POLITECNICO DI MILANO

Facoltà di Ingegneria dei Sistemi

Corso di Laurea Specialistica in Ingegneria Gestionale – Energy management and sustainability

МГТУ им Баумана

Proposal of a Lifecycle Costing model for energy equipment. – A real application in the gas turbines of “Kolomenskoe” energy plant, Moscow

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Anno Accademico 2012/2013

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Abstract

Energy business is the base of all the other businesses and of people life, a lack of energy can imply big problems for everybody, for this reason PLM (Product Lifecycle Management) strategies have to guarantee reliability to energy equipment and thus reliability of energy supply; but at the same time they have to warranty profitability because energy business, as all the other businesses, must be profitable for its investors.

The target of this thesis is to find a model or instrument which allows energy companies to pursue these 2 targets at the same time.

The work is done in 4 steps:

- Analysis of PLM concepts and PLM strategies (Chapter 1) in order to find out what models are currently used in the market and how they work;
- Analysis of energy business (Chapter 2): necessary in order to understand the peculiarities of this business;
- Application of PLM in energy system (Chapter 3), development of a correct model;
- Application of the new model in a real case (Chapter 4);

The first step of this work showed that right now in the market there are systems, such as CAD, CAPP, CRM, ERP etc, which help companies in the phases of concept, design and production but not in the phase of utilization.

Energy equipment are characterized of a very long lifecycle (it can be also more than 50 years) so it's very important to minimize costs during this period.

There a 2 existing models which are adequate to manage costs during the whole life of energy equipment:

- FMECA (Failure Mode, Effect and Criticality Analysis) which helps to manage failures, thus it helps to find the correct maintenance policy in order to minimize failure and repair costs;
- LCC (Lifecycle Costing) which is a paradigm which consists on consider from the beginning all the costs which will take place during the whole life of a product.

The second step was important in order to really understand energy business. Energy business is characterized by its own rules, structure, processes ex.

It's important to know the following things:

- Business structure;
- Level of competition;
- Subjects;
- Form of ownership;
- Market structure and rules;
- Profitability;
- Technology effect;
- Social responsibilities;
- Risks;
- Ecological restrictions and emission control tools.
- Performance indicators;

In Chapter 2 are analyzed the most important characteristics, types and variants of structure, form of ownership, subjects and emission control tools. Also in the chapter are analyzed the main concept of social responsibility, the main risks, the competition and how market works using some models and tools.

The third step of the thesis analyzes 2 FMECA models which have been developed and used by Alla Brom (professor of MGTU Im. Baumanka), they are both based on:

- the identification of all components;
- identification of their functions
- identification of failures they can undergo
- Evaluation of probability and criticality of every failure;

these models are useful in order to choose the best maintenance policy for every single item.

After the FMECA it's possible to calculate the lifecycle cost of the equipment which is represented by the following formula:

$$LCC = C_{buy} + C_{use} + C_{O\&M} + C_{CR} + C_{DIS}$$

Where:

LCC= Life cycle cost [Rubles];

C_{buy}=Price of the equipment when the company buys it [Rubles];

$C_{O\&M}$= Total O&M cost [Rubles];

C_{CR}= Total cost of capital repair-works [Rubles];

C_{DIS}= Total cost of disposal [Rubles];

In chapter 3 are shown all the formulas and calculus to get the LCC.

The contribution of this thesis is that in this formula has been added the opportunity costs.

The opportunity costs in the case of energy equipment represent the loss in the sale of energy to final costumers related to the stops in the production (because of failures, planned maintenance etc.).

The formula including opportunity costs is:

$$LCC = C_{buy} + C_{use} + C_{O\&M} + C_{CR} + C_{DIS} + C_{OP}$$

And opportunity costs are calculated with the following formula

$$C_{OP} = (p_{EE} - CV) * P * h_{stop}$$

Where:

C_{OP}= Opportunity costs [Rubles];

p_{EE}= Price of electrical energy [$\frac{Rubles}{kWh}$];

CV= Variable costs [$\frac{Rubles}{kWh}$];

P= Effective electrical power produced [kWh];

h_{stop}= Number of hours in which electrical energy is not produced [h];

Opportunity costs have very important implications.

First of all it is possible to notice that it is obviously cheaper for the company to make repairs when opportunity costs are lower, this means that the quantity $\left(P_{EE} - