frequency, which represents the number of accidents that occurred in a fixed interval of time. Failure consequence is studied from three aspects such as the safety consequence, environmental consequence and economic consequences, which is affected by failure consequence, while the economic cost is proportional to MTBO.

- Reliability;

Reliability, a probabilistic measure of the failure-free operation, is the probability of the equipment functioning without failure during a given time period under certain conditions which is often expressed as Equation 2.4. It can be improved by reducing failure frequency.

$$R(t) = \exp\left({}^{-t}/_{MTBF}\right) = \exp\left(-\lambda \mathrm{t_i}\right) \tag{2.4}$$

Where, λ is a constant defined as the failure frequency.

Reliability determines whether the output is as expected or can be profitable, so it helps determine what and how much maintenance should be carried out. Equipment with a long failure-free period can reduce accessories reserves and maintenance cost. High-reliability can increase equipment availability while decreasing outrage time, maintenance cost and secondary failure loss, and thus contribute huge benefit for the company. The key indicators which describe reliability include MTBF, MTTF, mean life of components, failure frequency, and maximum number of failures permitted in a specific time-interval and so on.

- Availability;

Availability is defined as the ability of equipment functioning well during a definite period or even beyond it. It gives an indication of available working time during operation and can be expressed as in Equation 2.5;

$$Availability = {}^{MTBF}/_{(MTBF + MTTR)} \tag{2.5}$$

Increasing failure-free time and decreasing downtime can enhance availability, which can be converted into reliability and maintainability requirements in terms of acceptable failure frequency and outage hours.

- Maintainability

Maintainability is the ability that equipment can restore to normal function in a specified period of time or beyond it. It correlates with design and installation quality. Maintainability indicator can be used to evaluate, ascertain and explain maintenance programs and requirements. Maintenance project, personnel, organization, preparation and procedures all affect maintainability, which is often expressed in Equation 2.6. Designed maintenance procedures and maintenance time are the baseline of maintainability, and the key figure of merit for maintainability is MTTR.

$$M(t) = 1 - \exp\left({}^{-t_{0i}}/_{MTTR}\right) \tag{2.6}$$

The shorter MTTR is, the higher the maintainability will be. Three main parameters: repair time (which is the function decided by equipment design, and it is related to the training and skill of the personnel in charge of maintenance), logistic time (i.e. time for supplying parts) and administrative time (a function of operational structure of the organization, standard maintenance procedure, and maintenance quality assurance document) are concerned with downtime.

High availability, reliability and maintainability and excellent performance are characteristics of highly effective management, and they are main indicators of lowering safety cost, environmental cost and economic cost, which was discussed by (Qingfeng et al., 2011).

2.3.2.1 Risk rank indicator

The importance of equipment integrity may be represented by risk rank. In general, the risk of equipment in process industry is studied in terms of (i) Safety Risk; (ii) Environmental Risk, and (iii) Economic Risk, and it is concerned with the failure frequency, failure consequence, risk matrix and risk criterion established according to management goals.

- Safety Risk;

  Safety Risk rank is determined by safety consequence, failure frequency, safety risk criteria and safety risk matrices;

- Environmental Risk;

  Environmental Risk rank is determined by environmental consequence, failure frequency, environmental risk criteria and environmental risk matrices;

- Economic Risk;

  Economic Risk rank is determined by economic consequence, failure frequency, economic risk criteria and economic risk matrices. The criteria which are related to reliability, availability and maintainability are mainly defined by engineers, maintenance staffs, safety authorities.

Risk is the product of failure Probability P_f and Consequences of failure C_f (safety, environmental and economic) which is calculated by Equation 2.7.

$$R = P_f \times C_f \tag{2.7}$$

In some cases, risk criteria are certain, so the main influence factors to dynamic risk changes are the failure frequency and failure consequences, while failure frequency, also be called failure rate, is usually more important. On one hand, the dynamic risk rank indicator is an effective way of evaluating the previous risk rank and inspection/maintenance task; on the other hand, it lays the foundation for managers to revise management objectives and establish the next risk evaluation task. If the failure mode is identified, the risk is evaluated by analyzing failure frequency, failure consequence and failure detect ability. If the risk is too high, efforts are needed either to reduce the frequency and/or consequence, or to increase failure detect ability in order to make it possible to avoid or at least to reduce the severity of the failure.

Using the definitions of Mechanical Integrity, Reliability, and Risk, we can graphically display the maintenance approach determination process. In addition, Mechanical Integrity and Reliability are NOT the same thing.

Mechanical Integrity is focused on keeping chemicals contained-purely a safety and environmental consideration focused specifically on consequence reduction with no consideration for production capability or impact.

Reliability, on the other hand, is focused on equipment working when and how you expect it to essentially relate to production, but with safety and environmental considerations as well. In other words, Reliability is Mechanical Integrity (containment, safety and environmental considerations) plus the ability to produce a desired product on demand. It is easier to maintain equipment to meet Mechanical Integrity expectations than it is to meet Reliability expectations. The distinction between Mechanical Integrity and Reliability sets the stage for making risk determinations. It is one of the tools that can be used to identify and categorize all equipment within a facility in order to develop an appropriate customized set of risk based maintenance programs for the facility.

Below there is an example of a risk based approach and determination matrix shown in Figure 2.4 that could be used for developing an appropriate set of maintenance programs for facilities. Figure 2.4 is a common and simple 3x3 risk matrix plotting Probability against Consequence. Added to it is an overlay of the three potential maintenance approaches positioned using a fictitious company's risk tolerance criteria. The locations of the maintenance programs in the individual cells within the matrix may be different from company to company depending on each company's tolerance for risk. This example Maintenance Approach Risk Matrix has nine cells; three representing Breakdown Maintenance; three representing Predictive Maintenance, and three representing Preventive Maintenance. It is not symmetrical, though. This example matrix is biased toward consequences that is it gives more consideration to consequences than probability which fits the fictitious company's risk management approach, which was shown by (Sepeda, 2009).

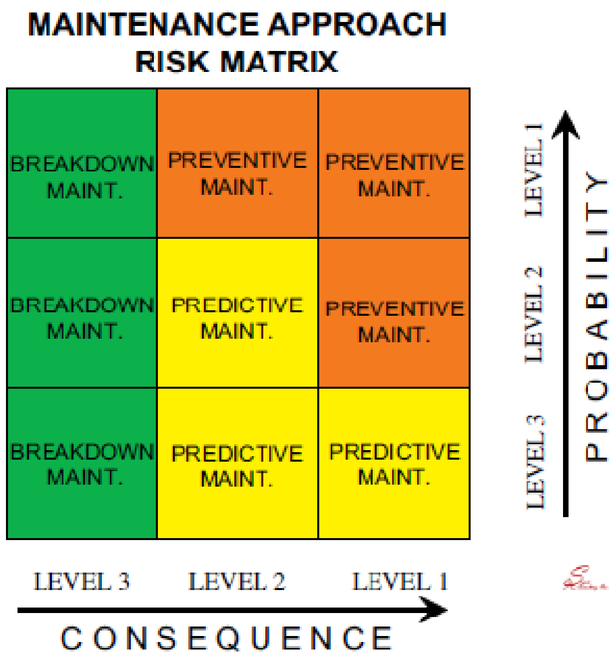

Figure 2.4. Maintenance approach risk matrix (Sepeda, 2009).

To be able to select the appropriate cell within this matrix, the user must clearly define the "Consequence of Failure" and the "Probability of Failure" levels.

For this example, the "Consequence of Failure" levels are defined as:

- Consequence of Failure Level 1: Mechanical Integrity Issues identify equipment whose failure would reasonably result in:

  -Loss of containment causing a safety and/or environmental hazard;

  -Shrapnel and/or flying debris causing a safety hazard and potential damage to other equipment, and

  -Noticeable negative impact on the surrounding community.

- Consequence of Failure Level 2: Reliability Issues identify equipment whose failure would reasonably result only in:

  -Loss of production or production capacity;

  Product quality issues;

  -Significant increase in operational costs, and

  -Potential for short term regulatory non compliance.

- Consequence of Failure Level 3: Low Level Mechanical Integrity and/or Reliability Issues identify equipment whose failure would result only in:

  -Operational inconveniences;

-Maintenance inconveniences, and

-Minor increase in (operational or maintenance) costs.

The "Probability of Failure" levels for this example are defined as:

- Probability of Failure Level 1: Two or less independent safeguards* plus operator intervention, or human error alone can cause failure.
- Probability of Failure Level 2: Three independent safeguards* plus operator intervention.
- Probability of Failure Level 3: At least four independent safeguards* plus operator intervention.

*Note: Independent Safeguards are not limited to instrumented systems. They may include anything from inherently safer design to mechanical protection systems (such as double wall pipe or burst disks) and can include prevention and/or mitigate devices and systems such as containment areas, protective barriers, etc. Some Safeguards, often instrumentation with defined Safety Integrity Levels SILs, are Independent Layers of Protection and may warrant higher consideration and credit than simple Safeguards with relatively low performance characteristics.

The resultant actions are one of the three maintenance approaches Preventive, Predictive, or Breakdown maintenance. These are already written in on the cells within the example risk matrix (Figure 2.4). Note that the user can and should adjust the placement of these to suit their particular risk tolerance criteria. If a company already has a functioning Risk Ranking Matrix that can be adapted to determining appropriate maintenance approaches, they should do so instead of using this risk matrix example. This display is for illustrative purposes and should be considered an example only, that it was illustrated by (Sepeda, 2009).

2.4 Risk Based Maintenance

The main aim of this methodology is to reduce the overall risk that may result as the consequence of unexpected failures of operating facilities. The inspection and maintenance activities are prioritized on the basis of quantified risk caused due to failure of the components, so that the total risk can be minimized using risk-based maintenance. The high-risk components are inspected and maintained usually with greater frequency and thoroughness and are maintained in a greater manner, to achieve tolerable risk criteria.

The Risk-based maintenance methodology consists of six modules as was shown by (Arunraj & Maiti, 2007).

- Hazard analysis;

  Hazard analysis is done to identify the failure scenario. The failure scenarios are developed based on the operational characteristics of the system, physical conditions under which operations occur, geometry of the system and safety arrangements.

- Likelihood assessment;

  The objective here is to calculate occurrence of the undesired event. The frequency of failure or failure probability for defined period of time is calculated in this step.

- Consequence assessment;

  The objective here is to quantify the potential consequences of the credible failure scenario. The consequences are production loss, asset loss, environmental loss, and health and safety loss. In some of the literature, the production loss is specified as performance loss and operational loss.

- Risk estimation;

  Based on the result of consequence analysis and probabilistic failure analysis, the risk is estimated for each unit.

- Risk acceptance;

  The computed risk is compared against the risk acceptance criteria. If any of the unit/component risk exceeds the acceptance criteria, maintenance is required to reduce the risk.

- Maintenance planning;

  Maintenance planning is adopted to reduce the risk.

2.4.1 Decision making method

A decision generally deals with three elements: alternatives, consequences, and preferences. The alternatives are the possible choices for consideration. The consequences are the potential outcomes of a decision. Decision analysis provides methods for quantifying preferences tradeoffs for performance along multiple decision attributes while taking into account risk objectives. The decision outcomes may be affected by uncertainty; however, the goal is to choose the best alternative with the proper consideration of uncertainty.

The methodology can be considered complementary to the Reliability Centred Maintenance RCM philosophy. According to the decision-making diagrams proposed by the RCM philosophy, the maintenance cost-effectiveness must be considered as a decision variable for maintenance policy selection. The risk-based method as was shown by (Carazas & Souza,

2010) can be used for cost-effectiveness analysis supporting the maintenance managers to select the most useful maintenance policy among a set of technically feasible maintenance alternatives. The method integrates financial and technical aspects associated with all applicable maintenance policies for an equipment, including the evaluation of the equipment reliability when assisted by a given maintenance policy and the costs associated with the equipment failure, named cost of failure consequences. That cost is estimated based on the equipment failure effects over the operation plant, including environmental, safety and operational aspects, mainly the reduction of plant output that causes production loss.

Based on RCM concepts, a primary maintenance practice selection procedure for equipment can be developed. That procedure, presented in Table 2.2, is based on the presence of symptoms that indicate whether a given failure mode is being developed and on the pattern of failure occurrence frequency that can be random or repetitive.

Table 2.2. Simple decision-making procedure for maintenance selection.

		Failure frequency of occurrence	
		Random	Repetitive pattern
Equipment failure	With symptom	Predictive	Preventive or predictive
	Without symptoms	Corrective	Preventive

According to RCM concepts, equipment failed states are known as functional failures, because they occur when the equipment is unable to fulfill a function to a standard of performance which is acceptable by the user. In addition to the total inability to function, this definition encompasses partial failures, where the equipment still functions but at an unacceptable level of performance.

In Figure 2.5 a graphic indicates, in a generic way, the functional behavior of equipment, the performance of which presents degradation during operational time.

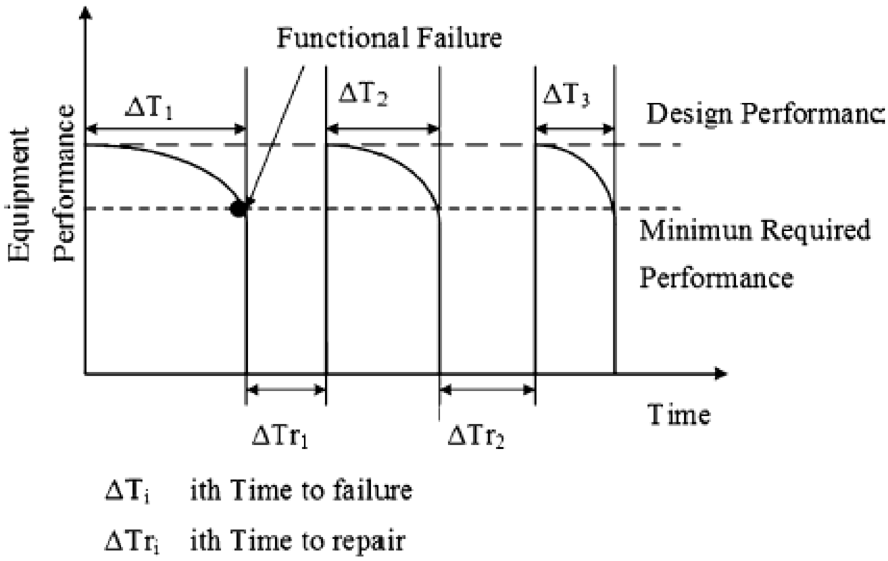

Figure 2.5. Degradation of equipment performance with operational time.

If the time to failure (ΔTi) recorded in the maintenance database is quite similar or repetitive failure pattern, the equipment presents a frequency of failure that is almost constant during the operational period. If the failure Root Cause Analysis RCA indicates that most of the failures are caused by the same age-related degradation mechanism, the equipment failure mode presents a repetitive pattern. The aging failure is a gradual failure, meaning that the performance of the equipment is gradually drifting out of the specified range.

According to Table 2.2 as was shown by (Carazas & Souza, 2010), preventive maintenance tasks may be used to lower that frequency of failure. Those tasks, based on the scheduled replacement or restoration of components the failure of which causes the operational performance degradation of the equipment, aims at restoring the initial performance of equipment at a specified operational time limit, regardless of its apparent condition at the time. The frequency of scheduled maintenance tasks is governed by the operational age at which the equipment shows a rapid decrease in performance. If the equipment presents performance degradation “failure symptoms”, as shown in Figure 2.5, due to some component loss of performance associated with a failure mode development, a monitoring system may be used to detect failure mode development aiming at the use of predictive maintenance practice instead of preventive practice.

The predictive or on-condition tasks entail checking for potential failures, so that action can be taken to prevent the equipment failure. The maintenance tasks are not previously scheduled, being executed based on the assessment of the condition of the equipment. The use of that maintenance practice is recommended for both random frequency of failure (quite different ΔTi) and constant frequency of failure.

If in the functional behavior of equipment, the performance of which does not present degradation until the occurrence of functional failure. In that case the failure occurs suddenly without any previous symptoms. As it was proposed by (Carazas & Souza, 2010) for that case; if the equipment presents a repetitive failure pattern the use of preventive maintenance is recommended. On the contrary, if the equipment does not present performance degradation and the failure pattern is random, the maintenance planner can only use corrective actions to restore the equipment to its normal operational condition. Corrective maintenance is performed after failure has occurred in order to return the equipment to service as soon as possible.

Although the decision-making procedure that was presented in Table 2.2 before, allows the selection of a set of maintenance practices to be used in equipment, it does not indicate the selection of the most cost effective maintenance practice. So as to deal with this issue, one needs to evaluate the equipment failure probability and the costs of maintenance and failure consequences. The methodology proposed, for maintenance policy selection is presented in Figure 2.6.

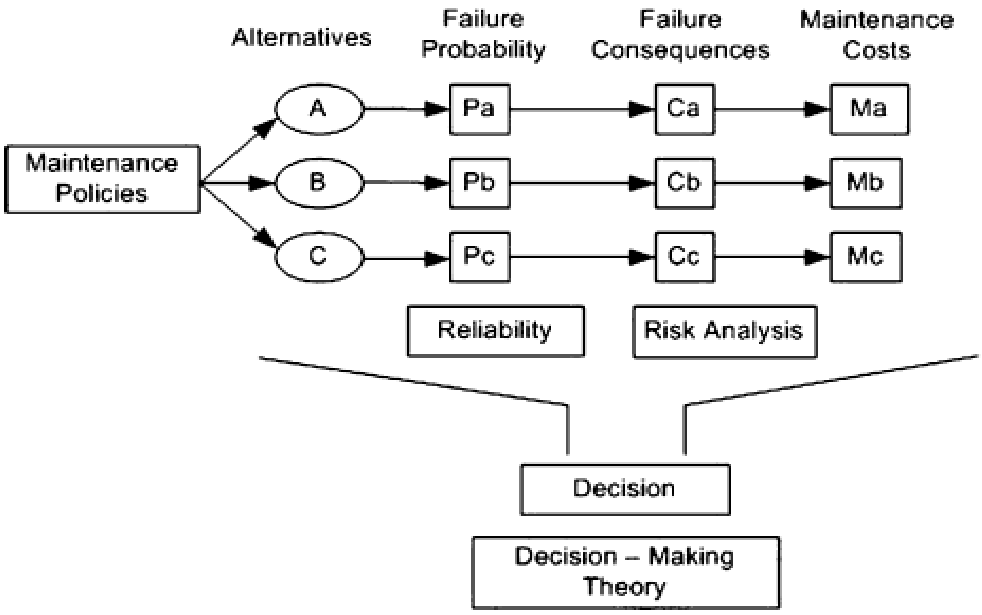

Figure 2.6. Flowchart for risk-based methodology.

Initially, the maintenance planner must list all possible maintenance procedures that present technical feasibility to be applied to the equipment. For each one of those maintenance procedures, the equipment failure probability must be evaluated through the use of reliability concepts. Based on “time to failure” database, the analyst can calculate the equipment reliability. Also for each one of those maintenance procedures the future equipment reliability can be predicted.

The second step in the procedure is the assessment of maintenance procedures costs and equipment failure consequence costs based on cost database. The equipment failure consequences costs assessment involves the definition of the equipment failure effects on the plant operational availability and safety, including environmental impact.

The risk analysis concepts are usually used to predict the equipment failure consequences given an industrial plant operational scenario. Once the equipment failure probability is evaluated for each of the feasible maintenance procedures and the failure consequences and maintenance costs are estimated, a decision-making procedure, based on decision tree, is used to select the maintenance procedure that minimizes the risk associated with the equipment failure expressed by the mean failure costs.

To be added, the present method was discussed by (Carazas & Souza, 2010); also he has illustrated the result of this study with a practice example in power plant. It can be used not only to select maintenance procedures but also to evaluate the feasibility of changes in industrial plant design such as the use of redundant equipment, installation of new control and monitoring systems, equipment retrofitting and even changes in the plant operational procedure.

2.4.2 Risk analysis concept

Risk analysis is a technique for identifying, characterizing, quantifying, and evaluating the loss of an event. Risk analysis approach integrates probability and consequence analysis at various stages of the analysis and attempts to answer the following questions:

_ What can go wrong that could lead to a system failure?

_ How can it go wrong?

_ How likely is its occurrence?

_ What would the consequences be in case it happens?

In this context, risk can be defined qualitatively/quantitatively as the following set of duplets for a particular failure scenario. The risk analysis method aims at the evaluation of the likelihood of occurrence of equipment failures and their consequences for the plant operation, characterizing a quantitative risk analysis.

The output of a quantitative risk assessment will typically be a number, such as cost impact in € per unit time. The number could be used to prioritize a series of items that have been risk assessed. Quantitative risk assessment requires a great deal of data both for the assessment of probabilities and assessment of consequences. The procedure is presented in Figure 2.7 that was also shown by (Carazas & Souza, 2010).

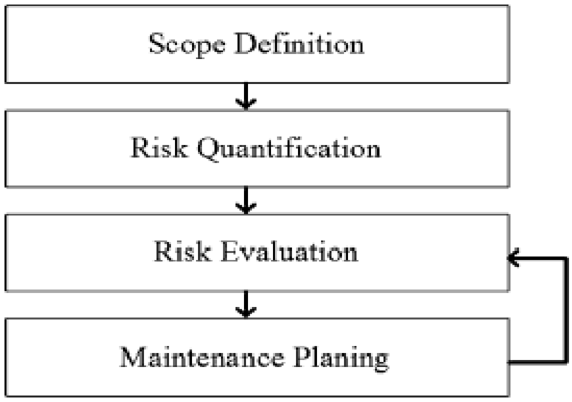

Figure 2.7. Risk analysis method.

2.4.3 Risk quantification

The second step involves the risk quantification that must be executed in two steps:
(i) Equipment failure probability, (ii) Estimate and failure consequences analysis.

2.4.3.1 Reliability analysis

Reliability as has been discussed before can be defined for a system or a component as its ability to fulfill its design functions under designed operational or environmental conditions for a specified time period. This ability is commonly measured using probabilities.

Reliability is, therefore, the occurrence of the complementary event to failure as provided in the following expression (Equation 2.8).

$$R(t) = 1 - F(t) \tag{2.8}$$

Probably the single most used parameter to characterize reliability is the Mean Time to Failure MTTF. It is just the expected or mean value of the failure time, expressed as Equation 2.9.

$$MTTF = \int_0^\infty R(t)dt \tag{2.9}$$

Random failures (represented by the exponential probability function) constitute the most widely used model for describing reliability phenomena. They are defined by the assumption that the rate of failure of a system is independent of its age and other characteristics of its operating history. On the other hand the constant failure rate approximation is often quite adequate even though a system or some of its components may exhibit moderate early failures or aging effects. The magnitude of early failures is limited by strictly quality control in manufacturing and aging effects can be sharply limited by careful predictive or preventive maintenance.

The Weibull probability distribution is one of the most widely used distributions in reliability calculations involving time-related failures. Through the appropriate choice of parameters a variety of failure rate behaviors can be modeled, including constant failure rate, in addition to failure rates modeling both wear-in and wear out phenomena.

The two-parameter Weibull distribution, typically used to model wear-out or fatigue failures is represented by the following Equation 2.10, as was shown by (Carazas & Souza, 2010):

$$R(t) = e^{-(t|\eta)^{\beta\prime}} \tag{2.10}$$

Where β is the Weibull distribution shape parameter and η is the Weibull distribution characteristic life (h). The distribution parameters are estimated through the use of parametric estimation methods that fit the distribution to the 'time to failure' data. There are procedures for estimating the Weibull distribution parameters from data, using what is known as the maximum likelihood estimation method. The reliability of an equipment or component, the failure of which can be considered as an initiating event as for risk analysis, should be determined from historical data if a significant number of failures have occurred in the past.

For the present study equipment failure probability can be estimated based on 'time to failure' database developed in the industrial plant process.

If some maintenance actions are performed on the system at constant time intervals T (characterizing preventive intervention), smaller than the expected operational time, it is possible to define the reliability of the maintained system as is shown by Equation 2.11:

$$R_M(t) = [R(T)]^N R(t - NT),\ NT \le t < (N+1)T \tag{2.11}$$

Being N= 0, 1, 2... the number of maintenance intervention in a given operational time t.

The analysis is based on the hypothesis that the system is restored to an 'as good as new' condition after the maintenance action. This implies that the maintained system at time t> T has no memory of accumulated wear effects for times before T. Thus, in the interval $NT < t \leq (N+1)T$, the reliability is the product of the probability $[R(T)]^{N}$ that the system operated without failures to NT, and the probability R(t – NT) that a system 'as good as new' at NT will operated without failure for a time (t – NT).

Preventive maintenance has a quite effect when aging or wear causes the failure rate to become time-dependent, and the effect on reliability is presented in Figure 2.8 as was shown by (Carazas & Souza, 2010).

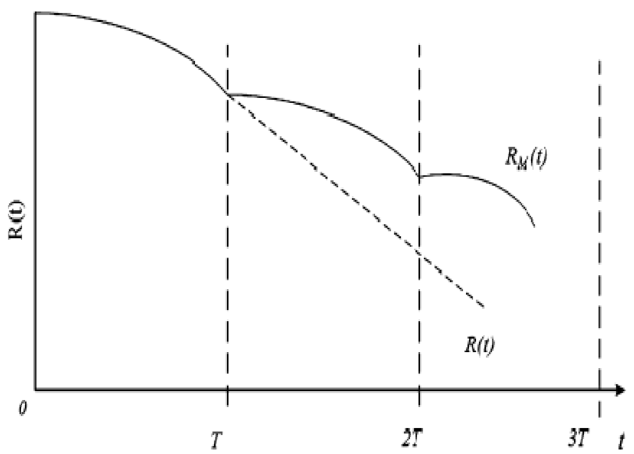

Figure 2.8. The effective of preventive maintenance on reliability.

The use of predictive maintenance has similar effect on the system reliability but the maintenance actions are executed at variable time intervals. The reliability of the maintained systems can be expressed as Equation 2.12:

$$R_M(t) = [\prod_1^N R(T_i)]R(t - \sum_{i=1}^{N} T_i), t > \sum_{i=1}^{N} T_i \qquad (2.12)$$

Considering that the maintenance actions will increase the system mean time to failure, the availability of the system will also increase. So the selection of a maintenance policy has a direct effect on the failure probability of a system thus affecting its operational risk profile.

2.4.3.2 Failure consequence analysis

The goal of the scenario development is to derive a complete set of scenarios that encompasses all of the propagation paths following the occurrence of the initiating event. To describe the cause and effect relationship between initiators and the event progression, it is necessary to identify those functions that act as barriers to the failure progression.

A failure scenario is a description of a series of events, which leads to a failure event. It may contain a single event or a combination of sequential events. The expectation of a scenario does not mean it will indeed occur, but that there is a reasonable probability that it would occur. A scenario is neither a specific situation nor a specific event, but a description of a typical situation that covers a set of possible events or situations. Failure scenarios are generated based on the operational characteristics of the system, physical conditions under which operation occur, geometry of the system, and safety arrangements.

The development of a failure scenario should be based on the following steps as was shown by (Carazas & Souza, 2010):

- Identify the mitigating functions for each initiating event,
- Identify the corresponding human actions, systems or hardware operations that can be considered barriers for the initiating event propagation,
- Develop a failure scenario based on cause-consequence analysis methodology, such as Fault Tree Analysis or Event Tree Analysis.

The cause–consequence diagram focuses on the occurrence of an initiating event. Once that event has been identified all potential consequences can be developed based o the Event Tree Analysis. The event tree method is used as the link between the occurrence of the initiating event and the various consequences that could result. The initiating event is followed by
Other events leading to an overall result (consequence). Those events are named as reactionary events that can be interpreted by the barriers to the initiating event progression and should be arranged according to the temporal action of the system. The reaction can either be a success of failure. The functionality of each event (usually represented by the operational condition of a given component) is investigated, and expressed as ‘yes’ or ‘no’ answers.

That answer is probabilistic, once the component may fail during the plant operation. The probability of failure (representing the ‘no’ answer) is estimated based on the reliability analysis of the component (or group of components) associated with the event under analysis. The probability of success (‘yes’ answer) is represented by the component reliability.

The consequence tracing part of the diagram involves taking the initiating event and following the resulting chain of events through the system. At various steps, the chains may branch into multiple paths. The consequence analysis results in a description of the relevant failure scenarios given the occurrence of the initiating event and is used to calculate both the likelihood and the consequences of each failure scenario. A quantitative evaluation of the diagram probability values can be used to estimate the probability of the overall system state. The probabilities of various events in a sequence can be viewed as conditional probabilities and therefore can be multiplied to obtain the occurrence probability of a given sequence. The probabilities of various sequences can be summed up to determine the overall probability of a certain outcome. The addition of consequence evaluation of a scenario allows for generation of a risk value. The risk associated with a given cause-consequence diagram branch can be calculate, as it was illustrated by (Carazas & Souza, 2010). Below, Figure 2.9 shows the cause-consequence logic.

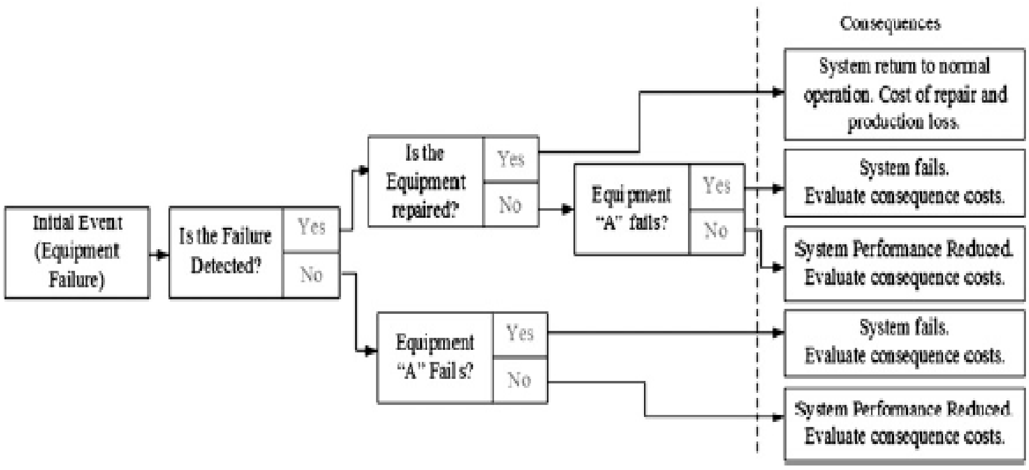

Figure 2.9. Cause-consequence diagram logical notation (Carazas & Souza, 2010).

Once the cause-consequence diagram is developed for the main equipment in a process plant, the risk analysis can select the most important equipment for plant operation using as prioritization criterion the severity of its failure consequences. The higher that severity, the higher is the priority of the equipment for maintenance planning. Further more for that equipment, the maintenance planner can select the most feasible maintenance procedures aiming at the reduction of the failure probability and, consequently, aiming at risk minimization.

2.4.3.3 *Risk analysis methodologies*

Risk analysis methodologies are listed in 62 from varied references as was revisited by (Arunraj & Maiti, 2007). The risk analysis methodologies and techniques are categorized from diverse references into deterministic, probabilistic, and combination of deterministic and probabilistic approaches. The deterministic methods take into consideration the product, the equipment, and the quantification of consequences for various targets such as people, environment and equipment. This approach assumes that the occurrence of a hazard and its consequences are known and certain. The probabilistic methods are based on the probability or frequency of hazardous situation apparitions or on the occurrence of potential accident. Again they are cross classified into qualitative, quantitative and semi-quantitative as shown in Table 2.3, which was shown and discussed by (Arunraj & Maiti, 2007).

Table 2.3. Classification of risk analysis methodologies, Revisited by (Arunraj & Maiti, 2007).

Method types	Deterministic	Probabilistic	Deterministic and probabilistic
Qualitative	Action error analysis [14], checklist [15], concept hazard analysis [15], goal oriented failure analysis [14], hazard and operatibility (HAZOP) [15–22], failure mode effect analysis (FMEA) [15,19], human hazard operability (HumanHAZOP) [23], hazard identification system (HAZID) [24], master logic diagram [25], optimal hazard and operatibility (OptHAZOP) [15,26], plant level safety analysis (PLSA) [27], preliminary risk analysis [14], process hazard analysis (PHA) [28–30], reliability block diagram (RBD) [14], task analysis [14], Whatif? analysis [14,15,18], sneak analysis [31], risk matrix [32–34]	Delphi technique [14], expert judgment [35], rapid ranking [36]	Maximum credible accident analysis, [15,37–40], safety culture hazard and operability (SCHAZOP) [23], structural reliability analysis (SRA) [14]
Quantitative	Accident hazard index [41], chemical runaway reaction hazard index [42], Dow's chemical exposure index (CEI) [43,15], Dow's fire and explosion index (FEI) [44,15], fire and explosion damage index (FEDI) [15], hazard identification and ranking (HIRA) [15], instantaneous fractional annual loss (IFAL) [15], reactivity risk index (RRI) [45], safety weighted hazard index (SWeHI) [46], toxic damage index (TDI) [15]	Event tree analysis (ETA) [14,15,47,48], fault tree analysis (FTA) [14,15,48], petri nets [48], probabilistic fault tree (PROFAT) [49], fuzzy fault tree analysis [50,51], risk integral [52]	Method organised systematic analysis of risk (MOSAR) [14], quantitative risk analysis (QRA) [9,15,45,53–55], rapid risk analysis [15,56–59], probabilistic risk analysis (PRA) [15,60], international study group on risk analysis (ISGRA) [15], optimal risk assessment (ORA) [15,61], IDEF methodology [62]
Semi-quantitative	Domino effect analysis [15,63], layers of protection analysis (LOPA) [64], predictive risk index [65], world health organization (WHO) [15], risk priority number [14]	IAEA-TECDOC-727 [66,67], maintenance analysis [14], semi-quantitative fault tree analysis [68], short cut risk assessment [14,69]	Safety analysis [15], failure mode effect criticality analysis (FMECA) [15], facility risk review (FRR) [19,70]

2.5 Maintenance Cost

In many industries there is the problem of not only how to control the maintenance activities of the plant, but also to identify areas and equipment which are considered higher risk of failure and be able to handle any upgrades. The production, which is usually made from more elementary operation performed on the manufactured article, involves costs linked in part to the time of production and in part to support structures that allow the performance. Are therefore always present expenditure items in addition to the cost of raw materials and labor, resulting from centralized systems in general, commercial and administrative, depreciation, logistics, and etc.

We can then define the costs into three categories:

- Direct costs, related to the pure phase of production of the product, divided into:
  • Cost of raw materials and components,
  • Labour costs,
  • Energy,
  • Cost of auxiliary materials and consumables.
- Indirect costs arising from the structures are not strictly production of company, divided into:
  • Labour costs are not directly involved in the production,
  • Cost of services (administration, sales, logistics etc.),
  • Amortization charge,
  • Cost of maintenance of the equipment directly involved in the production,
  • Cost of maintenance of equipment not directly involved in production.
- Costs not directly associated to one of the previous two categories, divided into:
  • Cost of adjustment of the machines (set-up),
  • Organizational costs of maintenance service with reference to a generic production system can be defined as the costs in unit time of production such as raw material costs, direct costs of consumables, direct labour costs, indirect costs, the sum of which is the cost attributable apparatus in the unity of time and production.

3 Energy saving by Life Cycle Cost Analysis

Economic evaluation of the life cycle "Life Cycle Cost LCC" is a method of cost analysis with economic and energy savings benefits. Using this method of evaluation allows making decisions and helps save the use of energy and reducing the consumption of resources and materials with environmental benefits. LCC is the analysis method which considered the whole life cycle of energy-saving benefit factors; from the project decision-making and design phase, construction phase, and operational phase to the final disposal phase, which also considered economic viability and social effects by using life cycle theory, which was recently discussed by (Li et al., 2012).

The life cycle cost of any piece of equipment is the total "lifetime" cost to purchase, install, operate, maintain, and dispose of that equipment. Determining LCC involves following a methodology to identify and quantify all of the components of the LCC equation. When used as a comparison tool between possible design or overhaul alternatives, the LCC process will show the most cost-effective solution within the limits of the available data.

The components of a life cycle cost analysis typically include initial costs, installation and commissioning costs, energy costs, operation costs, maintenance and repair costs, down time costs, environmental costs, and decommissioning and disposal costs, as was shown in (Hydraulic institute, 2001).

Below this analysis is followed by a practical example on the pump system which is often one of the elements that uses a lot of energy in process plants operations, so making decisions and adopt energy saving measures can significantly reduce consumption and more get efficiency.

3.1 Improving System Performance

Pumping systems are widespread used, and providing domestic, commercial and industrial services. Pumping systems account for nearly 20% of the world's electrical energy demand and range from 25-50% of the energy usage in certain industrial plant operations. Although pumps are typically purchased as individual components, they provide a service only when operating as part of a system. The energy and materials used by a system depend on the design of the pump, the installation design, and the way the system is operated. These factors are interdependent. What's more, they must be carefully matched to each other, and remain so throughout their working lives to ensure the lowest energy and maintenance costs, equipment life, and other benefits. The initial purchase price is a small part of the life cycle cost for high usage pumps. While operating requirements may sometimes override energy cost considerations, an optimum solution is still possible. A greater understanding of all the components that make up the total cost of ownership will provide an opportunity to dramatically reduce energy, operational, and maintenance costs. Reducing energy consumption and waste also has important environmental benefits.

3.2 Life Cycle Cost Analysis

Life Cycle Cost LCC analysis is a cost effective management tool that can help companies minimize waste and maximize energy efficiency for many types of systems, including pumping systems. However here is presented and discussed LCC for pumping systems to clarify.

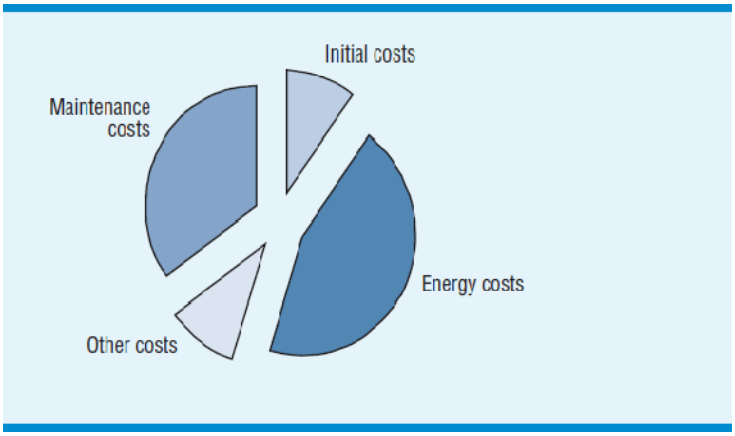

Figure 3.1. Typical life cycle costs for a medium-sized industrial pump.

As shown in the Figure 3.1, the energy consumption is often one of the most expensive elements which can dominate the LCC, especially if pumps run more than 2000 hours per year. In addition, maintenance costs, unexpected costs for spare parts, downtime and loss of production are a very important element in the total LCC and can rival energy costs.

LCC analysis, both for new installations or renovations, requires the evaluation of alternative systems. For most structures, the energy and maintenance costs will dominate the cost of cycle life. It is therefore important to accurately determine the current cost of energy, the expected annual energy price for the estimated life, together with the costs of expected maintenance work and material. Other elements, such as the cost of life time “life time cost” of downtime, security, decommissioning, and environmental, can often be estimated based on historical data of the system. According to the process, the costs of time may be more meaningful than the energetic elements or maintenance in the equation. It should therefore be administered in loss of productivity due to downtime. This overview also provides an introduction to the life cycle costs of the whole process.

In Equation 3.1 are presented necessary elements for calculating LCC.

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d \tag{3.1}$$

Where;

LCC is life cycle cost of equipment.

C_{ic} is the initial costs, purchase price (pump, system, pipe, auxiliary services).

C_{in} is installation and commissioning cost (including training).

C_e is energy costs (predicted cost for system operation, including pump driver, controls, and any auxiliary services).

C_o is operation costs (labor cost of normal system supervision).

C_m is maintenance and repair costs (routine and predicted repairs).

C_s is down time costs (loss of production).

C_{env} is environmental costs (contamination from pumped liquid and auxiliary equipment).

C_d is decommissioning/disposal costs (including restoration of the local environment and disposal of auxiliary services).

As was presented above these constructive elements of LCC, also include important and dominant costs as the cost of energy and maintenance.

3.2.1 Energy Costs Ce

Energy consumption is often one of the larger cost elements and may dominate the LCC, especially if pumps run more than 2000 hours per year. Energy consumption is calculated by gathering data on the pattern of the system output. If output is steady, or essentially so, the calculation is simple. If output varies over time, then a time-based usage pattern needs to be established.

The plant manager needs to obtain separate data showing the performance of each pump or system being considered over the output range. Performance can be measured in terms of the overall efficiencies of the pump unit or of the energies used by the system at the different output levels. Driver selection and application will affect energy consumption. For example, much more electricity is required to drive a pump with an air motor than with an electric motor. In addition, some energy use may not be output dependent. For example, a control system sensing output changes may itself generate a constant energy load, whereas a variable speed electric motor drive may consume different levels of energy at different operating settings. The use of a throttling valve, pressure relief, or flow by-pass for control will reduce the operating efficiency and increase the energy consumed.

The efficiency or levels of energy used should be plotted on the same time base as the usage values to show their relationship to the usage pattern. The area under the curve then represents the total energy absorbed by the system being reviewed over the selected operating cycle. The result will be in kWh. If there are differential power costs at different levels of load, then the areas must be totalled within these levels. Once the charge rates are determined for the energy supplied, they can be applied to the total kWh for each charge band (rate period). The total cost of the energy absorbed can then be found for each system under review and brought to a common time period.

Finally, the energy and material consumption costs of auxiliary services need to be included. These costs may come from cooling or heating circuits, from liquid flush lines, or liquid/gas barrier arrangements. For example, the cost of running a cooling circuit using water will need to include the following items: cost of the water, booster pump service, filtration, circulation, and heat extraction/dissipation.

3.2.2 Operation Costs Co

Operation costs are labour costs related to the operation of a pumping system. These vary widely depending on the complexity and duty of the system. For example, a hazardous duty pump may require daily checks for hazardous emissions, operational reliability, and performance within accepted parameters. On the other hand, a fully automated non-hazardous system may require very limited supervision. Regular observation of how a pumping system is functioning can alert operators to potential losses in system performance. Performance indicators include changes in vibration, shock pulse signature, temperature, noise, power consumption, flow rates, and pressure.

3.2.3 Maintenance and repair Costs Cm

Obtaining optimum working life from a pump requires regular and efficient servicing. The manufacturer will advise the user about the frequency and the extent of this routine maintenance. Its cost depends on the time and frequency of service and the cost of materials. The design can influence these costs through the materials of construction, components chosen, and the ease of access to the parts to be serviced.

The maintenance program can be comprised of less frequent but more major attention as well as the more frequent but simpler servicing. The major activities often require removing the pump to a workshop. During the time the unit is unavailable to the process plant, there can be loss of product or a cost from a temporary replacement. These costs can be minimized by programming major maintenance during annual shut-down or process change-over. Major service can be described as “pump unit not reparable on site” while the routine work is described as “pump unit reparable on site”.

The total cost of routine maintenance is found by multiplying the costs per event by the number of events expected during the life cycle of the pump. Although unexpected failures cannot be predicted precisely, they can be estimated statistically by calculating mean time between failures MTBF. MTBF can be estimated for components and then combined to give a value for the complete machine.

It might be sufficient to simply consider best and worst case scenarios where the shortest likely life and the longest likely lifetimes are considered. In many cases, plant historical data is available.

It must be recognized that process variations and user practices will almost certainly have a major impact upon the MTBF of a plant and the pumps incorporated in it. Whenever available, historical data is preferable to theoretical data from the equipment supplier. The cost of each event and the total costs of these unexpected failures can be estimated in the same way that routine maintenance costs are calculated.

3.2.4 Downtime and Loss of production Costs Cs

The cost of unexpected downtime and lost production is a very significant item in the total LCC and can rival the energy costs and replacement parts costs in its impact. Despite the design or target life of a pump and its components, there will be occasions when an unexpected failure occurs. In those cases where the cost of lost production is unacceptably high, a spare pump may be installed in parallel to reduce the risk. If a spare pump is used, the initial cost will be greater but the cost of unscheduled maintenance will include only the cost of the repair. The cost of lost production is dependent on downtime and differs from case to case.

3.2.5 Environmental Costs Cenv

Environmental Costs includes disposal of parts and contamination from pumped liquid.

The cost of contaminant disposal during the lifetime of the pumping system varies significantly depending on the nature of the pumped product. Certain choices can significantly reduce the amount of contamination, but usually at an increased investment cost. Examples of environmental contamination can include: cooling water and packing box leakage disposal; hazardous pumped product flare-off; used lubricant disposal; and contaminated used parts, lik seals. Costs for environmental inspection should also be included.

3.2.6 Decommissioning or disposal Costs Cd

Decommissioning or disposal costs, includes restoration of the local environment. In the vast majority of cases, the cost of disposing of a pumping system will vary little with different designs. This is certainly true for non-hazardous liquids and, in most cases, for hazardous liquids also. Toxic, radioactive, or other hazardous liquids will have legally imposed protection requirements, which will be largely the same for all system designs.

A difference may occur when one system has the disposal arrangements as part of its operating arrangements (for example, a hygienic pump designed for cleaning in place) while another does not (for example, a hygienic pump designed for removal before cleaning). Similar arguments can be applied to the costs of restoring the local environment. When disposal is very expensive, the LCC becomes much more sensitive to the useful life of the equipment.

3.2.7 Total Life Cycle Costs

The costs estimated for the various elements making up the total life cycle costs need to be aggregated to allow a comparison of the designs being considered. This is best done by means of a tabulation which identifies each item and asks for a value to be inserted. Where no value is entered, an explanatory comment should be added. The estimated costs can then be totaled to give the LCC values for comparison, and attention will also be drawn to non-qualitative evaluation factors.

There are also financial factors to take into consideration in developing the LCC. These include:

- Present energy prices,
- expected annual energy price increase (inflation) during the pumping system life time,
- Discount rate,
- Interest rate,
- expected equipment life (calculation period).

In addition, the user must decide which costs to include, such as maintenance, down time, environmental, disposal, and other important costs, which was discussed in (Hydraulic institute, 2001).

4 Cost/Risk Optimization

Most engineering, maintenance and operating decisions involve some aspect of cost/risk trade-off. Such decisions range from evaluating a proposed design change, determining the optimal maintenance or inspection interval, when to replace an ageing asset, or which and how many spares to hold. The decisions involve deliberate expenditure in order to achieve some hoped-for reliability, performance or other benefit. We may know the costs involved, but it is often difficult to quantify the potential impact of reduced risks, improved efficiency or safety, or longer equipment life. Not only are the benefits difficult to quantify, but the objectives often conflict with each other (we could clean the heat exchanger more often to achieve better performance, but the cleaning may damage the tubes and shorten their life). Finding the optimal strategy is difficult, therefore, but the wrong maintenance interval will result in excessive costs, risks or losses.

Optimum is defined as minimal total business impact. In the other words optimum is defined as “the optimum performance” or “maintenance strategy”. An optimum represents some sort of compromise in areas where there are conflicting interests, such as pressures to reduce costs at the same time as the desire to increase reliability, performance or safety. It is clearly impossible to achieve the component ideals or zero costs at the same time as total 100% reliability or safety etc. Reliability costs money, or, to put it the other way around, to spend less money we must choose what not to do or achieve. The resulting and inevitable trade-off can be drawn graphically as was shown by Figure 3.2, but we must be careful with the labelling, as it was illustrated by (Woodhouse, 1999).

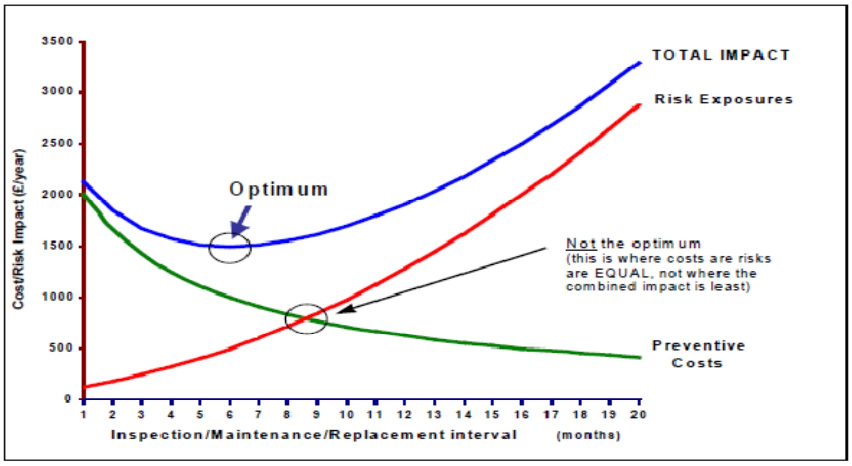

Figure 3.2. Optimum is defined as minimal Total Business Impact.

Many such diagrams show the bottom of the Total Impact curve neatly aligned above the cross-over point of the conflicting components, giving rise to confusion as to where and what is the true optimum. The Total Impact is the sum of the costs and risks etc. When this sum is at a minimum, we have defined the optimum combination of the components: the best value mixture of costs incurred, residual risks, performance losses etc. Crossover points do not signify the optimum; they merely show where the components are equal (i.e. the risks or losses have the same value as the amounts being spent to control them). The concepts of ‘balancing costs and risk’ or finding a ‘breakeven point’ are critical, because they imply this equivalence point as a target, rather than focus on the best value-for-money combination.

4.1 Difficulties in Quantifying Risks

The risks are difficult to quantify and often do not know exactly the economic value of the risks and costs involved. If we knew exactly what the risk were, and what they are worth, we could have the optimal amount of risk to be taken, and the cost to be incur, so we could make better decision or more optimal. Therefore the first barrier is lack of relevant data. Similarly, we could make better decisions, if we knew the value of improved performance, longer life, greater safety and quality.

In addition because of the complexity of the interactions, the reliability becomes a complex subject (e.g. effects of a failure mode on the probability of being subjected to other forms of failure). Whatever information, further problem is how we could use these data.

The difficulties in quantifying risk are reassumed below as:

- Lack of relevant risk data and economic value involved;
- Complexity of interactions and reliability, so the quality of data;
- If data were available, how we would interpret and use them.

4.2 Optimal Strategy for Decision Making

As before was discussed, the first challenge is therefore the understanding of what information is required for specific decisions, and how it should be used. This issue can be addressed by designing and using templates and checklists; to make sure that the right questions are asked in the first place.

Even if hard data is not available, there is a considerable volume of knowledge in the operators, maintainers and engineers. This can be obtained in the form of range estimates or “worst case” and “best case” extremes of opinion. With a range of possible interpretation, we can see if the decision is affected, whether we need to dig deeper, and at what cost. This is achievable if we have the means rapidly to calculate the Total Impact for different assumptions. We must adopt a “What if?” approach to the problem: try the optimistic extreme and the pessimistic, does the data uncertainty have a significant effect?

The calculations require specialist software tools. Given their availability, however, even rough or range estimates can be explored for their effect. Sensitivity testing reveals which pieces of information are important, and which have little or no effect upon the relevant decision. Using range estimates "worst case" and "best case" we would be able to identify the optimum strategy, as shown in the Figure 3.3 by (Woodhouse, 1999).

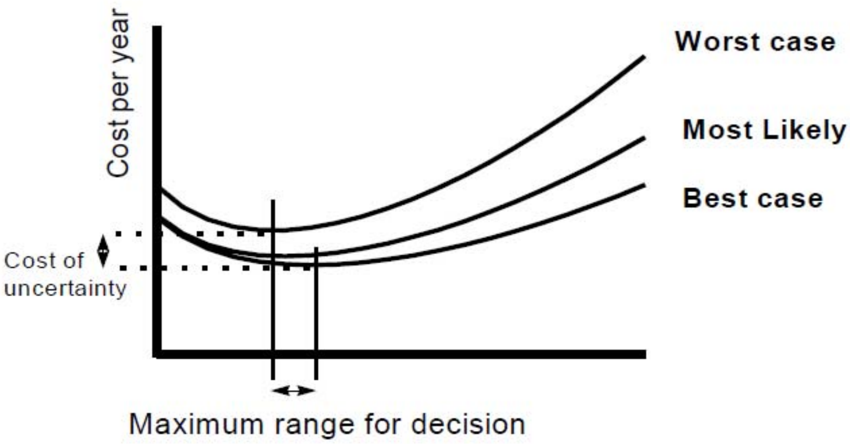

Figure 3.3. Maximum range for decision.

4.3 A Practice Example: **Pump overhauls**

Below, it have been illustrated a practice example, which was shown by (Woodhouse, 1999). If the performance of a pump deteriorates as its impeller becomes fouled, and the reduced capacity is having an effect upon production or process efficiency, then there must be an optimum time to clean the impeller. To determine the best maintenance strategy, we need to know how the performance falls with time or use, the economic effect of the losses, perhaps the pump has to operate for longer to deliver the required volumes, or maybe the drive motor draws more electricity to compensate. We also need the cost of cleaning, including any operational downtime to do it. Some of this information may be known if there is some operational experience, but otherwise it must be range-estimated and explored for sensitivity.

Estimated Data, which are used in this example are:

- By 6 months of operation, pump performance is 5-10% down, and this is likely to accelerate if left further.
- 10% lost performance is worth 10-30£/day in extra energy/production impact or extended operating costs.
- The costs of cleaning or overhaul are 6-800£ in labour and materials, and 2-3 hours downtime to swap over to an alternative pump.

4.3.1 Calculating the Impact

The first step involves 'fitting' a performance curve to the examples given as is shown in Figure (3.4).

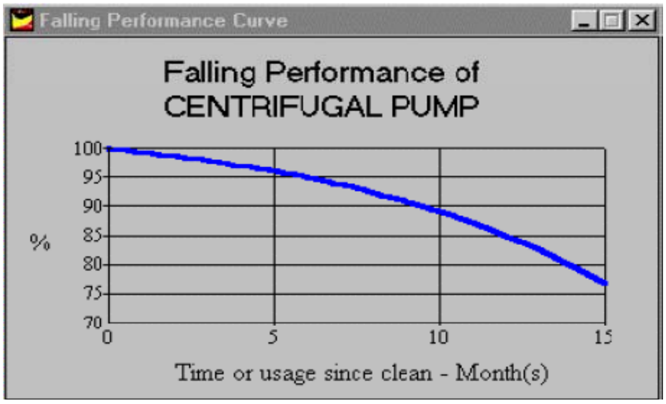

Figure 3.4. performance curve (Woodhouse, 1999).

Then, a series of calculations can show the Total Impact of performance losses, cleaning costs and equipment downtime for various maintenance intervals as was shown in Figure 3.5.

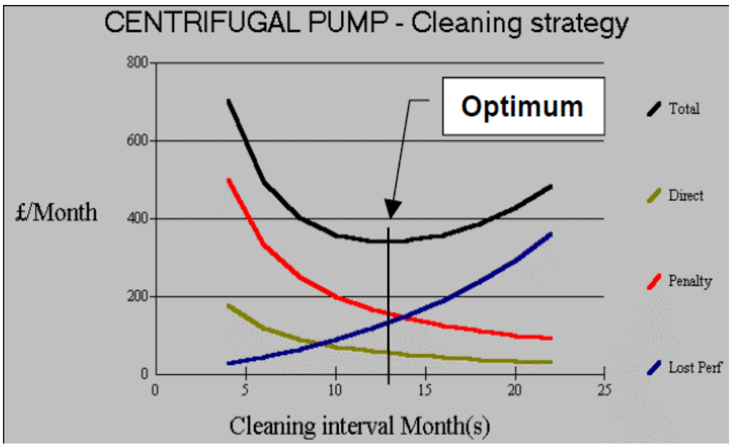

Figure 3.5. Total impact of performance (Woodhouse, 1999).

4.3.2 Sensitivity Testing

The "worst case" and "best case" interpretations combine the extremes of all the range-estimates as was shown by Figure 3.6. They show that the cleaning interval must be between 11 and 16 months. No interpretation of the problem could justify more, or less, frequent cleaning.

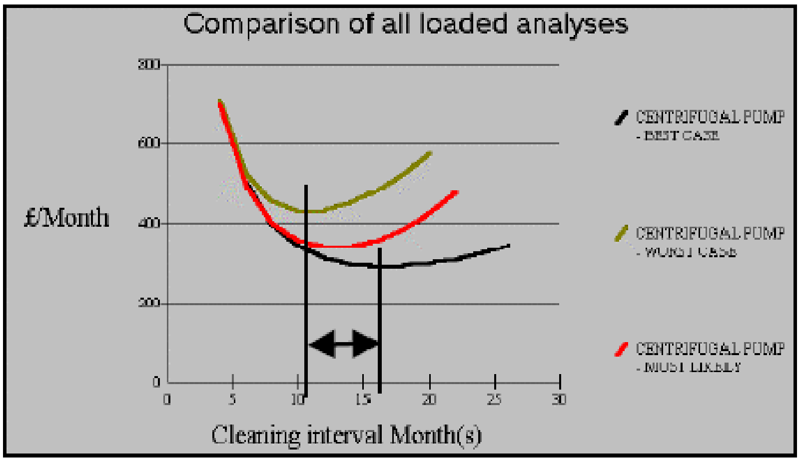

Figure 3.6. comparision of ranges estimated (Woodhouse, 1999).

4.3.3 The importance of reliability

The optimisation can be extended to include the reliability of the pump, with a variety of failure modes. The complexity lies in the interaction between failure risks. Historically, reliability studies have been obliged to simplify their assumptions to the point of impracticality; assuming just one mode of failure, only randomness, or all repairs "reset the clock" to "as new" condition. Real life is much more complicated: maintenance-induced failures (such as misalignments, faulty work or materials) influence the rates of subsequent deterioration. What might seem "random" in one view (e.g. lubrication failures of young or old pumps) is certainly not random in another context (e.g. time since last checking of the oil level).

Maintenance options are nearly always faced with combinations of interacting failure modes. To make sense of the navigation, therefore, a disciplined structure is vital. This has been developed as part of the "MACRO program" that is very useful for estimating the probability of interaction failure modes and maintenance with different ways of view for the reliability and was discussed by (Woodhouse, 1999): it reveals how cumulative effects are much more useful than estimates of specific probabilities. It can make estimates of "how long things will last” much more easily than “the chance of a xyz failure is ….” The cumulative information is called the Survival Curve and the following is a typical description of a complex mixture of failure modes:

With respect to time since last overhaul;

- Typically 5-10% will need repeat work (maintenance errors etc) in the first month,
- Most (80-0%) survive the first year or two without failure,
- Not many (less than 20%) would last longer than 5 years without some sort of failure.

Computer software can fit a curve to this Survival information, and calculate the pattern of risks that would be necessary for these symptoms to be achieved. In fact there are two further forms of this reliability data. The Hazard Rate is the “conditional” chance of failure, assuming the equipment has survived so far. The Failure Density quantifies how many would fail at different time points (i.e. a combination of how many reach each point and the risks they face). It is the Hazard Rate that is needed for decisions about how long to leave the equipment in service (and risk failure), or deliberately maintain/replace it instead. Different views of reliability patterns are shown in Figure 3.7 below. APT- AINTENANCE software is currently the only tool available to perform this analysis comprehensively, that can analysis of multiple failure modes and the optimum maintenance strategy, such program was discussed by (Woodhouse, 1999).

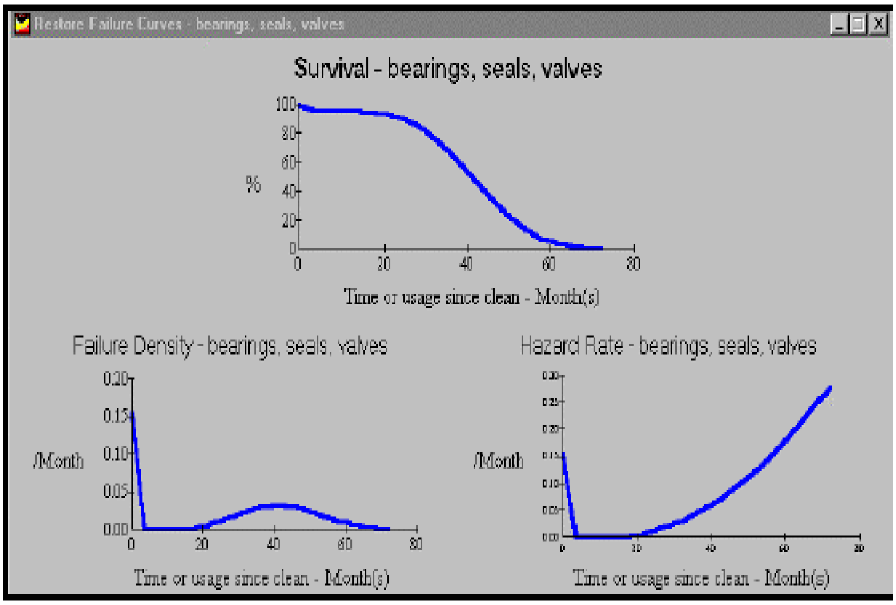

Figure 3.7. Different views of reliabilty patterns (Woodhouse, 1999).

5 Energy Efficiency Model Development

As it was mentioned before, the main reason for the research was the importance of energy for the industry also the main purpose of this work, is based on a simple philosophy: "everything that is measurable, can be optimized" and was the optimization of energy consumption through efficiency measures also increase performance of systems and equipments which are used in process industry. In our point of view, it is possible to achieve this objective, through use of an interactive energy management system, which includes a decision support system. The model that was developed for the analysis of energy efficiency is able to support decisions for the management of energy consumption in the systems, using an analytical presentation of alternative costs and benefits of the use of energy in terms of probability and consequence. Using this model, it is possible to quantify the impact of maintenance activities and operating procedures, on energy savings (cost-effectiveness). So it's possible to calculate Cost of Conserved Energy CCE, also the potential of emissions reduction (like CO_2).

The implementation of energy saving measures, for our case study was based on both the technical feasibility and the economic feasibility, since not all feasible measures from the technical point of view, they are cost effective. Other drawbacks, in an industrial reality there are the difficulties of obtaining all the historical data required for evaluation and also the presence of multiple factors that can affect the analysis as the production capacity, working hours, the average cost of electrical energy , interest rates etc.. However, thanks to the cooperation by the company, the analysis and the results were validated and compared with the experts' assessment of the system.

5.1 An Interactive Energy Efficiency Management System

Energy efficiency is achieved not only through implementation of adequate equipment, process and operating practice, but also by implementation of energy efficiency management system, which presents various strategies, tools, methods and technologies to optimize present systems and offer effective measures and solutions to face consumption and achieve performance, also production and environmental benefits. That is possible also together with energy audit, monitoring, control and continues improvement of the system that is also was shown and discussed in details, before, in the section 1.

In this work, it was define an interactive energy efficiency management system that is shown in Figure 5.1.

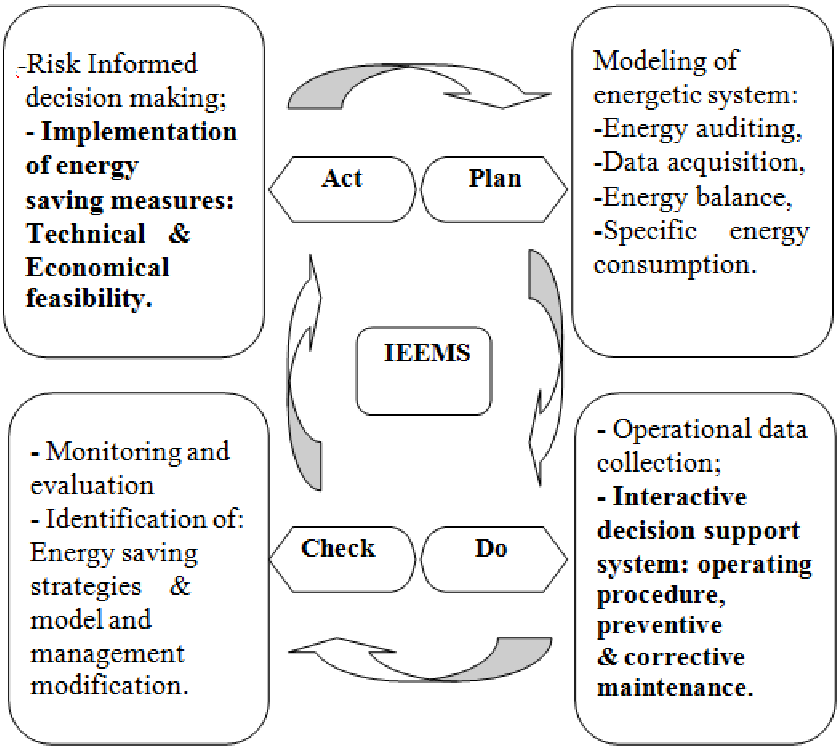

Figure 5.1. An Interactive Energy Efficiency Management System.

As it was shown by the Figure 5.1, in this scheme in the doing phase, was introduced an interactive decision support system. The model that was developed for the analysis of energy efficiency is able to support decisions for the management of energy consumption in the systems, using an analytical presentation of alternative costs and benefits (balanced) of the use of energy in terms of probability and consequence, which includes optimization of operating procedures and maintenance activities. Decision making and implementation of the energy saving measures are based on the condition of the system, so technical and economical feasibility and it's important to balance these two important facts to arrive an optimum point.

It should be noted the implementation of energy saving measures, for our case study also was based on both the technical feasibility and the economic feasibility, since not all feasible technical measures, are cost effective and vice versa.

Here was developed a model for analyzing energy efficiency, formed by integration of a deterministic and probabilistic model based on optimization of maintenance interventions and operating procedures, with the first goal of maximizing energy efficiency.

Must be noted, that it is important balance costs and risks of inefficiency and the benefits, furthermore, focus on the best value for the quality-price. Where optimal is defined as the minimum impact, and represents a sort of compromise between reducing the costs and at the same time increasing reliability, performance, or safety of the system.

The decision-making process of the model with the data analysis, were shown through the application to a case study in an industrial production process, Bitumtec Ltd. plant, which produces bituminous materials for road paving. The energy consumption was analyzed, as an example, for the more critical system or the electric motor with greater energy consumption.

5.1.1 Energy audit process

A systematic approach, to monitor industrial energy consumption is known as energy audit. An energy audit study helps an organization to understand and analyze its energy utilization and identify areas where energy use can be reduced, decide on how to budget energy use, plan and practice feasible energy conservation methods that will enhance their energy efficiency, curtail energy wastage and substantially reduce energy costs. The energy input is an essential part of any manufacturing process and often form a significant part of expenditure of the plant. The energy audit serves to identify all the energy streams in a facility, quantify energy usage, in an attempt to balance the total energy input with its use. An energy audit is thus the key to a systematic approach for decision-making in the area of energy management. As a result, the energy audit study becomes an effective tool in defining and pursuing a comprehensive energy management programme, which was also discussed by (Saidur, 2010). As the focus of the paper is about electric motor energy usage, details of energy audit are also towards electric motor energy management through an energy audit.

Following are the objectives that can be considered for an electric motor energy audit:

- To identify motor energy use in an industry.
- To implement energy savings measures by which individual industry can conserve energy used in their high-energy using equipment/processes such as motors.
- To provide a pathway to benchmark energy usage of electric motors in other industries.
- Identify electric motor energy wastages.

Following benefits can be achieved through an electric motor energy audit:

- Identifies energy losses for corrective action.
- Impact of operational improvements can be monitored.
- Reduces the specific energy consumption and operating costs (approximately 5-20%) by systematic analysis.
- In addition to the potential cost savings from an energy audit, the results may lead to environmental benefits such as greenhouse gas reductions, environmental credits as greenhouse gas reductions.
- Improves the overall performance of the total system and the profitability and productivity.
- Averts equipment failure.
- Estimates the financial impact of the energy conservation projects.
- Serves as a very good self-auditing cum correction system for performance improvement.

Below, Figure 5.2 is showing the typical energy audit management program, which also elaborate in this work.

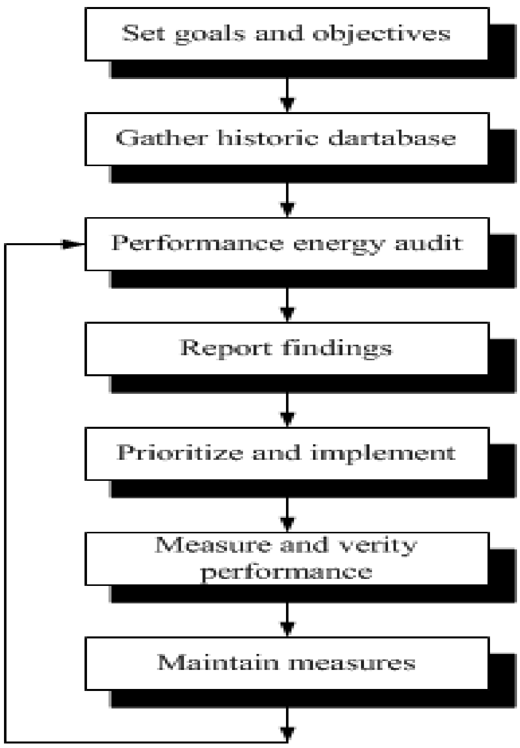

Figure 5.2. Typical energy audit management program.

5.1.2 Efficiency analysis method

Here is used the concept of a Conservation Supply Curve CSC to make a bottom-up energy analysis model to capture the cost effective as well as the technical potential for energy efficiency and emission reduction (CO_2) as an example for the industrial motor system in our industrial case study. Must be mentioned, the motor systems represent a largely untapped cost effective sources for industrial energy efficiency savings that could be realized with existing technologies, and have the potential to contribute substantial energy savings. A major barrier to effective policymaking, and to more global acceptance of the energy efficiency potential in industrial motor systems, is the lack of a transparent methodology for quantifying the magnitude and cost-effectiveness of these energy savings. So here, the motor system has chosen to develop the energy conservation supply curves.

The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy. The Conservation Supply Curve is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. It was first introduced by Rosenfeld and his colleagues at Lawrence Berkeley National Laboratory (Meier, 1982). Later CSCs were used in various studies to capture energy efficiency potential sin different economic sectors (Koomey et al., 1990); (Levine & Meier, 1999); and (Hasanbeigi et al., 2010). Recently, (McKinsey & Company, 2008) has also developed green house gas abatement cost curves for different countries using the concept of the conservation supply curve.

The approach used in this study to develop the energy conservation supply curves (in this paper called motor system energy efficiency supply curve) is slightly different from the one often used in prior studies. Because of data limitations for industrial motor system, detailed bottom-up data typically used for developing a CSC was not available. To over-come this problem, an innovative approach was developed that combines available data with expert opinion to develop energy efficiency supply curves as an example for the motor system in our case study.

5.2 Cost Effective Energy Saving by Maintenance Optimization

The importance of the cost effective energy saving measures in industry facilities is to reduce energy consumption of major energy using equipment. Cost minimization is also one of the objectives of maintenance planning. Over the recent decades plant maintenance strategies have evolved from corrective to a preventive approach and deterministic models have been replaced by those based on reliability and risk, which are probabilistic. Approaches to obtain the optimum maintenance interval bring to minimization of total cost. On the other hand the aim of these approaches is to achieve productivity and cost benefits in industries. Even if their purpose is not directly energy related, their benefits often are applied also to energy saving. For example, the most common cost benefits of improved maintenance and operation system is achieved from reduced equipment wear and tear.

For quantifying the impact of productivity benefits on energy saving, it is possible to calculate the Cost of Conserving Energy CCE that also includes the "non-energy benefits" of maintenance and operation system optimization, as shows by Equations 5.1 and 5.2:

$$CCE = \frac{I.q + M\&O}{S} \tag{5.1}$$

Where,

$$q = \frac{d}{(1-(1+d)^{-n})} \tag{5.2}$$

Where, CCE is the cost of conserved energy for the energy efficiency measure, in €/kWh; I is the capital cost, in €; q is the capital recovery factor; M&O is the annual change in Maintenance and Operation costs, in €/y; S is the annual energy saving, in kWh/y; d is the discount rate, in %; and n is the life time of the conservation measure, in y.

It should be noted that non-energy benefits, as operation system and maintenance optimization lead to reduction in M&O, as well as reduction of capital cost, that would lead to reduction in I, with a higher effects on CCE, which was also discussed by (Worrel et al., 2003).

Conservation Supply Curve CSC, which is also an economic tool, is applied in industry to show the energy conservation potential as a function of the cost of conserved energy. It is possible to construct an Electricity Conservation Supply Curve ECSC and a Fuel Conservation Supply Curve FCSC separately to capture the cost effective and total technical potential for electricity and fuel efficiency improvement in industry.

5.2.1 Maintenance cost analysis

The objective here is to quantify the potential consequences of the functional failure that represents a credible scenario. The total consequences assessment usually is a combination of four major categories of consequences: (i) system performance loss; (ii) financial loss; (iii) human health loss, and (iv) environmental and/or ecological loss. The method of quantification of these four categories may change according to the scope of the study undertaken.

To complete the risk analysis of process plant equipment that was discussed before, the consequences of equipment failure must be expressed in monetary values. Many aspects influence that cost evaluation, such as process plant location and configuration, operational pattern and also legislation. Additionally, the costs of maintenance procedures must also be evaluated. The cost analysis is dependent on the existence of a database that relates costs to some undesirable failure events associated with process plant equipment. For the present analysis as was shown by (Carazas & Souza, 2010), the costs are divided into three classes: (i) Fixed operational costs; (ii) Variable operational costs, and (iii) Unavailability costs.

The total maintenance and operational costs can be calculated by the sum of those costs, as is shown in Equation 5.3 below:

$$Total\ M\&O\ cost = Fixed\ cost + variable\ cost + Un\ availability\ costs \tag{5.3}$$

The Maintenance and Operation M&O fixed costs are related to the process plant operation independently. Those costs include plant operator’s wages, general and equipment maintenance costs (for procedures that do not depend on the equipment operation time history), insurance and taxes. The variable M&O include costs that are dependent on the amount of production or on the equipment operation time history. Both classes of costs are dependent on the maintenance policy applied on the process plant equipment.

The unavailability costs are related to the consequences of equipment unexpected failure, that requires corrective maintenance actions, defined according to the risk analysis procedure. Those costs consider corrective maintenance actions, including spare parts and labour hours, and a monetary expression of equipment failure consequence costs, mainly production loss cost. For that estimate, one should include reduction in the process plant output that affects commercial contracts, environmental and operational safety degradation. Both environmental and operational safety degradation costs are strongly influenced by the process plant location and by regulatory laws related to the environmental impacts.

Corrective maintenance cost typically includes the cost of labour, parts, and the down time associated with the repair. The maintenance cost can be calculated using the following Equation 5.4, as was showed by (Carazas & Souza, 2010):

$$Maintenance\ Cost = Cf + DT.Cv \quad (5.4)$$

Where; Cf is the fixed cost of the failure (cost of spare parts), Cv is the variable cost per hour of down time, and DT is process plant down time (in fraction of hour).

It must be added, the cost of spares includes the cost of raw material, internally manufactured parts, the parts sent away for repairs, new spare parts, consumables, small tools, testing equipment, and rent for special equipment. The cost of spares and raw materials is drawn from the plant stock book.

Maintenance down time includes the total amount of time the plant would be out of service as a result of failure, from the moment it fails until the moment it is fully operational again.

The cost of labour is an important component of the maintenance cost. This is based on the hourly rate for various trades and the information is drawn from the plant documentation. Those costs depend on the union agreements and federal laws, varying from country to country. Down time associated with forced outage and forced de-rating state must be estimated from the failure data collected on the power plant. Owing to the lack of data, the down time and the number of maintenance personnel involved in repair is estimated by interviewing the maintenance personnel.

The production loss cost can be estimated using the following formula (Equation 5.5):

$$PLC = DT.PL.SP \quad (5.5)$$

Where PLC is production loss cost, PL is production loss and must be computed from the failure data, DT is the process plant down time, and SP is the selling production price. The combination of production loss cost and the maintenance cost gives the consequence of the failure in monetary values, which was discussed by (Carazas & Souza, 2010).

5.3 Proposed Framework

In this work the proposed framework with flowing steps are introduced:

- Identification of the most important system MIS

  Specially, in this study a production process system through bituminous materials production process will be addressed.

- Identification of the most critical component MCC

  Particularly, in this study will be addressed the electrical motor rotor-stator “Siefer” that drives homogenization mill during production process of bituminous materials.

- Life time data and energy consumption data collection and observation, also maintenance (corrective and preventive) activities and failure’s related data.
- Estimated costs of maintenance and the economic evaluation of maintenance policies (based on balanced cost and risk of inefficiency)
- Maintenance optimization (in terms of probability and consequences),
- Evaluation of the operation costs of the motor;

  Analysis of energy efficiency through maintenance optimization and operating procedures, by using of bottom-up energy efficiency supply curve model, where it was introduced: Expert inputs (based on the information from the expert of the system); and Data assumption;

- Definition of scenarios and efficiency measures

  In this study, have been defined three levels of base case scenarios with the relative potential energy recovery which are; Low, Medium and High. Future, was proposed solutions and adequate measures (for our case study) to increase the performance, based on the maintenance activities, operating procedures and the conditions of the system.

- Determination of the impact of these measures on the performance

5.4 Motor System Efficiency Supply Curves

The conservation supply curve CSC used in this study is an analytical tool that captures both the engineering and the economic perspectives of energy conservation. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy, which was the first time introduced by (Meier, 1982).

As it was shown and discussed in details previously, CCE can be calculated from Equations 5.1 and 5.2, which also can be presented in another form as was shown by Equations 5.7 and 5.8 below:

$$CCE = {(Annualized\ Capital\ Cost + Annual\ change\ in\ M\&O\ costs)} \Big/ {Annual\ energy\ saving\ (S)} \quad (5.7)$$

$$Annualized\ Capital\ Cost = Capital\ Cost * \left[{d} \Big/ {1 - (1+d)^{-n}} \right] \quad (5.8)$$

Where; M&O is the annual maintenance and operation costs, d is the discount rate in % and n is the life time of the energy efficiency measure.

In our study, was assumed the real interest rate i 3% and the real discount rate equal to 0.75% per year to reflect the barriers to energy efficiency investment in industry such as: perceived risk, lack of information, management concerns about production and other issues, capital constraints, and preference for short payback periods about 3 years and high internal rates of return.

That must be noted, the annual effective discount rate is the annual interest divided by the capital including that interest, which is the interest rate divided by 100% plus the interest rate. It is the annual discount factor to be applied to the future cash flow, to find the discount, subtracted from a future value to find the value one year earlier. For every annual effective interest rate i, there is a corresponding annual effective discount rate d, given by the following formula (Equation 5.9).

$$d = \frac{i}{1+i} \quad (5.9)$$

Therefore using these formulas it is possible to calculate the Cost of Conserved Electricity CCE for respective technologies in order to draw CSCs for motor system. After calculating the CCE for all energy efficiency measures, the measures are ranked in ascending order of CCE, against determined an energy price line. All measures that fall below the energy price line are cost-effective. On the curves, the width of each measure (plotted on the x-axis) represents the annual energy saved by that measure. The height (plotted on the y-axis) shows the measure's cost of conserved energy. Finally, it should also be highlighted that the approach used in this study and the model developed is a good screening tool to present energy efficiency measures and capture the potentials for improvement. However, in reality, energy saving potential and cost of each energy efficiency measure and technology may vary and depend on various conditions such as material quality, production capacity, the average cost of electricity and etc. Moreover, it should be noted that some energy efficiency measures provide productivity and environmental benefits in addition to energy savings, but it is difficult and sometimes impossible to quantify those benefits. However, including quantified estimates of other benefits could significantly reduce the cost of conserved energy for the energy efficiency measures, as was discussed by (Hasanbeigi et al., 2010). Furthermore, in the interpretation of the results and their level of accuracy, the uncertainty of some input data such as energy saving and cost of the energy efficiency measures should be taken into account.

The CSC presented in this work gives some very useful information. It presents the Cost of Conserved Energy CCE, annualized cost of energy-efficiency measures, annualized energy cost saving, annualized net cost saving, and annualized energy saving by each individual technology or a group of technologies. Further, calculation of CCE is already explained. If dES is the Energy Saving by a technology, then the Annualized Cost of energy-efficiency measure AC, Annualized Energy Cost Saving AECS, and the Annualized Net Cost saving (ANC) of that technology can be calculated by Equations 5.10, 5.11 and 5.12.

$$AC = dES * CCE \tag{5.10}$$

$$AECS = dES * P \tag{5.11}$$

$$ANC = AECS - AC = dES * (P - CCE) \tag{5.12}$$

Where, AC is the annualized cost of energy-efficiency measure in €, AECS the annualized energy cost saving in €, ANC the annualized net cost saving in €, P the energy price € in , and dES the energy saving in CSC. For the cost-effective energy-efficiency measures in the CSC, the annual net cost saving is positive, yet for the measures whose CCE or CCF is above the energy cost line, the annualized net cost saving is negative. However, always was talked about the “Cost” of energy-efficiency improvement. The common use of the term “Cost” usually gives the impression that company has to spend money. However in many cases, especially the case of cost-effective energy efficiency measures as was presented above, money is actually earned by saving the cost of energy. The amount of revenue obtained by an energy-efficiency measure can be accurately presented if calculate the Life Cycle Cost LCC of the measure. By LCC, it means that must be taking into account the cost and benefits of an energy-efficiency measure over its lifetime. A CSC gives the annualized cost with a constant energy price in the base year, where as in reality the energy price is usually changing from year to year. Thus for policy analysis, when was calculated the LCC of energy-efficiency measures, it should be taken into account the changes in energy price; otherwise we significantly over estimate or underestimate the energy cost savings. We have used 2010 as the base year and conducted the economic analysis based on the constant cost of energy (electricity), 0.15 (€/kWh).

5.5 Calculation of the Annual Energy Savings

The calculation and data analysis methodology is used for the electrical motor system and is presented below. Figure 5.4 shows the schematic of calculation process for the construction of motor systems efficiency supply curves.

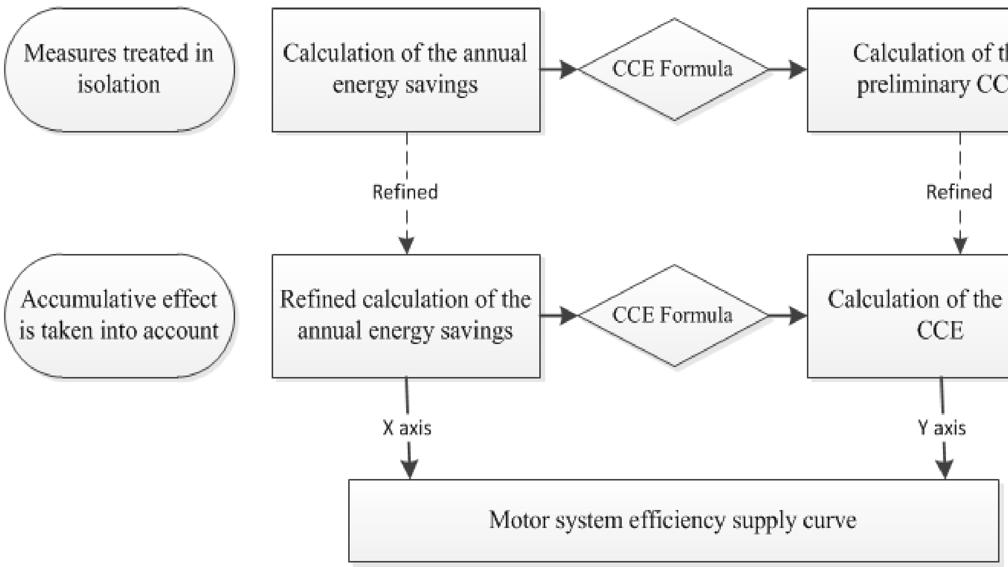

Figure 5.4. Schematic of calculation process for the construction of motor system efficiency supply curve.

Further, each step is explained in details which was also illustrated by (McKane & Hasanbeigi, 2011).

For the calculation of energy saving achieved by the implementation of each efficiency measure for the motor system, the following inputs were available:

- The efficiency base case scenarios for motor system (Low, Medium, and High), was developed, based on data collection and expert input, as was briefly described before.
- Then were defined efficiency measures for motor system, and provide the typical % improvement in energy efficiency over each base level efficiency scenario.
- Also was calculated electricity used by the motor system.
- By using of the above information and following the steps given below, the annual electricity saving from the implementation of each individual efficiency measure for the motor system was calculated.

Must be noted, was assumed that the measures are treated individually and can be implemented regardless of the implementation of other measures. Also was calculated the accumulative effect of the measures.

5.5.1 Annual electricity savings calculation

Here is presented various steps of annual electricity savings calculation for the motor system (our industrial case study "Siefer") measures treated in isolation (without additive effect):

1. Annual input energy for the motor system (kWh/y) = motor system energy use in industry in the base year.
2. Annual useful energy used in the motor system with base case efficiency = annual input energy for the motor (kWh/y) * base line efficiency of the motor system.
3. New system efficiency after the implementation of the efficiency measure = base case efficiency of the motor system * (1+% system efficiency improvement by the implementation of the measure).
4. Annual useful energy used in the motor system with New efficiency = annual input energy for the motor system (kWh/y) * new system efficiency.
5. Annual useful energy saving = annual useful energy used in the motor system with New efficiency – annual useful energy used in the motor system with base case efficiency.
6. Annual input energy saving = annual useful energy saving / New system efficiency after the implementation of the efficiency measure.

It must be added in our study the results were evaluated for the Medium base case scenario about 0.7; (load factor * motor efficiency).

- Procedures for calculating the annual energy saving achieved by the implementation of only one unit of each measure under each base case scenario was showed by the steps below:

1. Annual input energy for one unit of system (kWh/y) = (hp * hours used per year * load * 0.746) / motor efficiency.
2. Annual useful energy used in one unit of system with base case efficiency = annual input energy for one unit of system (kWh/y) * base case efficiency of the motor system.
3. New system efficiency after the implementation of the efficiency measure = base case efficiency of the motor system * (1+% system efficiency improvement by the implementation of the measure).
4. Annual useful energy used in one unit of system with New efficiency = annual input energy for one unit of system (kWh/y) * new system efficiency.
5. Annual Useful energy saving for one unit of system = annual useful energy used in one unit of system with New efficiency – annual useful energy used in one unit of system with base case efficiency.
6. Annual Input energy saving for one unit of system=annual useful energy saving for one unit of system / New system efficiency after the implementation of the efficiency measure.

5.5.2 Cumulative energy saving approach

Using this refined approach, the efficiency improvement by the implementation of one measure depends on the efficiency improvement achieved by the previous measures implemented. In practice, the implementation of one measure can influence the efficiency gain by the next measure implemented because the second measure is implemented against an improved base case efficiency. Therefore, the efficiency improvement by the second measure will be less than if the second measure was implemented first or was considered alone.

This methodology treats measures in relation with each other, as a group. In this method, the Cumulative electricity saving is calculated by taking into account the additive effect of the measures, rather than treating the measures completely in isolation from each other. The method was described as shown below;

- Cumulative annual electricity savings calculation; motor system "Siefer" measures treated in relation to each other.

1. Annual input energy for the motor system (kWh/y) = motor system energy use in industry in the base year.
2. Annual useful energy used in the motor system with baseline efficiency = annual Input energy for the motor (kWh/y) * baseline efficiency of the motor system.
3. Cumulative new system efficiency after the implementation of the efficiency measure = base case efficiency of the motor system * (1 + sum of the % efficiency improvement by the implementation of the measure and all the previous measures implemented).
4. Cumulative annual useful energy used in the motor system with New efficiency = annual input energy for the motor system (kWh/y) * cumulative new system efficiency.
5. Cumulative annual useful energy saving = annual useful energy used in the motor system with New efficiency – annual useful energy used in the motor system with base case efficiency.
6. Cumulative annual input energy saving = cumulative annual useful energy saving/cumulative New system efficiency after the implementation of the efficiency measure.

As might be anticipated, the ranking of the measures significantly influences the energy saving achieved by each measure. The higher the rank of the measure, the larger is the energy saving contribution of that measure to the cumulative savings. To define the ranking of the efficiency measures before calculating the cumulative energy saving from the method described above, the Preliminary Cost of Conserved Electricity (CCE) was calculated (see below for the explanation on CCE calculation) for each measure assuming that the measures are independent of each other (i.e. treating them in isolation without taking into account any additive effect). Then, these measures were ranked based on their Preliminary CCE. This ranking was used to calculate the final CEE.

5.5.3 Calculation of the cost of the conserved electricity CCE

Conserved energy was calculated from the CCE formula (Equation 5.7);

Final CCE calculation is described below:

1. Annual input energy for one unit of system (kWh/y) = (hp * hours used per year * load * 0.746) / motor efficiency.

2. Cumulative new system efficiency after the implementation of the efficiency measure = base case efficiency of the motor system * (1 + sum of the % efficiency improvement by the implementation of the measure and all the previous measures implemented). However, unlike the energy saving that is shown as cumulative saving on the supply curve (x-axis), the CCE for each individual measure is shown separately on the supply curve. In other words, the y-axis on the supply curve shows the CCE for the individual measure. Therefore, the cumulative input energy saving for one unit of system cannot be used in the calculation of Final CCE. For the calculation of Final CCE, it is necessary to determine the Individual Input energy saving for one unit of system for each measure. This is done, for example for measure number (i) from the following procedure:

3. Cumulative Annual Useful energy used in one unit of system with Cumulative new efficiency after the implementation of the efficiency measure (i) = annual Input energy for one unit of system (kWh/y) * cumulative new system efficiency after the implementation of the efficiency measure (i).

4. Cumulative annual useful energy used in one unit of system with cumulative new efficiency after the implementation of the efficiency measure (i-1) = annual Input energy for one unit of system (kWh/y) * cumulative new system efficiency after the implementation of the efficiency measure (i-1).

5. Individual annual useful energy saving for one unit of system for measure (i) = cumulative annual useful energy used in one unit of system with cumulative new efficiency after the implementation of the efficiency measure (i) – cumulative annual useful energy used in one unit of system with cumulative new efficiency after the implementation of the efficiency measure (i-1).

6. Individual annual input energy saving for one unit of system measure (i) = individual annual useful energy saving for one unit of system / cumulative new efficiency after implementation of the efficiency measure (i).

Once the measures are ranked based on the Preliminary CCE, it’s possible to calculate the Final CCE from the calculation procedure which was shown above. The final CCE is used for the construction of Motor System Efficiency Supply Curve along with the Cumulative Annual Input Energy Saving. These results are shown and discussed in details in chapter 7.

6 Case Study: Production Process of Bituminous Materials

The application part was presented, through a practical example in a production process industry, Bitumtec Ltd. plant. First of all, here is introduced the brief introduction of the bituminous materials production plant, process, characteristics and some particular to safety regards. Further, it was followed by the application part in chapter 7, where is showed and discussed analysis of historical data related to energy consumption and maintenance (corrective and preventive) of a high energy consumption system, such as three phase electric motor (rotor-stator) “Siefer”, that drives homogenization mill during production process of modified bitumen, also the results of this study. Objective of this work is to prevent and/or reduce malfunctioning and the negative effects due to failures, by means of an energy management system also define the appropriate efficiency measures to increase efficiency and performances of the system under study, and moreover their environmental benefits like reducing greenhouse gas mission.

6.1 Bitumen Emulsions

By the term bitumen is meant a mixture of hydrocarbons of natural or remnants resulting from the distillation or refining of crude oil. The bitumen, such as tar, asphalt and tar pitch, belongs to the category of bituminous materials. Bitumen is a substance in colour from brown to black, has viscoelastic semi-solid consistency, is thermoplastic, but does not have a well defined melting temperature.

Impermeability, ductility, adhesivity or resistance to the effect of weathering and chemicals are some of the bitumen properties that make it a coating material suitable in many applications, among which road and highway pavements construction and roofing membranes manufacture should be highlighted. However, the limits of mechanical stability of pavements have been often exceeded and this has resulted in damage, as thermal cracking and permanent deformation. The use of polymer modified bitumen makes it possible to improve the performance of bituminous pavements under particularly severe conditions of service. Nevertheless, polymers commonly used to modify bitumen require both high shear and high processing temperatures in order to get to a suitable dispersion, what stands for a high risk of bitumen ageing and polymer degradation, leading to a decrease in its mechanical performance.

Bitumen emulsions are increasingly used in road surfacing. Their range of applicability is fairly diversified and includes cold mixes, surface dressing and tack coating. A bitumen emulsion is an oil-in-water emulsion that is the dispersed phase is composed of bitumen and the continuous phase of water. A surfactant either anionic or cationic must be used for phase compatibility at a concentration of about 1 wt. %. Industrial experience has shown that for road applications, the correct emulsion is characterized by high dispersed phase content about 55% - 65% and a unimodal droplet size distribution with an average diameter between 5 and 15 μm.

Due to the large amount of products required by the paving industry, bitumen emulsions are made in continuous inline processes involving dispersing technologies like rotor-stators, colloidal mills and static mixers. In practice, the fabrication of the right emulsion for given surfacing conditions poses numerous challenges mainly related to the emulsion viscosity, stability and breakage. In the literature, it has been shown that the emulsion physical chemistry characteristics are significantly affected by the droplet size distribution, in particular the emulsion viscosity, the stability and the breakage as was discussed by (Gingras et al., 2005).

Emulsions contain usually a variety of emulsifiers added to fulfill different requirements. Such systems are designed for wide applications in industry. However, the rheology or the flow characteristics of the emulsions are under influence of various factors. These factors are the volume fraction of the disperse phase, the viscosity of the disperse droplets, the droplet size distribution, the viscosity and chemical composition of the medium, the interfacial rheology of the emulsifier film and the nature and concentration of the emulsifier. Further, due to their binding characteristics and easier handling, the aqueous bitumen emulsions, cationic or anionic ones, are mostly used for road construction and maintenance. However, the stability during transportation and the break speed of such bitumen emulsions in contact with mineral aggregates depend mainly on their rheology and electrical properties, which in turn are function of the emulsifier structure, adsorptive properties and concentration. Therefore, it is useful to determine the viscosity of the aqueous phase and the surface charge of the bitumen droplets for the control of the emulsion stability and break speed.

The bitumen used for road construction is the heavy crude oil fraction and is obtained by distillation under vacuum of crude petroleum. The bitumen structure is a complex mixture of hydrocarbons of various chemical structure and molecular weight. In the aqueous bitumen dispersions and bitumen emulsions, the interfacial film structure and composition control both the bitumen–water interface polarity and the emulsion rheological properties. The interfacial film in emulsions can be made of molecular or macromolecular surfactants, while in bitumen dispersions the interfacial film can be made of natural surfactants, such as asphaltenes and resins, which are extracted from the bitumen. Hence, when bitumen emulsions are prepared, the surfactant molecules will diffuse from the water phase and will arrange at the bitumen–water interface. The kinetic of the diffusion of the surfactant, the magnitude of the resulted surface charge at the bitumen–water interface, will depend on the structure and the composition of the surfactant. Cationic and nonionic surfactants are frequently used as emulsifiers in aqueous bitumen emulsions. Further, it has been reported that a blend of emulsifiers will be more efficient than a single compound, which was illustrated by (Jada et al., 2004).

6.2 Production Process of Bitumen Emulsions

As was mentioned before, bituminous emulsions mostly are used for road surfaces. Their range of application is quite diverse and includes cold mixes, seasoning and surface coating walls. A bitumen emulsion is oil in water emulsion which is composed of a dispersed phase of bitumen and the continuous phase of water. To disperse the bitumen is necessary to use a mechanical energy of cut (mill) and a surfactant or emulsifier. Scientifically, however, an emulsion is heterogeneous and unstable. Its minimum stability can be increased by surfactants and emulsifiers that lowering the surface tension between the phases favor to maintain a certain balance.

The emulsification of a bitumen is to fragment the bitumen into very fine particles with a few microns in diameter, electrically charge them and providing them with a repulsive power of towards each other. The optimum viscosity is that which enables the bitumen to shatter with the minimum shear stress and simultaneously enables surfactant to bind to the surface of the globule of bitumen and bind perfectly.

The Bitumtec plant produces 20-21 tons/h which is the maximal range of processing mill as was shown by (Castagno & Musarò, 2010). Below, the process scheme of bituminous emulsion production was presented in Figure 6.1.

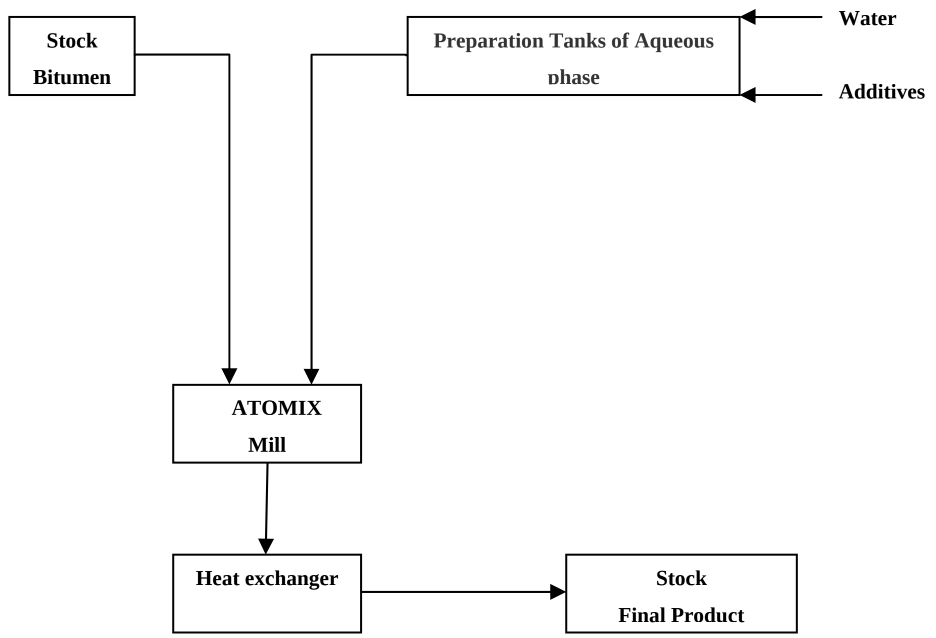

Figure 6.1. Production process scheme of bitumen Emulsions.

6.3 Characteristics of Emulsions

Asphalt emulsions are classified into three categories; anionic, cationic, or non-ionic. The anionic and cationic classes refer to the electrical charges surrounding the asphalt particles. The absence of the letter "C" denotes anionic emulsions. Asphalt emulsions are further classified on the basis of how quickly they coalesce; i.e., revert to asphalt cement. The terms RS (Rapid Set), MS (Medium Set), SS (slow set), and QS (Quick Set) have been adopted to simplify and standardize this classification. Additionally, trailing numbers are used to delineate the relative viscosity if the emulsion and the letters "h" and "s" indicate whether hard or soft base asphalt is used to make the asphalt emulsions. Thus, a CSS-1h is a cationic slow set emulsion with a relatively low asphalt emulsion viscosity made with hard base asphalt. Types of emulsions are shown in Table 6.1 below:

Table 6.1. Types of emulsions.

<table>
<tr><th></th><th colspan="4">Cationic Emulsion</th><th colspan="4">Anionic Emulsion</th></tr>
<tr><td>Rapid Settings (RS) Type</td><td colspan="2">CRS-1</td><td colspan="2">CRS-2</td><td colspan="2">RS-1</td><td colspan="2">RS-2</td></tr>
<tr><td>Medium Settings (MS) Type</td><td colspan="4">CMS-2</td><td colspan="4">MS-2</td></tr>
<tr><td>Slow Settings (SS) Type</td><td>CSS-1</td><td colspan="2">CSS-1h</td><td>Modified CSS-1h</td><td>SS-1</td><td colspan="2">SS-1h</td><td>Modified SS-1h</td></tr>
</table>

The properties of the emulsions can be divided into two groups:

- The Intrinsic Properties: it comes to its own characteristics of the emulsion that are independent of their use; like viscosity and storage stability.
- The Extrinsic Properties: these are characteristics related to their behaviour in various application fields that are, the rupture velocity, and adhesion.

A final group of features are typical of bitumen and bituminous emulsion as related to residual Penetration, Elastic and so on.

The quality control refers to the UNI EN, which later was shown in Table 6.2 as was shown in (Castagno & Musarò, 2010).

Table 6.2. Reference standard UNI EN.

Characteristics	**Measure**	**Reference standard**
Content of Water	% by weight	UNI EN 1428
Content of Bitumen	% by weight	UNI EN 1428
Content of flux	% by weight	UNI EN 1431
Break Index	Adimens.	UNI EN 13075-1
Mixing stability with cement	g	UNI EN 112848
retained by the sieve 0.5mm	% by weight	UNI EN 1429
Sedimentation days	% by weight	UNI EN 12847
Viscosity	seconds	UNI EN 12846
Adhesion	% by weight	UNI EN 113614

6.3.1 Viscosity

The viscosity, measures the residence of the particle to the movement of bitumen and it's clear that increases with binder percentage increase so, for dispersing bitumen in the aqueous phase it is necessary that its viscosity remains around 0.2 Pa.sec.

6.3.2 Stability

An emulsion is stable, if it's not separated into its components. Many of these properties depend on the type and quantity of emulsifiers and also the origin and gradation of bitumen. In general the stability of an emulsion depends on the distribution and the average size of microscopic droplets of bitumen. The phenomenon is translated in the three steps of sedimentation, flocculation and coalescence.

- Sedimentation: The process by which, in a container, the concentration of the particles of bitumen increases with the progress towards the bottom;
- Flocculation: Process in which the particles of bitumen agglomerate, and
- Coalescence: Total separation between the binder emulsion and the aqueous phase.

6.4 Breaking Emulsion Process

As said before, there are in common two broad types of emulsions, namely anionic emulsions and cationic emulsions. The breaking of anionic emulsions is dependent on the evaporation of water from bitumen emulsion. As such, it poses difficulty in wet weather condition. However, for cationic emulsions, instead of relying on the evaporation of water the breaking is achieved by chemical coagulation. Hence, cationic emulsions are particularly useful in wet weather conditions.

6.4.1 Anionic emulsions

The term anionic is derived from the migration of particles of asphalt under an electric field. The droplets migrate toward the anode (positive electrode), and hence the emulsion is called anionic. In an anionic emulsion, there are "billions and billions" of asphalt droplets with emulsifying agent at the water asphalt interface. The tail portion of the emulsifying agent aligns itself in the asphalt while the positive portion of the head floats around in the water leaving the rest of the head negatively charged and at the surface of the droplet. This imparts a negative charge to all the droplets. Since negatives repel each other, all the droplets repel each other and remain as distinct asphalt drops in suspension. A typical anionic emulsifying agent is shown below (Figure 6.2) along with a diagram showing the orientation of the agent at the asphalt-water interface and the negative charge imparted to each drop.

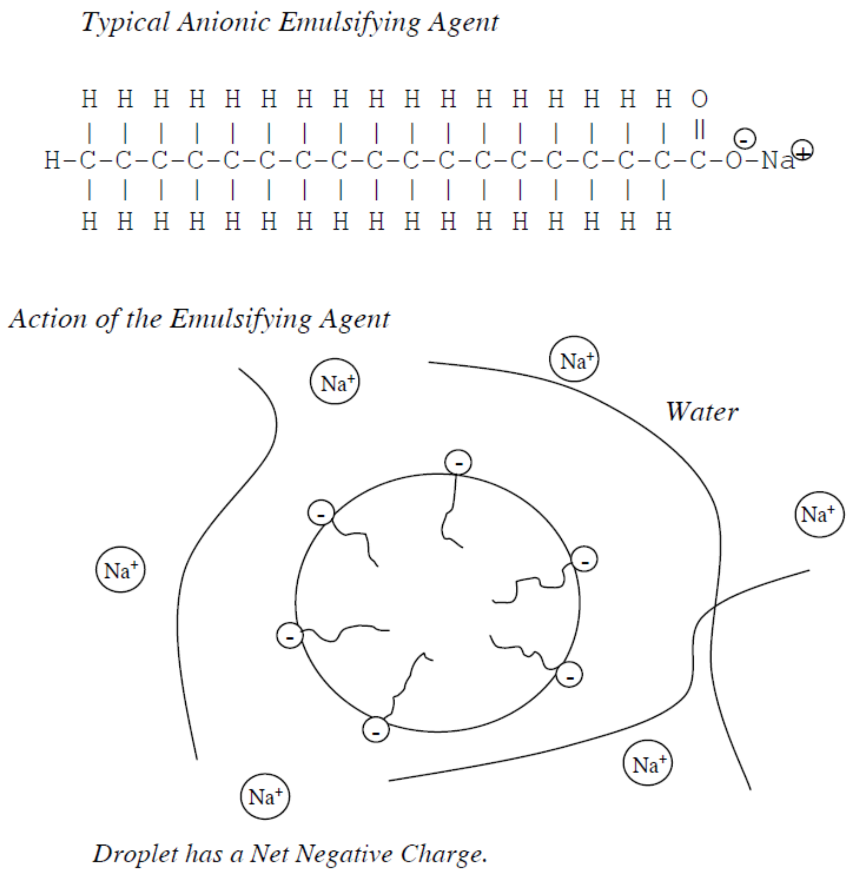

Figure 6.2. Anionic emulsifying.

6.4.2 Cationic emulsions

The term cationic is derived from the migration of particles of asphalt under an electric field also. The droplets migrate toward the cathode (negative electrode), and hence the emulsion is called cationic. The cationic emulsifying agent functions similarly to the anionic; the negative portion of the head floats around in the water leaving a positively charged head. This imparts a positive charge to all the droplets. Since positives repel each other, all the droplets repel each other and remain as distinct asphalt drops in suspension. A typical cationic emulsifying agent is shown below (Figure 6.3) along with a diagram showing the orientation of the agent at the asphalt-water interface and the positive charge imparted to each drop.

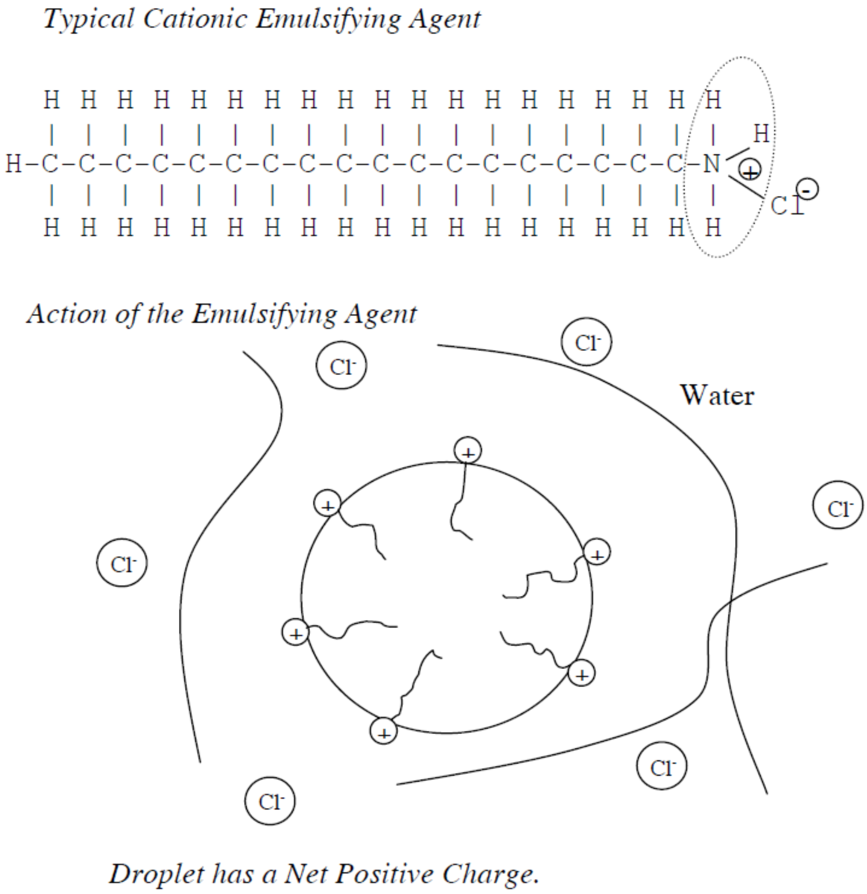

Figure 6.3. cationic emulsifying.

6.4.3 Breaking characteristics of emulsions

The breaking of emulsions is the phenomenon electro physics for which the bitumen is separated from the water. In a bitumen emulsion the emulsify molecules are present in the aqueous phase and on the surface of the particles of bitumen. Some types of emulsifiers (more complex structures and branched) create micelles that are oriented to each other as on the surface of the particles of bitumen. When the emulsion is in contact with a mineral aggregate, the negative charge present on the surface of the aggregate quickly attracts the ions of the micelles and the ions of emulsify present on the particles of bitumen. As the process goes on the charge present on the particles of bitumen tends to weaken this favours their aggregation, and the final setting of the bitumen on the aggregate.

The type of emulsion used has a large effect on the speed of the “break” of an emulsion. Almost all surfaces have a net negative charge. The strength or intensity of this negative charge may be different from material to material. Because of this phenomenon, anionic and cationic emulsions break in different ways.

In an application of anionic emulsion, were applied negatively charged drops of asphalt to a negatively charged surface. All components repel each other. The only way the emulsion can break is through the loss of water by evaporation. As more and more water is lost through evaporation, the particles are forced closer and closer together until they can no longer be separated by a film of water. At this point droplets coalesce into larger and larger drops and ultimately a sheet of asphalt on the road. A depiction of the application is shown below in Figure 6.4.

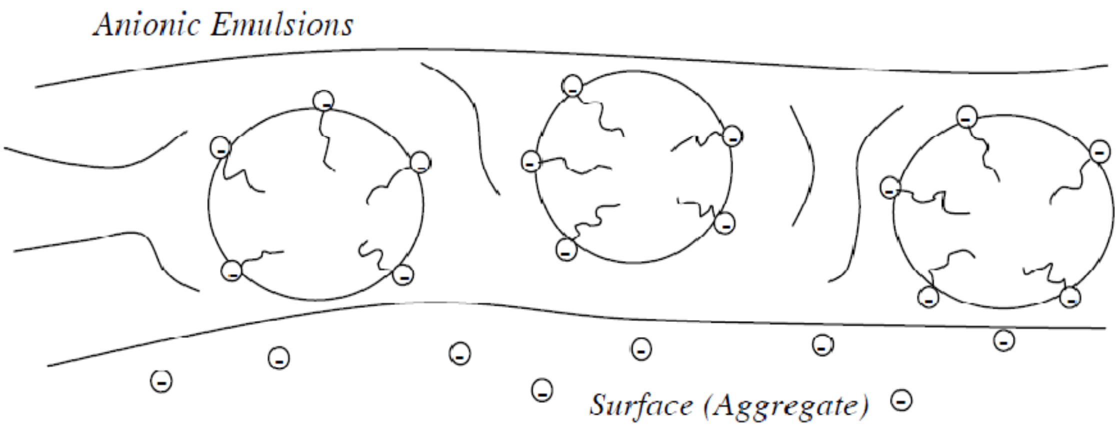

Figure 6.4. Application of anionic emulsions.

In an application of cationic emulsion, were applied positively charged drops of asphalt to a negatively charged surface. The asphalt drops are immediately attracted to the surface and begin to break. The emulsion also losses water by evaporation. Thus the cationic emulsion has two breaking mechanisms at work and will break faster than a corresponding anionic emulsion. A depiction of the application is shown below by Figure 6.5.

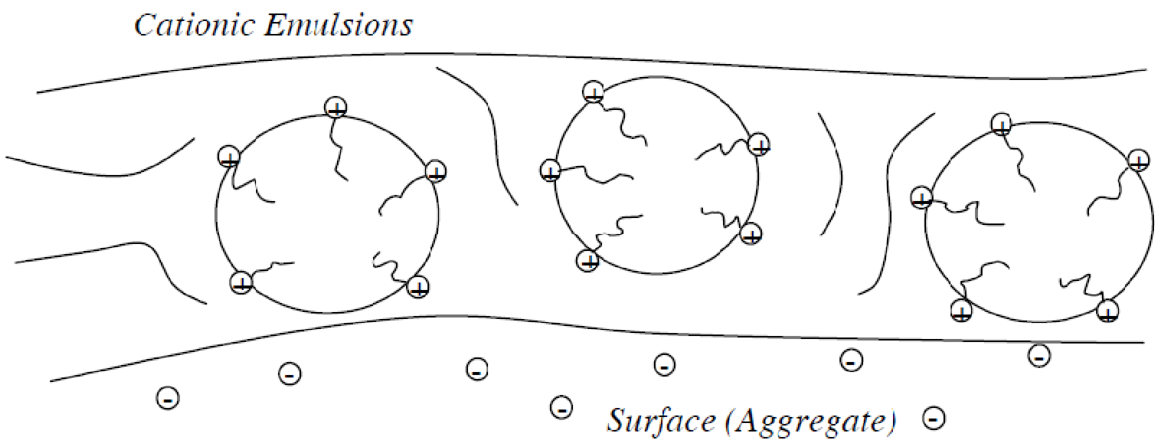

Figure 6.5. Application of Cationic emulsions.

The object of a surface treatment is to seal the road from moisture intrusion and provide a new skid resistant surface, but be open to traffic as soon as possible and retain aggregate. Due to the chemistry of emulsions, they may react differently in specific weather and application conditions. If you have problems in any of these areas, the problem could be because of the weather, aggregate condition or emulsion used. In general anionic emulsions will work better than cationic emulsions in low humidity and dry dusty aggregate conditions.

6.5 Polymer Modified Asphalt PMA

In general terms, the addition of polymers to asphalt binders results in the modification of certain key physical properties including the:

- Elasticity,
- Tensile strength,
- High and low temperature susceptibilities,
- Viscosity,
- Adhesion and cohesion.

Depending upon the form of modification desired, improvements in pavement longevity can be achieved through the reduction of fatigue and thermal cracking, decreased high temperature susceptibility (e.g., rutting, shoving, bleeding), and enhanced aggregate retention in applications such as chip seals. Polymer modifiers are used to extend the lower and/or upper effective temperature operating ranges of pavements and to add elastic components that allow it to recover from loading stress.

The modified binder are more stable under heavy loads, braking and accelerating forces and shows increased resistance to permanent deformation in hot weather. It resists fatigue loads and having better adhesion between aggregates and binders.

There are 3 type of bitumen modifier or additive, namely:

(1) Physical modification,

(2) Chemical modification,

(3) Other type modification.

The Table 6.3 below shows different types of modifiers and additives that are usually used to modify the bitumen, which was shown by (Read & Whiteoak, 2003).

Table 6.3. Types of physical modifier and additive used in the material.

TYPE OF MODIFIER	TYPE OF ADDITIVE
Thermoplastic Elastomers	Styrene – butadiene – styrene (SBS) Styrene – butadiene – rubber (SBR) Styrene – isoprene – styrene (SIS) Styrene – ethylene – butadiene – styrene (SEBS) Ethylene – propylene – diene terpolymer (EPDM) Isobutene – isoprene copolymer (IIR) Natural rubber Crumb tyre rubber Polybutadine (PBD) Polyisoprene
Thermoplastic Polymer	Ethylene vinyl acetate (EVA) Ethylene methyl acrylate (EMA) Ethylene butyl acrylate (EBA) Atactic polypropylene (APP) Polyethylene (PE) Polypropylene (PP) Polyvinyl Chloride (PVC) Polystyrene (PS)
Thermosetting Polymers	Epoxy Resin Polyurethane Resin Acrylic Resin Phenolic resin

Among many different polymers used in bitumen modification such as thermoplastics, thermosets, thermoplastic elastomers, the rubbers seems to be more attractive. Although thermoplastic elastomers such as styrene-butadiene-styrene triblock copolymer SBS or its hydrogenated forms and plastomers such as ethylene-vinyl acetate copolymer EVA are good bitumen modifiers, rubbers are preferred due to their lower prices. In fact, bitumen is supposed to keep its physical and rheological properties constant at different service temperatures and loading conditions and transforms itself to a low viscosity Newtonian fluid at mixing temperature (165ºC). This type of bitumen is called “ideal bitumen”. Constant rheological properties in a wide range of temperatures correspond to rubbery behaviour. It is concluded that the rubbers should be able to modify bitumen properties very well. Therefore, many types of rubbers were introduced in bitumen (PBR, SBR and its latex, ground tire rubber etc.).

Chemical modification used the additive such as organ metallic compounds, sulphur and lignin. It used the chemical agent as additive to modify the characteristic of pure bitumen. Due to vary complex structure of bitumen, chemical modification of bitumen have not been commercialized as physical modification. As conclusion, each modifier has their own additives as modifier agent. There are many modifier materials that can be used to mix with bitumen to improve their performance as paving material. Rubbers are preferred as bitumen modifier due to their lower prices and the availability. Nevertheless, the selection of modifier is depending on the user or company.

6.5.1 Production process of modified bitumen

The modified bitumen is a bitumen which through processing in a special plant is modified so chemical-physical with thermoplastic polymers both type of plastomeric and elastomeric type, in order to increase its performance. The binder thus obtained has rheological characteristics and performance comparable to those of the polymer modifier used and at the same time preserves all the binding properties of the bituminous base. This improvement in performance has a positive effect on mixtures, allowing for the asphalt for road surfaces more resistant to wear caused by the stress generated by increased traffic congestion on roads and highways.

All operations are directed and controlled through PLC and software by the staff in a special control room.

From storage tanks, the bitumen is transferred into a mixer equipped with mechanical stirrers where, is mixed with polymers and additives, according to the quantity and quality required by the formula of the processing.

There are two mixers present in the factory which having the same characteristics and the transport of the bitumen from the tanks to the mixer takes place by means of special pumps. Each of the two mixers is composed of:

- Motor with gearbox (installed power: 30 kW at a speed of 1470 rpm),
- 3 rotating mixing blades and three fixed mixing blades,
- Shaft (speed: 17.5 rpm and 35 rpm)

The polymers are loaded into the mixer from big bags; in fact, the same content is poured into a first loading hopper and then transferred, by means of screw feeder, on a second dosing hopper which provides the exact dosage of the product. Additives, packed in bags or liquids are loaded into the mixer by means of a bucket elevator or dedicated dosing lines. The obtained mixture is made to pass several times through a homogenizer mill until complete dispersion of the polymer in the bitumen.

The finished product from the mixing mixer is then send to the storage tanks, where it is still retained at a temperature of about 175 ° C and acquires the characteristics of the final project.

After successful analysis of quality, the product will be loaded onto trucks for transport to customers. The production process scheme is shown in Figure 6.6. They produce maximum 20-21 ton/h modified bitumen.

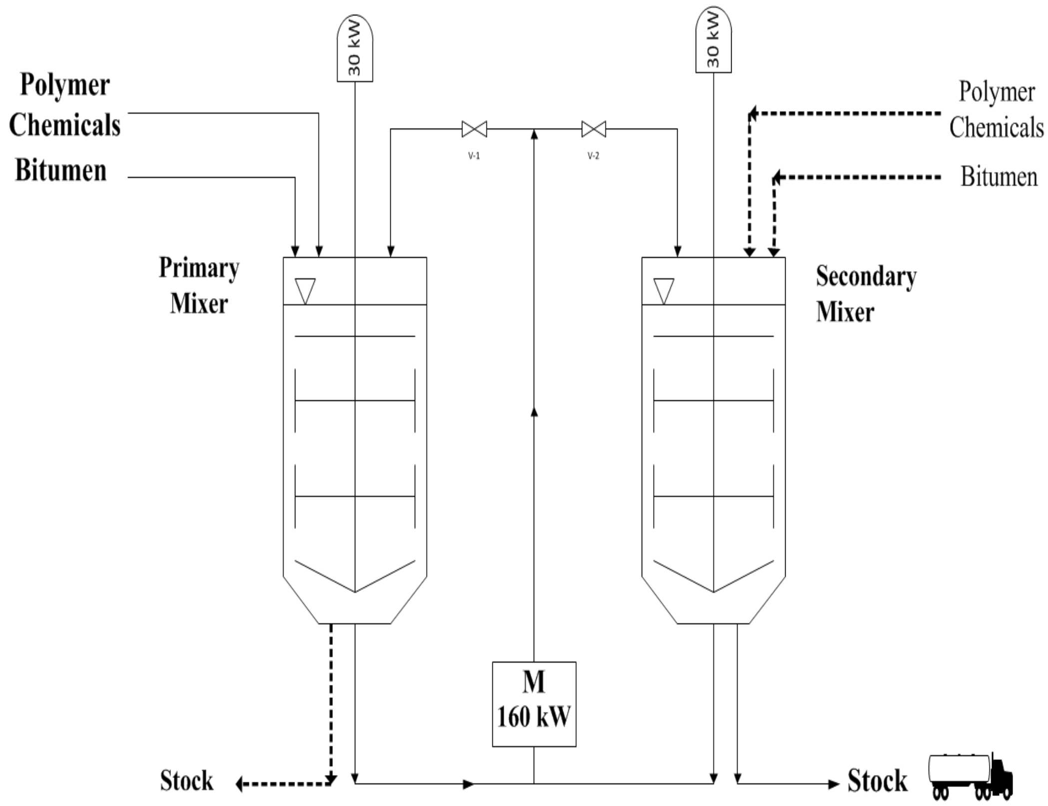

Figure 6.6. Batch production process of modified bitumen.

It must be noted, during all stages of the production process, are carried out a number of checks on the main process parameters and product characteristics that have direct influence on the quality of the finished product.

6.6 Colloidal Mill

The colloidal mill is the heart of the system and consists of a fixed part "stator" and a movable part "Rotor" that by turning micronizes the bitumen into very fine particles. The good micronization depends on: Gap separation stator - rotor rotational speed (rpm mill). The mill must be predominantly heated and once hot passes before the aqueous phase and then the bitumen. By stopping the production works in reverse using water to clean the system and prepare it for the next production. The aqueous phase containing emulsifier is to keep at a suitable temperature so that the emulsion at the exit of the mill and atmospheric pressure is at a temperature of less than 95°C, otherwise the water turns to steam and creates foam bitumen. Conversely the aqueous phase cannot be cold because it would cause a thermal shock by sharply raising the viscosity of the bitumen and compromising the right micronization.

6.7 Emulsion Storage

Emulsion can be stored for a period which can reach several months. During storage may be occur two phenomena that are the sedimentation or creaming respectively the increase in the content of the bitumen in the lower part of the tank or in the upper part of the same. These phenomena depend on the storage time and the size of the globules of bitumen. This duration of storage is achieved with some particular attention, such as the handling periodic (weekly) of the product by means of recirculation in the tank stock, otherwise, as any mixture of products having different molecular weight, it has a physiological tendency to sedimentation/stratification.

6.7.1 Emulsion storage requirements

Emulsion is a cold product which may be stored for up to several months. This characteristic has the following advantages:

- The emulsion may be manufactured as soon as bitumen used to make it received, which makes it possible to avoid storage of this raw material at a given temperature. It is said that the plant “stores cold”.
- The application sites whose emulsion consumption is variable (weather conditions, equipment availability, miscellaneous incidents) are practically independent of the production plants. Similarly, a short shutdown at manufacture does not affect the job site progress.

* As the hourly production rate of emulsion plants is usually greater than the demand, the storage facilities make it possible to have larger production runs, thus improving factory productivity.

6.7.2 Emulsion storage places

Emulsion may be stored:

* Either at the production site itself,
* In mobile or fixed depots close to the job sites.

Do not forget that drum storage is practically no longer used for economical and practical

6.7.3 Emulsion storage time

The highly variable storage time depends on:

* Product requirements,
* Job site requirements and unforeseeable,
* Relative capacity of supply and storage tanks.

The present-day emulsions may be stored for up to several months without any of their properties being altered.

6.8 Bitumen Materials Transportation

6.8.1 Transportation legislation

Bitumen emulsion is a non-flammable product. Consequently, it is not in the nomenclature of dangerous materials ADR; the product contains however hazardous additives which although in low concentrations causing the labeling of danger on the final product.

Risk Phrases (R)

Safety Advice Phrases (S)

R-36/37 Irritating to eyes and respiratory system.

R-37/38 Irritating to respiratory system and skin.

R-42/43 May cause sensitization by inhalation and skin contact.

S-23 Do not breathe fumes / vapor / spray.

S-24 Avoid contact with skin.

S-25 Avoid contact with eyes.

S-44 If you feel unwell, seek medical advice (show them the label if possible).

Verifications of tanker consist of; control tank (temperature, cleaning and the absence of residual solids or liquids that could compromise the quality of the product and unloading), and verification of the temperature T of the bottom.

6.8.2 Emulsion transport conditions

Bitumen emulsion may be transported, either from the manufacture plant to the storage depot, or from the plant or the depot to the job site. The transport facilities are the same as those used for the transport of hot bituminous products. However, they may be simpler as it is not necessary to provide them with a temperature maintaining or heating system.

Depending on the transport distance, the transport facilities are provided with tanks of highly varying capacity, from 23 m^3 tanks (approx.) mounted on trailers, up to small 2 ton tanks designed for maintenance teams. All shapes of tanks may be used; cylindrical or elliptical. For high capacities, in excess of 8 to 10 m^3 it is mandatory to divide the inside of the tank with breaker partitions. For fluid transport, these partitions help to improve transport facility stability and, for emulsions prevent excessive mixing which may be prejudicial to the good stability of the emulsion. That must be mentioned, because of stock and transport conditions for the modified bitumen, and the stock is at a high temperature (150-175 ° C), it must preferably agitated, and the transport ADR is in ONU 99/3257, Class 9 (high temperature liquid).

6.9 Safety regards

Personal protective equipments which are obligatory to be used are shown below by Figure 6.7.

Figure 6.7. Personal protective equipments.

7 Application of the Model to the Case Study

Here is presented, the application of developed model (as an example) to an industrial production process system. Where, are illustrated and discussed the results.

7.1 Proposed Framework

In this work as was mentioned before, the proposed framework with flowing steps are introduced:

- Identification of the most important system MIS

  Specially, in this study a production process system through bituminous materials production process will be addressed.
- Identification of the most critical component MCC

  Particularly, in this study will be addressed the electrical motor rotor-stator "Siefer" that drives homogenization mill during production process of bituminous materials.
- Life time data and energy consumption data collection and observation, also maintenance (corrective and preventive) activities and failure's related data.
- Estimated costs of maintenance and the economic evaluation of maintenance policies (based on balanced cost and risk of inefficiency).
- Maintenance optimization (in terms of probability and consequences).
- Evaluation of the operation costs of the motor.
- Analysis of energy efficiency through maintenance optimization and operating procedures, by using of bottom-up energy efficiency supply curve model, where it was introduced: Expert inputs; which are based on the information from the expert of the system); and Data assumption.
- Definition of scenarios and efficiency measures

  In this study, were defined three levels of base case scenarios with the relative potential energy recovery which are; Low, Medium and High. Future more were proposed solutions and adequate measures (for our case study) to increase the performance, based on the maintenance activities, operating procedures and the conditions of the system.
- Determination of the impact of these measures on the performance.

7.2 Most important system

The motor-driven equipment accounts for approximately 60% of manufacturing final electricity use worldwide. Motor systems represent a largely untapped cost effective source for industrial energy efficiency savings that could be realized with existing technologies, so motor systems have the potential to contribute substantial energy savings. A major barrier to effective policymaking, and to more global acceptance of the energy efficiency potential in industrial motor systems, is the lack of a transparent methodology for quantifying the magnitude and cost-effectiveness of these energy savings. Using a combination of expert opinion and available data, from our selected industrial case study we have introduced an approach where is used the concept of a "conservation supply curve CSC" and bottom-up energy saving model to capture the cost effective as well as the technical potential for energy efficiency and CO_2 emission reduction in the industrial motor systems, where include the importance of maintenance activities, also risk/cost optimization impacts.

In this work, as an example, was chosen the production process of bituminous materials in Bitumtec Ltd. Plant, which was previously introduced in details, in chapter 6. We have chosen the batch production process of modified bitumen for this study. That must be noted, before, the production process was discussed and illustrated in details in section 6.5.1 and the production scheme was shown by the Figure 6.6 (see page 92).

Bitumtec Ltd. produces maximum 20-21 t/h modified bitumen. For this batch production process of modified bitumen, as was discussed before, they possess two mixers which alternate with each other. Polymer and chemical additives and bitumen enter in the primary mixer and recycled for many times that depends on the quality of the product and in the end of the process for the last time the mixture passes in to the secondary mixer and exits modified bitumen that have the necessary characteristics and quality. In the next steps, there are storage, quality control (in laboratory) and transport of the materials to the customers.

7.3 Most critical component

Three-phase electric motor (rotor-stator) "Siefer" is the most critical system or the greater consumer of energy (160 kW) in the chosen process.

For more information must be added; three-phase motors are common for industrial grade tools, as their efficiency is higher than their single phase counterparts. Three-phase motors are motors designed to run on the three-phase alternating current AC power used in many industrial applications. AC electricity changes direction from negative to positive and back many times a second. A three-phase motor has two main parts: the rotor, which turns, and the stator that turns it. The rotor is often called a squirrel cage because it consists of a circular network of bars and rings that look a bit like a cage connected to an axle. The stator consists of a ring with three pairs of coils, evenly spaced around the rotor. Each pair of coils is attached to one phase of power. Because they are all out of phase with each other, they set up a rotating magnetic field that spins around the stator at a continuous rate. The moving magnetic field creates a continuing moving current inside the rotor. This current always lags slightly behind the field in the stator. The out-of-sync currents create a slight pull in the rotor as it tries to line up with the magnetic field of the stator. Since it never quite catches up, the rotor is pulled around and around in a circle, chasing the moving magnetic field of the stator.

The motor is used during production and drag the mill (Siefer type SM-D3/HK) which homogenizes the polymer. Must be noted, Motor speed is about 1485 rpm and mill speed is about 1773 rpm. Below, Figures 7.1 and 7.2 are presenting the motor and the mill “Siefer”.

Figure 7.1. Electric motor (160 kW) and the mill “Siefer”.

Figure 7.2. Siefer type SM-D3/HK.

Typical electric energy absorption of the Siefer during starting and working is shown in Figure 7.3. As is shown, immediately after turning on the motor, there is a peak of energy absorption (about 400 Ampere) which last only 5 seconds. The motor is started only one time a day, at the beginning of the work in the morning and is shut down at the end of the work in the afternoon. If the motor works unloaded absorbs a little power (electricity), and if it works loaded, it has almost a uniform consumption that depends on some factors; such as motor efficiency, type of the product (viscosity) and so on.

It must be noted, first, the motor is started (turned on) and then is loaded, but the time that is working unloaded is very small, only about 5 seconds. It means they have just managed the use of energy in a good way.

Objective of the study of historical data and observations was to prevent and/or reduce malfunctioning and the negative effects due to failures with appropriate measures and define efficiency measures to increase efficiency and performances of the system and the present conditions also environmental benefits and decrease costs of energy.

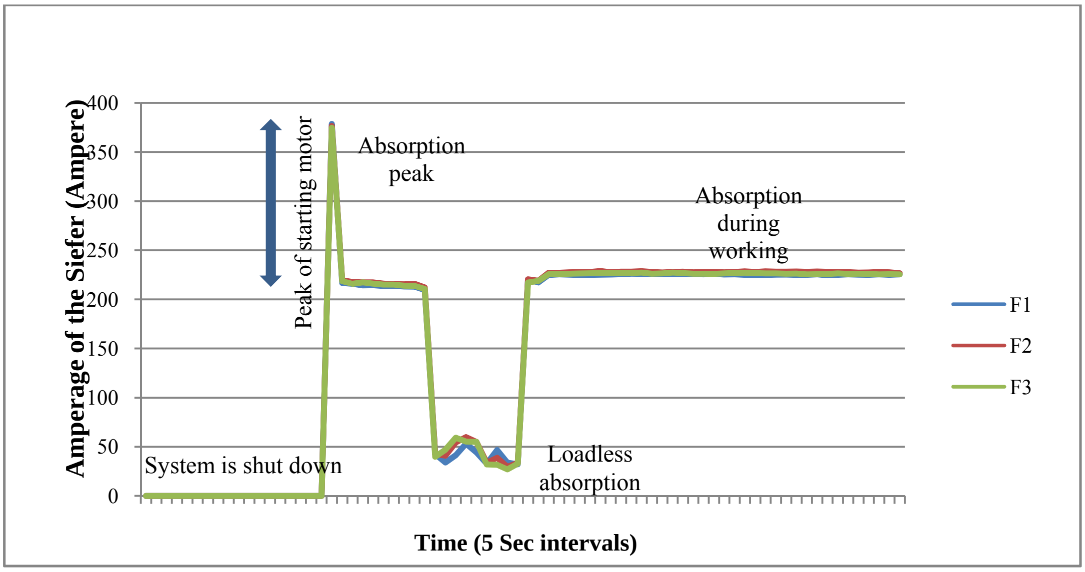

Figure 7.3. Typical electrical energy absorption of Siefer during starting and working.

7.4 Data collection and observation

The first step was a literature review to develop a base line of information. The research was carried out in the field of energy management systems, energy saving and industrial energy efficiency technologies and models, also impacts of energy consumption on production systems and on the environment. In our point of view, also maintenance activities and reliability of the systems are important issues, to reduce consumption and energy costs. For this motive also was reviewed maintenance models and impact of productivity benefits and maintenance optimization on energy cost-effectiveness, and environments. This information was used to develop the model of analysis of energy efficiency, so to achieve our goals. A part of these studies as theory's part, were introduced in this work and illustrated in previous sections.

Then, as a case study, the production process of bituminous materials in Bitumtec Ltd. plant was chosen. The next step was a historical data collection, observation and gathering of the expert opinions. Inputs were obtained from studies of the electrical energy consumption and related maintenance activities and failures data of the motor system Siefer. Therefore, a framework was developed to obtain enough inputs for the further analysis.

Following, are shown the most important results of these studies and data gathering, which were useful to reach our goals.

Trend of electric energy absorption of old motor Siefer, before failure in date of 22.07.2010, is shown in the Figure 7.4. As seen, before the failure was happened, the motor has had regular cycles (each cycle last about 1 h) and the maximum consumption was around 230 Ampere. To be noted, the old motor efficiency was about 89%.

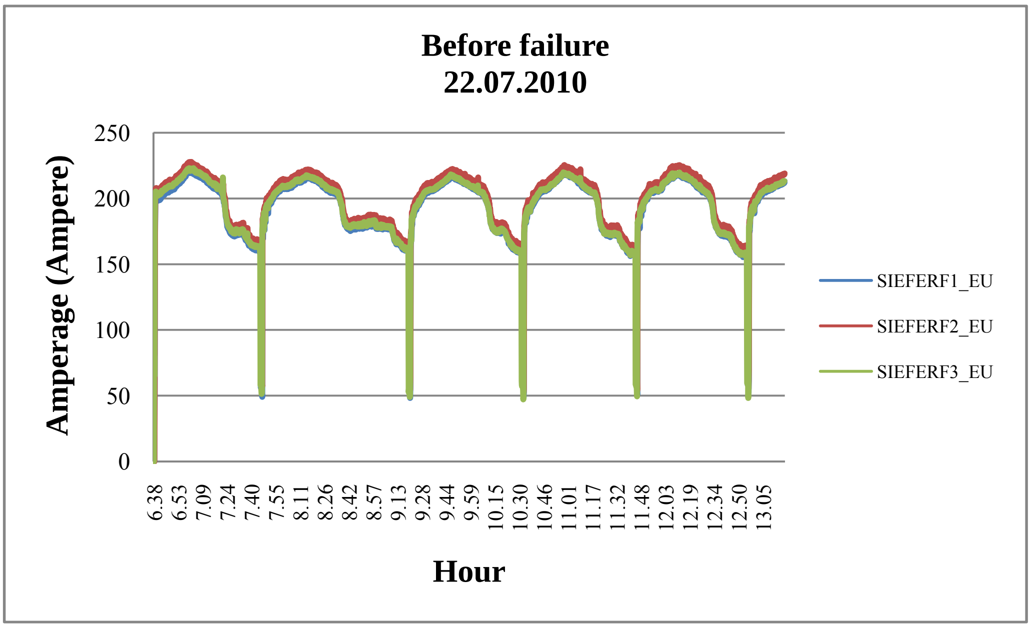

Figure 7.4. Trend of absorption old motor before failure (Ampere/hour).

Studying the historical data was noted that the old motor has broken after 8,000 h (4 years) working, on July 2010 (23.07.2010), fortunatley they have had also a new motor in the stock, so they had only 10 hours of stop working and loss of production (time to remove old motor and instal the new one). Therefore, in 2010, in addition to preventive (ordinary) maintenance for the motor system, they also had corrective maintenance.

The breakdown was due to the condensation that was formed inside the motor and dripped on the terminal block so has burned out the terminal block. Therefore starting the motor, it has had anomalies in phases and after a few minutes stopped working.

Trend of energy absorption of the old motor Siefer during breakdown is shown in Figure 7.5.

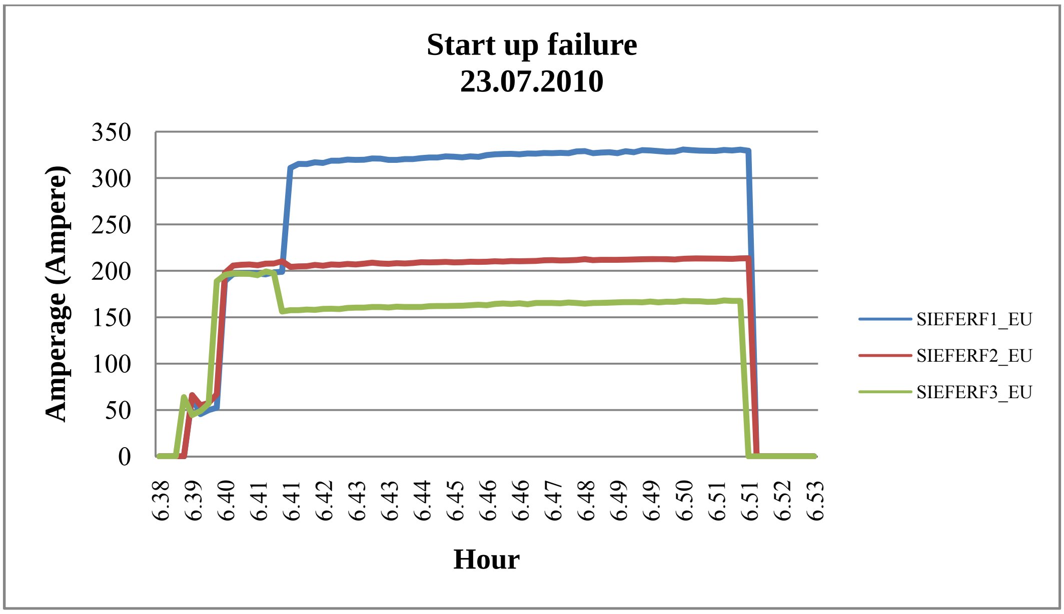

Figure 7.5. Trend of energy absorption of the old motor Siefer during breakdown (Ampere/hour).

As was mentioned before, they have had a new motor in stock and after 10 hours of downtime and stopped production, the new motor has been activated. New motor efficiency is 96%. Trend of electricity absorption of the new motor Siefer, immediately after starting, is shown in the Figure 7.6. As seen, the new motor at the beginning of work has a peak (high consumption) around 400 Ampere and during operation has a uniform consumption, in this case is around 150 Ampere.

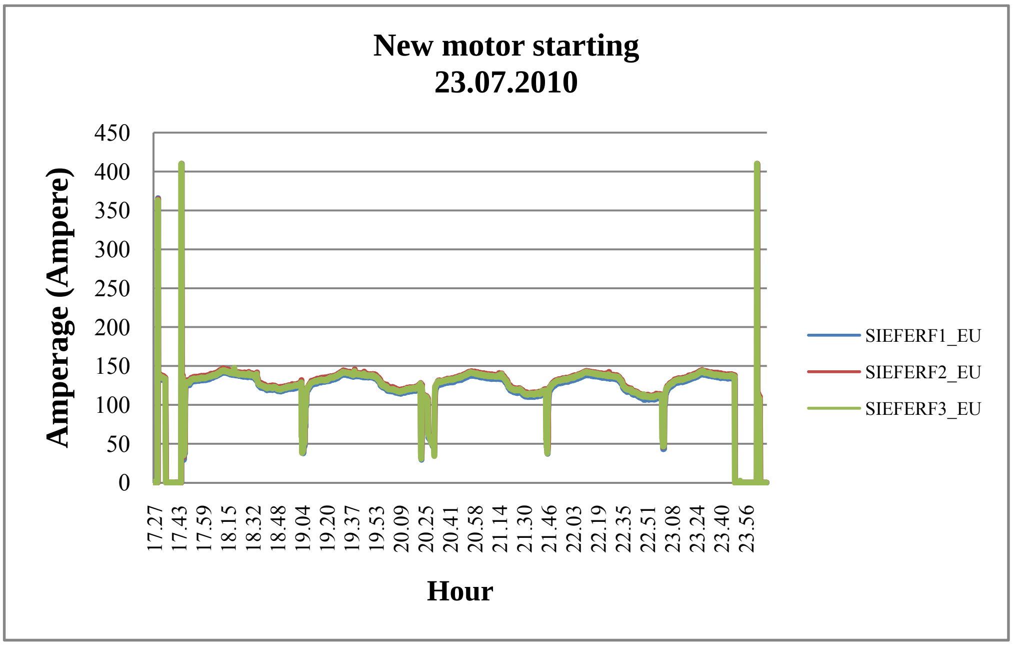

Figure 7.6. Trend of energy absorption of the new motor (Ampere/hour).

There are many other factors that may affect the trend of energy consumption of the motor, like the mill driven by the motor and type of product. Follow, is showed these effects on the electricity consumption of the motor.

They possess two mills for this process, which they alternate. Annually the mill, driven by the motor, is changed. Trend of electric energy absorption of the motor Siefer with a new mill and with SBS linear polymer, after stationary of winter maintenance is shown in Figure 7.7. As seen, use of new mill also increases consumption of the motor.

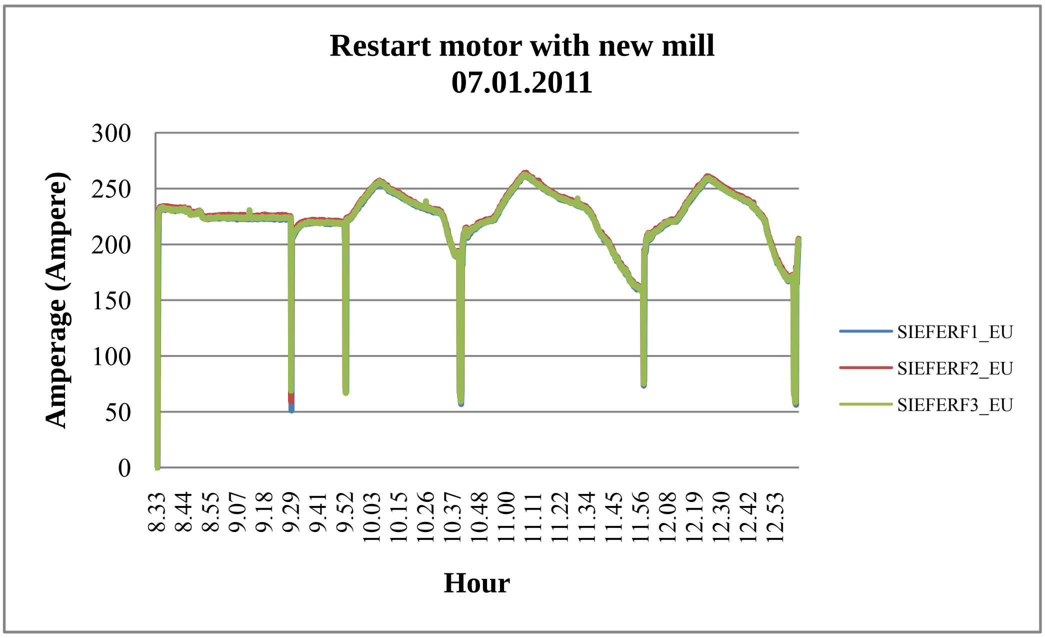

Figure 7.7. Trend of electric energy absorption of the motor with a new mill (Ampere/hour).

Trend of electric energy absorption of motor Siefer (after running about 40 h) with a new polymer (radial SBS) is shown in Figure 7.8. Increasing the viscosity of the product, motor fatigue is more, therefore electricity consumption increase.

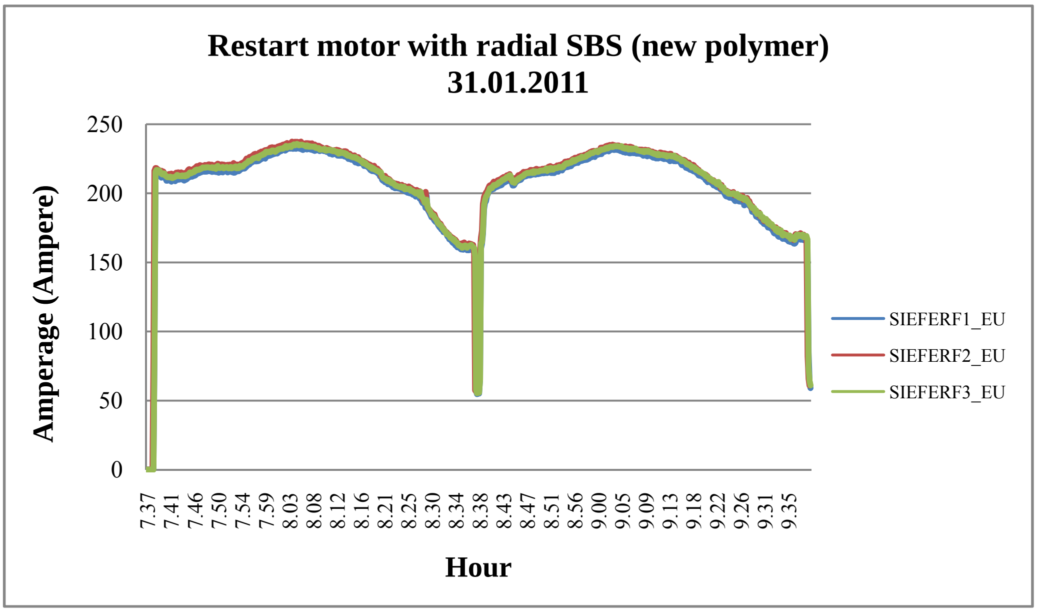

Figure 7.8. Trend of motor absorption with a new polymer, radial SBS (Ampere/hour).

We can summarize the factors that affect the performance, in three cases, which are:

1. Efficiency of the motor and the connected equipment
2. Failures and malfunctioning
3. Processed product

7.5 Economic evaluation of maintenance

Here, is presented economic evaluation of maintenance policies. Previously in the section 5.2.1, the theoretical part of maintenance & operation costs model was discussed in details, which are used to estimate economic evaluation. To be noted, in an industrial realty, maintenance policies (ordinary, preventive and corrective) are chosen based on the recommendation of the manufacturer and the experiences.

Following are summarized maintenance activities related to motor Siefer:

Preventive maintenance:

- Tightening the terminal block; every 2 months, duration 10 min.
- Greasing of the bearings; monthly, duration of 5 min.
- Tensioning of the belts; monthly, duration 5 min.
- Annual cleaning of the mill.

Corrective maintenance (after breakdown of old motor in 23.07.2010):

- Repair of the old motor Siefer.

- Repair after damaging during transport.

To be noted, estimated costs also include loss of production. In the Table 7.1 is presented estimated costs of maintenance activities of the motor Siefer from 2006 to 2012, which is used Equation 5.3 based on the data collected from the company.

Table 7.1. Estimated costs of maintenance activities (related to motor Siefer).

Estimated costs of maintenance activities						
	Siefer	**Year**	**No. of the mill**	**Costs (Euro)**		
Preventive				**Preventive**	**Ordinary**	**Corrective**
• Tightening the terminal block; every 2 months, duration 10 min. • Greasing of the bearings; monthly, duration of 5 min. • Tensioning of the belts; monthly, duration 5 min.	**Old Motor**	**2006**	17980	4237.85	750	-
		2007	10870	4389.6	750	-
		2008	17980	5130.95	750	-
		2009	10870	5295.35	750	-
Corrective	**New Motor**	**2010**	17980	6110.15	750	2095
• Repair of the old motor Siefer. • Repair after damaging during transport. • 10 hours of stopped production		**2011**	10870	2922.1	750	-
		2012	17980	4401.55	750	-

Trend of estimated maintenance costs is shown by Figure 7.9. As seen they had an increase of costs in 2010 because of the corrective maintenance and loss of production. And costs decreased in the year 2011 because use of new motor.

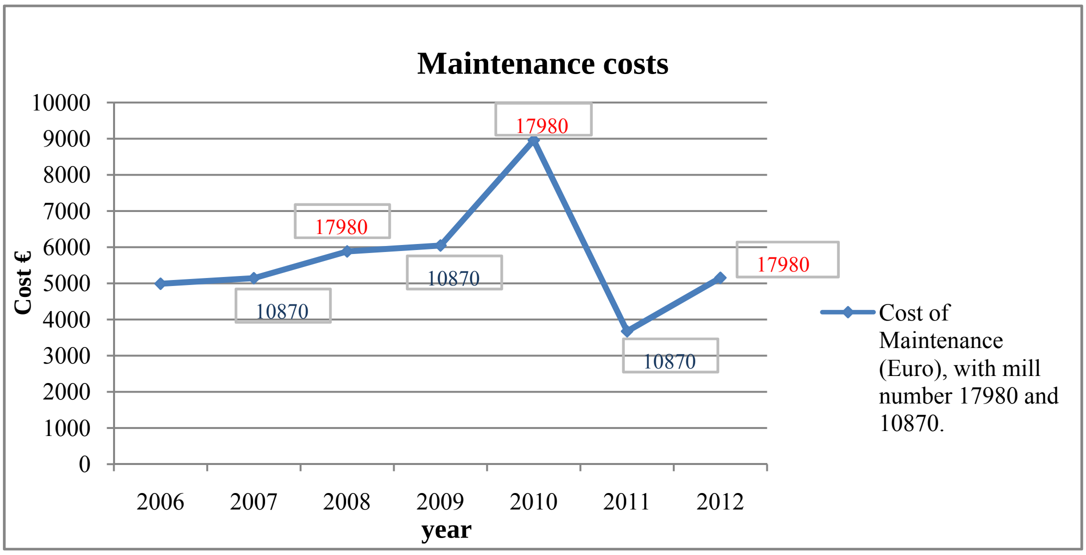

Figure 7.9. Annual trend of maintenance costs of Motor Siefer.

7.6 Optimization of maintenance operation

As was discussed before, optimization of maintenance operation gives opportunities to increase the performance of the system, also energy saving. In this work, is proposed measures based on decision making procedures that includes the expert opinion, and balanced cost effective, which are discussed in more details further and also presented here;

- Upgrade system maintenance such as: fix leaks, damaged seals and packing; and remove sediments from mixer.
- Use of new technologies and more efficient devices, as example new belts with higher power transition and maintenance free.
- Initiate predictive maintenance program.

7.7 Evaluation of the operating costs of the motor

Operating costs of power consumption of the motor Siefer, was calculated, based on the data collection from 2010 to 2012. Before, in the section 5.2.1, the theoretical part of maintenance and operation costs model was discussed in details, which is used also to estimate economic evaluation.

That must be mentioned in an industrial reality there are many factors that affect this trend like: an average production capacity, working hours that depends on the period of the year, the average cost of electricity and so on.

Here was estimated the motor system electricity use as % of overall electricity use in the sector.

Must be added, the total electricity use by the plant is about 1.3-1.4 GWh in a year.

Power factor of the old motor and the new motor that is used to calculations are:

Cos φ of the old motor: 0.89,

Cos φ of the new motor: 0.84.

Table 7.2 shows, the average evaluation costs of operation that was calculated for 2010, 2011 and 2012.

Table 7.2. Operation costs of Siefer.

Year	**Average production capacity, t/h**	**Average index of electricity cost €/kWh**	**Average working hours of Siefer, h**	**Average electric consumption of motor, kWh**	**Average cost of motor consumption, €/kWh**
2010	20.17	0.137	1958	239504	32971.07
2011	20.39	0.149	2528	300154	44891.85
2012	20.27	0.165	2250	267154	44535.77

In Figure 7.10 are shown the monthly trends of electricity consumption of the motor Siefer, and in Figure 7.11 are shown the monthly trends of costs of power consumption of the motor Siefer, which was calculated for the years 2010, 2011 and 2012.

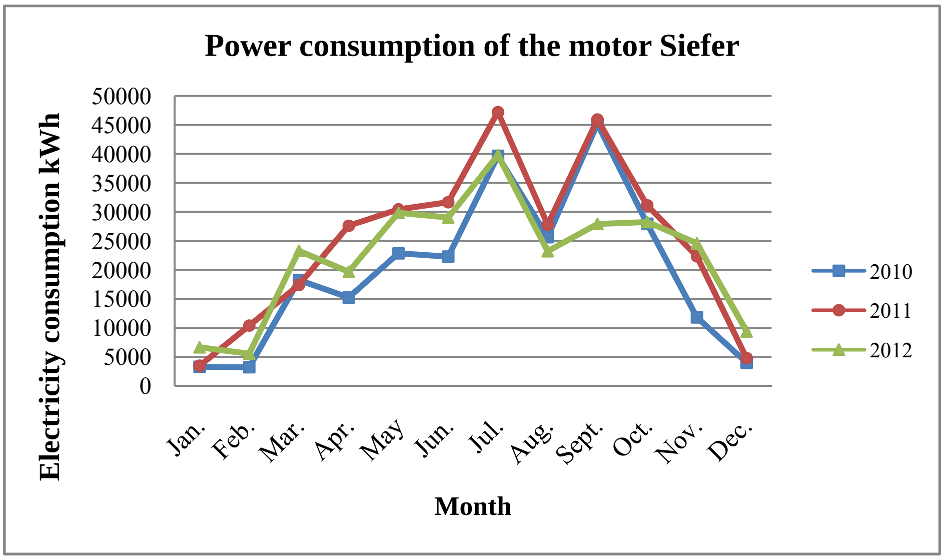

Figure 7.10. Monthly trends of power consumption of the motor Siefer.

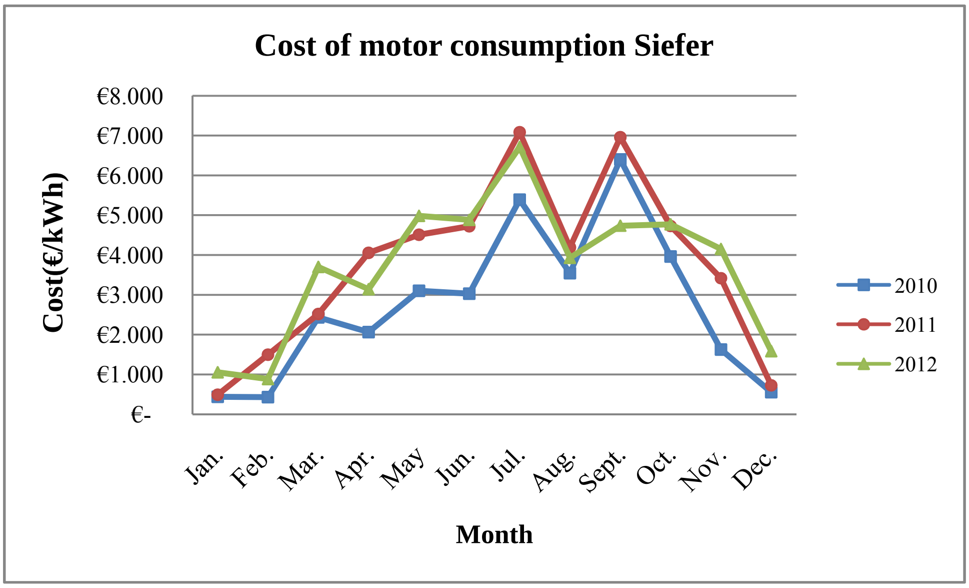

Figure 7.11. Monthly trends of cost of motor consumption “Siefer” (€/kWh).

7.8 Efficiency analysis

Here is used energy efficiency analysis model which is developed based on the concept of a “conservation supply curve” CSC. There was made a bottom-up model to capture the cost effective as well as the technical potential for energy efficiency and CO_2 emission reduction for the industrial motor system in our industrial case study. The curve shows the energy conservation potential as a function of the marginal Cost of Conserved Energy. The Conservation Supply Curve is an analytical tool that captures both the engineering and the economic perspectives of energy conservation.

The approach used in this study to develop the energy conservation supply curves (in this study called motor system energy efficiency supply curves) is different from the one often used in prior studies. Because of data limitations for industrial motor systems, detailed bottom-up data, typically used for developing a CSC was not available. To overcome this problem, an innovative approach was developed that combines available data with expert opinion to develop energy efficiency supply curves for the motor system. This approach was explained before in details in the chapter 5.

As was mentioned previously, the first step was a literature review to develop a baseline of information. Next, a data collection framework was developed to obtain expert input to supplement the existing data. Input (energy audit) was obtained from our industrial case study for motor system Siefer. At least expert opinion was used to refine the final inputs to the analyses. After receiving expert input and completing data, the Motor System Energy Efficiency Supply Curve is constructed based on the methodology explained and discussed in details before in chapter 5. We can also summarize it as is presented below;

The procedure can be summarized in:

- Develop a baseline information;
- Energy audit and data collection;
- Data assumption;
- Expert inputs (depending on the information by the expert of the system);
- Definition of three base efficiency scenarios and efficiency measures;

For this case study, three levels of potential of electricity power recovery were defined, where is used the expert opinion and data obtained from the literatures (McKane & Hasanbeigi, 2011) which are: Low, Medium and High. Establishing three base scenarios are based on maintenance activities, operating procedure and condition of the system. Table 7.3 represents characteristics of three base case scenarios.

Table 7.3. Efficiency base scenarios.

Efficiency base scenarios	Characteristics	Possibility of energy recovery
Low Level	Maintenance is limited to what is required to support operation.	15%
Medium Level	Maintenance is a routine part of operations and includes some preventive actions.	10%
High Level	Both routine and predictive maintenance are commonly practiced.	5%

To determining the impact of the energy efficiency measures also was asked expert of the system to provide his opinion on energy savings likely to result from implementation of each measure expressed as a % improvement for each of the Low, Medium and High base cases. The percentage efficiency improvement by the implementation of each measure decreases as the base case moves from Low to High. Also was estimated Costs based on balanced cost-effectiveness for each measure. The implementation of energy saving measures, for our case study was based on both the technical feasibility and the economic feasibility. Must be noted that not all feasible technical measures, are also economical, in the other words are not cost effective. Decision making was made on the base of these three levels, so at least were established and proposed solutions to increase the efficiency based on the maintenance activity, operating procedures and the conditions of the system. Would be added, since the Low base case is defined by limited maintenance, the % improvement from maintenance-related measures would be expected to be greater than that of the High base case, for which both routine and predictive maintenance are common.

Here, using the energy efficiency formula, Equation 5.1 is estimated annual potential energy saving and annual potential CO_2 reduction (environmental benefits) for each efficiency base case scenarios, and is presented in Table 7.4.

Must be noted, in our study, was assumed the real interest rate i 3% and the real discount rate equal to 0.75% per year to reflect the barriers to energy efficiency investment in industry such as: perceived risk, lack of information, management concerns about production and other issues, capital constraints, and preference for short payback periods about 3 years. So using Equation 5.2, capital recovery factor q is equal 0.922.

Table 7.4. Cost effectiveness and environmental benefits estimated for each base case scenario.

<table>
<tr><th>Average annual energy consumption kWh</th><th>Average Energy price €/kWh</th><th>Capital recovery factor q</th><th>Efficiency base case scenario</th><th>Potential recovery efficiency %</th><th>Annual saved energy kWh/y</th><th>Annual CO_2 reduction tCO_2/y</th></tr>
<tr><td rowspan="3">300,000</td><td rowspan="3">0.15</td><td rowspan="3">0.922</td><td>Low</td><td>15</td><td>45000</td><td>22.5</td></tr>
<tr><td>Med.</td><td>10</td><td>30000</td><td>15</td></tr>
<tr><td>High</td><td>5</td><td>15000</td><td>7.5</td></tr>
</table>

Expert input for motor system characteristics described above were reduced to a single value for each characteristic based on an analysis of average and median values. These consolidated values were further validated through expert review before being included in the analyses.

It was also estimated cost of conserved energy for each three base case scenarios for the year 2010, 2011 and 2012, and is shown by Figure 7.12. As was explained before, in 2010 followed by breakdown of the old motor, in addition to preventive (ordinary) maintenance they also had corrective maintenance. Therefore, the CCE in 2010 is more than other next years. If we compare two CCE curves for 2011 and 2012, because of higher production capacity costs in 2012 are a little more than 2011 (the average price of electricity is assumed 0.15 €/kWh for three years).

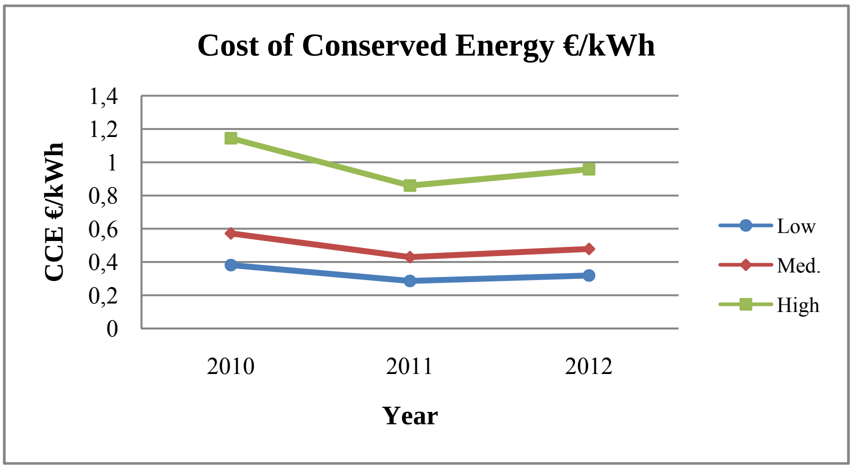

Figure 7.12. Annual trends of cost of conserved energy for three efficiency base case scenarios.

Must be mentioned, in an industrial realty there are many factors in addition to M&O costs that affect these trends such as; an average production capacity, energy price, working hours that depends on the period of the year too and so on.

Here is presented a sensibility analysis, where it was used the real discount rate d=1.25 for 2010 for estimating CCE, so using Equation 5.2, the capital recovery factor for 2010 is q =1.37, and for the years 2011 and 2012 (d=0.75) is q=0.922. As is seen in Figure 7.13, CCE for 2010 is higher than other next two years.

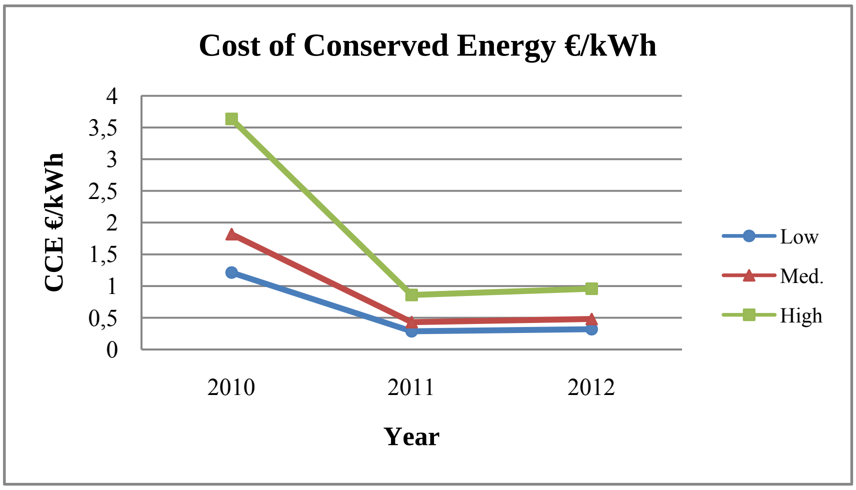

Figure 7.13. Annual trends of cost of conserved energy for three efficiency base case scenarios.

Table 7.5 describes the final values for typical % improvement in efficiency over each base case efficiency (Low, Med and High). Expert opinion and data obtained from source (McKane & Hasanbeigi, 2011) were used to construct a preliminary table for motor system (our case study). Also was estimated typical capital cost and annual M&O changes for each measure. Further, these data are used to construct the cost of conserved energy CCE for the Medium base case scenario, because our industrial case study falls in to Medium efficiency base level.

Table 7.5. Efficiency improvement% over each base case scenario.

<table>
<tr><th rowspan="2">Energy efficiency measure for motor system</th><th colspan="3">The possibility of energy recovery for the base case efficiency (improvement %)</th><th rowspan="2">I cost €</th><th rowspan="2">Changes in M&O cost €</th></tr>
<tr><th>Low (Up to 15%)</th><th>Med. (Up to 10%)</th><th>High (Up to 5%)</th></tr>
<tr><td>Upgrade system maintenance
1. Fix leaks, damaged seals and packing
2. Remove sediments from mixer</td><td>
3.0
7.0</td><td>
2.0
5.0</td><td>
1.0
3.0</td><td>
200
1500</td><td>
100
700</td></tr>
<tr><td>3. Replace Motor with more energy efficient type</td><td>14.0</td><td>7.0</td><td>5.0</td><td>6000</td><td>0</td></tr>
<tr><td>4.Use of new technologies and more efficient devices, like:
New belts (higher power transition and maintenance free)</td><td>1.0</td><td>1.0</td><td>1.0</td><td>303.7</td><td>-300 (saved)</td></tr>
<tr><td>5. Initiate predictive maintenance program (maintenance optimization)</td><td>7.0</td><td>5.0</td><td>2.0</td><td>2000</td><td>200</td></tr>
<tr><td>6. Use of inverter (o Variable speed drive)</td><td colspan="3">*not economical convenient for the case study.</td><td>5000</td><td>0</td></tr>
<tr><td>*Management consumption of the motor, to minimize peaks during start/end of the work (economic alternative for 6).</td><td colspan="5">Starting motor only one time a day, and turned off motor only at the end of the daily work.</td></tr>
</table>

7.8.1 Energy balance sheet of efficiency measures

Here, is presented the energy balance sheet or cost effectiveness of the proposed efficiency measures. Previously, in chapter 4, was illustrated and discussed in details, how is important balancing the costs and benefits of the energy saving measures for the industrial section. Therefore, it must be focused on the best value for money to fined optimal point (cost-effectiveness). Optimal is defined as the minimum economic impact and represents a sort of compromise between reducing the costs and at the same time increasing performance, reliability and safety.

The information and data which are used for the calculation of the energy balanced sheet (cost- effectiveness of the measures), is presented in Table 7.5 below.

Table 7.5. Data base used for the calculations.

Drive power (Three phase electric motor) Siefer type SM-D3/HK	160 kW (214.48 hp)
Voltage	380 v
Motor speed	1485 rpm
Old motor efficiency	0.89 %
New motor efficiency	0.96 %
Power factor old motor (Cos φ)	0.89
Power factor new motor (Cos φ)	0.84
Load factor	0.80
Daily motor running time	8 h
Annual motor running time	2000 h (250 days)
Annual energy consumption	300,000 kWh
Average electricity price per kWh	0.15 €/kWh
Annual energy costs	45,000.00 €

7.8.1.1 Management of power consumption of the motor

The goal of the management of electricity consumption is to minimize peaks during start of the work.

Experiences show that they can also managed the use of motor to reduce peaks at beginning of the work (turned on the motor), which last only 5 seconds. If they start the motor only one time in a day, and turned off it only at the end of the daily work, is more convenient than to apply the invertors, which are more expensive and the payback period is too long as is shown below;

If one peak is about 400 Ampere (210.368 kW) and takes about 5 sec:

250 days × 5 sec = 1250 sec/y,

(1250/3600 h/year) × 210.368 kW = 73.04 kWh/y,

0.15 €/kWh × 73.04 kWh/yr = 10.95 € per year, is cost of peaks (400 Ampere) per year. That is more convenient than to buy and install invertors (more expensive 500 € so payback time is about 46 years) for managing the peaks consumption.

* Must be noted, also use of variable speed drive for this case as shown above (same reason for invertors) is not economic convenient.

7.8.1.2 Use of new technologies and more efficient devices

For example, new belts like “Optibelt Red Power 3”, with high power transmission and zero maintenance, below are presented its characteristics;

- maintenance-free;

New production processes and raw materials make it possible to manufacture a new type of wrapped wedge belt which requires absolutely no maintenance or re tensioning throughout its life. Following the initial tensioning of manufacturer recommendations the Optibelt Red Power 3 will never need any further attention.

- high power rating;

The power ratings are substantially higher than present day wrapped wedge belts depending on section size and pulley diameter. The ratings for the Optibelt Red Power 3 are, in many cases, similar to those of raw edge, moulded cogged belts. The drive efficiency is as high as 97 %.

- cost effective,
- Set Constant,
- environmentally friendly.

Also they are oil-resistant, heat-resistant and dust-protected as standard. Based on an operational life of 25,000 hours, a running time of over 6 years is achieved.

Transmission requires 6 Optibelt (Super TX straps open sides, toothed 5VX/15NX 900/2286), which are presented by Figure 7.12.

Figure 7.12. New efficient motor belts “ Optibelt Red Power 3”.

Should be noted, the number of the current belts “V-belts” are 8, and each one costs about 34.20 €, which total cost is:

8×34.20 € = 273.6 €;

However, because of higher power rating, the number of new belts are only 6 and each one costs about 96 €, which total cost is 6×96 € = 576 €;

The difference is 576 – 273.6 = 302.4 €, still they are convenient as are shown below. Tables (7.6) and (7.7) present energy balance and cost effectiveness of new belts; also in Table (7.8) is shown maintenance optimization and cost saving by use of these new efficient devices.

Table 7.6. Energy balance before and after use of new belts.

Current drive		**Optimized drive**	
Efficiency of the current drive	96%	Efficiency of the optimized drive	97%
Annual energy loss: 0.04×300,000kWh	12,000 kWh	Annual energy loss: 0.03× 300,000kWh	9,000 kWh

Table 7.7. Cost effectiveness through use of new belts.

Annual usable energy through efficiency optimization	3,000 kWh
Costs effectiveness (annual energy saved)	450.00 €
Usable energy through efficiency optimization with a theoretical running time of 25,000 hours 3000 kWh×25000h/2000h(in a year)	37,500 kWh
Saved cost (for lifetime)	5,625.00 €

Table 7.8. Maintenance optimization and cost saving by use of new belts.

current system maintenance		**Optimized system maintenance**	
Tensioning of 8 belts, 5 min monthly (12 times in a year)	Costs 300 €	Zero maintenance	Costs 0 €

As a result total saved costs by use of this belts is (450.00€+300.00€): **750.00 €** per year.

7.8.1.3 Replace Motor with more energy efficient type

- classification and performance;

  IEC/EN 60034-30 standard was published by the International Electro technical Commission in October 2008. The standard defines efficiency classes for motors and harmonizes the currently different requirements for induction motor efficiency levels around the world. It will hopefully put an end to the difficulties encountered by manufacturers producing motors for the global market. Motor users will benefit through the availability of more transparent and easier to understand information.

  The standard defines three International Efficiency IE, efficiency classes for single-speed, three phases, cage induction motors, which are showed by Table 7.9 and Figure 7.13.

Table 7.9. Standard efficiency classes (motor).

CEMEP European voluntary agreement (old classes)	**Efficiency**	**IEC** New classes 60034-30
-	Premium efficiency	IE3
Eff1	High efficiency	IE2
Eff2	Standard efficiency	IE1
Eff3	Low efficiency	--

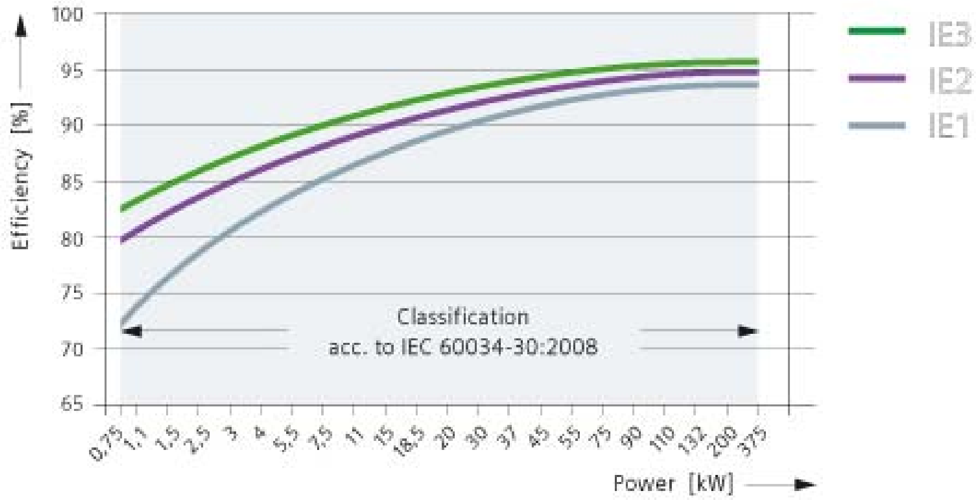

Figure 7.13. Motor Standard classiffication and performance.

Also IE4 level for asynchronous and synchronous motors were defined by IEC 60034-31:2010 Technical specification.

- classification calculation of return times;

With the following formula (Equation 7.1) it is possible to calculate the time of return of a possible replacement of the motor (out of use) with a motor equal to the one already installed or a high-efficiency motor.

$$T_{payback} = \frac{(C_{hem} - C_{riw})}{P.C_c.h.c.\left(\left(\frac{1}{eff_{std} - eff_{riw}}\right) - \frac{1}{eff_{hem}}\right)} \tag{7.1}$$

Where; C_{hem} is cost of high efficiency motor in €, C_{riw} is cost of rewinding or standard motor in replacement in €, P is power of the motor in kW, C_c is the coefficient of the motor load (percentage that the motor works in relation to nominal power), h is the hours of functioning motor in a year, eff_{std} is performance of the standard motor, eff_{riw} is loss of performance because of rewinding, eff_{hem} is performance of the high efficiency motor, and C is average cost of energy in €/kWh.

- cost effectiveness

Table 7.10 is shown the characteristics of old and new motors which was used to calculate the payback period. (kWh= (380 v× 230 A×1.75 × Cos φ / 1000) × 2000 h)

Table 7.10. Characteristics of old and new motors.

		Old motor	New motor
P power	kW	160	160
Power factor	Cos φ	0.89	0.84
C_c load factor	% That is the percentage of the full load at which the motor works.	0.80	0.80
h functioning	h/y	2000	2000
Eff. performance of the motor	%	89%	96%
c Average power cost	€	0.15	0.15
C cost of motor	€	28000	34000
E Energy per year	kWh/y	269140	254019
S Annual expenditure	€/kWh.y	40371	38103

It must be mentioned, comparing old motor with the new one; the old motor has lost about 3% of performance because of rewinding that was considered in the calculation.

Then $T_{payback} = \frac{34000-28000}{160*0.80*2000*0.15*(\frac{1}{0.86}-\frac{1}{0.96})} = 1.29$ y;

So the return time for the replacement of the old motor with the new one is about 1 year.

7.8.2 Motor system energy efficiency supply curve

Here is used developed bottom-up energy efficiency model based on the concept of a "conservation supply curve" CSC to capture the cost effective as well as the technical potential for energy efficiency and CO_2 emission reduction for the industrial motor system in our industrial case study. The curve shows the energy conservation potential for each measure that was presented in Table 7.5 before, as a function of the marginal Cost of Conserved Energy. The Conservation Supply Curve is an analytical tool that captures both the engineering and the economic perspectives of energy conservation.

As was mentioned previously, the approach used in this study to develop the energy conservation supply curve which in this study is called motor system energy efficiency supply curve, is different from the one often used in prior studies. Because of data limitations for industrial motor systems, detailed bottom-up data, typically used for developing a CSC was not available. To overcome this problem, an innovative approach was developed that combines available data with expert opinion to develop energy efficiency supply curves for the motor system. This approach was explained in details in the chapter 5, and schematic of calculation process to construction of motor system efficiency supply curve was shown before in Figure 5.3.

As was mentioned previously, the first step was a literature review to develop a baseline of information. Next, a data collection framework was developed to obtain expert input to supplement the existing data. Input (energy audit) was obtained from our industrial case study for motor system Siefer. At least expert opinion was used to refine the final inputs to the analyses. After receiving expert input and completing data, the Motor System Energy Efficiency Supply Curve is constructed based on the methodology that explained and discussed in details before in chapter 5.

Figure 7.14 shows the conservation supply curve for the electric motor system (presented case study), that presents the energy saving potential as a function of the marginal Cost of Conserved Energy CCE, which accounts for the costs associated with implementing of each measure (Table 7.5) that includes also maintenance and operation costs M&O. It must be added in our study the results was evaluated for the Medium base case scenario about 0.7.

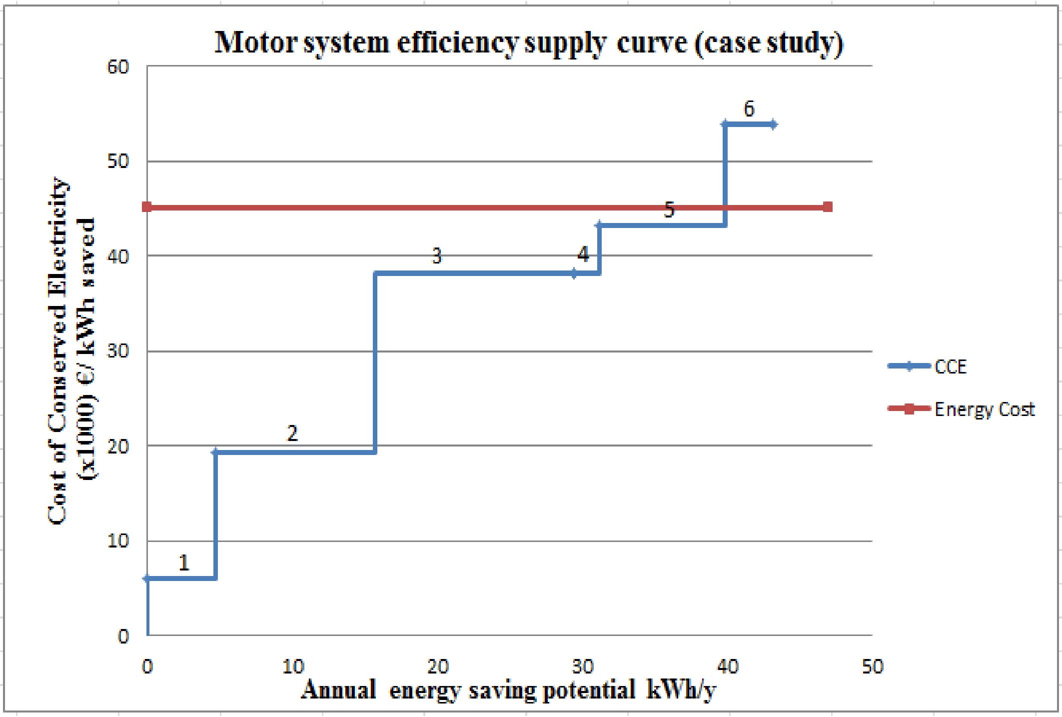

Figure 7.14. The conservation supply curve for electric motor system (case study).

In this study the energy price is assumed constant 0.15 €/kWh, so annual electrical energy cost is about 45000 €. The energy efficiency measures that are below the energy cost line, are cost-effective and the efficiency measures that are above the energy cost line are not cost effective, so in this study measure 6 is technically feasible, but is not economic (Technical electricity saving potential is 43.189 kWh/y). That must be mentioned 2010 was assumed the base year for the estimations and in this year the motor system was in medium level. After they have taken some of these measures which are ranked here by the priority of the use. Last year (2012) they have also changed the belts and now the motor system is in the high level base case scenario (in the 4th position in Figure 7.14), that means they can also recover about 4% of the efficiency by means of a measure like initiate a predictive maintenance program.

These results also confirmed, the results which was calculated using the traditional method of energy balance sheet, which was illustrated before in section 7.8.1. This results also are summarized and presented in Table (7.11), which is showing the cumulative annual electricity saving and CO_2 emission reduction for motor system (Siefer) efficiency measures in our industrial case study.

Table 7.11. Cumulative annual electricity saving and CO_2 emission reduction for motor system (Siefer) efficiency measures.

No.	Energy efficiency measure	Energy recovery %	Cumulative annual energy saving kWh/y	Final CCE €/(kWh-saved)	Cumulative annual potential CO_2 reduction $kgCO_2/y$
1	Upgrade system maintenance Fix leaks, damaged seals and packing	2.0	4.696	6.056	2.348
2	Upgrade system maintenance Remove sediments from mixer	5.0	15.668	19.350	7.834
3	Replace Motor with more energy efficient type	7.0	29.413	38.158	14.706
4	Use of new technologies : New belts	1.0	31.240	38.098	15.620
5	Initiate predictive maintenance program	7.0	39.917	43.214	19.959
6	Use of inverter	2.0	43.189	53.888	21.595

Results have also demonstrated that even only through maintenance optimization like; upgrade system maintenance, use of new technologies and initiate a predictive maintenance program, it is possible to increase the performance of the system up to 10%, for a medium base case scenario, as is shown in Figure 7.15.

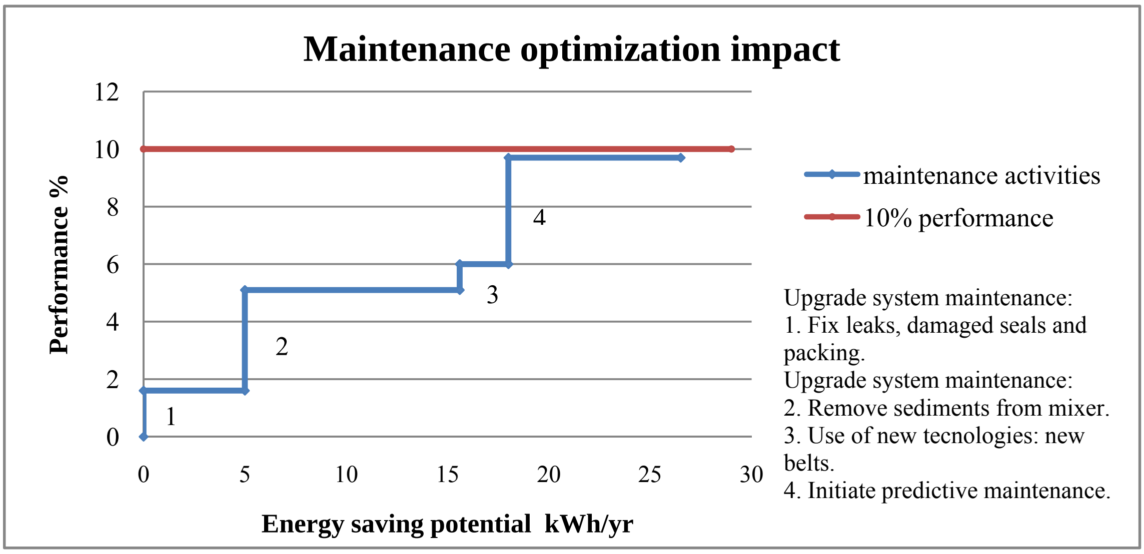

Figure 7.15. Maintenance optimization impact (case study).

8 Conclusion

As it was mentioned before, the reason for the research was the importance of energy saving for the process industries. The main purpose of this work, was the optimization of energy consumption through efficiency measures which is based on a simple philosophy; "everything that is measurable could be optimized". Therefore our goal, which was to increase the performance of industrial systems and equipments is achieved, by means of an interactive energy efficiency management system. The challenge of this work is to develop an energy efficiency analysis model that is able to support decisions to manage consumption, by using an analytical presentation of alternative costs and benefits of the use of energy in terms of probability and consequence, also increase the performance of the systems in the industrial process plants.

In particular, as an element of novelty with respect to literature models, the maintenance influence has been explicitly modeled and used as an optimization parameter. In this study the results have demonstrated, that even only through maintenance optimization the recovery can account for the 10% of the total.

Using this model, it is possible to quantify the impact of maintenance and operating procedures, in terms of energy savings (cost-effectiveness), and can be calculate the Cost of Conserved Energy CCE, also it is possible to calculate the potential reduce of greenhouse gas emissions (CO_2). The implementation of energy saving measures, for our case study was based on both technical feasibility and economic feasibility, since not all feasible technical measures, are economical (cost effective). Here would be added other drawbacks; in the industrial reality, there are some difficulties to obtain all the historical data required for evaluation. Also the presence of multiple factors can affect the analysis such as the production capacity, working hours, the average cost of electrical energy, interest rates etc. However, thanks to the cooperation by the company, the analysis and the results were validated and compared by the experts of the system.

The possibility development of the work for the further research will consist of developing specific models for other types of energy consumer (both electricity and fuel) equipments; these together constitute the generalization of the model to increase overall performance.

Acronyms

α Utilization Index of process production capacity

β Variation Index of process utilization

β' Weibull distribution shape parameter

η Weibull distribution characteristic life, h

λ Failure frequency

AC Annualized cost of energy-efficiency measure, €/y

ADR European Agreement concerning the International Carriage of Dangerous Goods by Road

AECS Annualized energy cost saving, €

ANC Annualized net cost saving, €

BCM Business Centered Maintenance

C_{ic} Initial costs, €

C_{in} Installation and commissioning cost, €

Ce Energy costs, €

Cf Fixed cost of the failure (cost of spare parts), €

C_f Consequences of failure

C_o Operation costs, €

C_m Maintenance and Repair costs, €

C_s Down time costs, €

C_{env} Environmental costs, €

C_d Decommissioning/disposal costs, €

Cv Variable cost per hour of down time, €

CBM Condition Based Maintenance

CCE Cost of Conserving Energy, €/kWh

CMMS Computerized Maintenance Management System

CSC Conservation Supply Curve

d Discount Rate, %

dES Energy saving by technology

DT process plant Down Time, in fraction of h

DOM Design Out Maintenance

I Capital cost, €

E_d Designed annual Energy consumption of the process

E_r Real annual Energy consumption of the process

EAM Enterprise Asset Management

ECPU Energy Consumption per Unit of the Product

EE Energy Efficiency

EEI Energy Efficiency Indicators

EEMS Energy Efficiency Management Systems

ERP Enterprise Resource Planning

FBM Failure based Maintenance

h Hour

HVAC Heating, Ventilating and Air Conditioning

ICT Information and Communication Technology

IE International Efficiency

KPIs Key Performance Indicators

LCC Life Cycle Cost

M&O Annual change in Maintenance and Operation cost, in €/y

MTBF Mean Time between Failures

MTBO Mean Time between Outage

MTTF Mean Time to Failure

MTTR Mean Time to Repair

n Lifetime of the Conservation measure, y

OEE Overall Equipment Effectiveness

OEM Original Equipment Manufacturer

P Energy price

Pa Pascal

P_f Failure Probability

PL Production Loss

PLC Production Loss Cost

PMA Polymer Modified Asphalt

PV Present Value

q Capital Recovery Factor

Q_d Designed annual Productivity of the process

Q_r Real annual Productivity of the process

RAM Reliability data and Maintenance evaluation

RAMS Reliability, Availability, Maintainability and Safety

RCM Reliability Centered Maintenance

RCA Root Case Analysis

S Annual Energy Savings, kWh/y

Sec Second

SBS Styrene-butadiene-styrene

SIL Safety Integrity Level

SIM Integrated Maintenance System

SP Selling production Price

t_i Operation time

t_{0i} Repair time

T_i Breakdown time

T Temperature

TBM Time Based Maintenance

TPM Total Productive Maintenance

UBM Use Based Maintenance

y Year

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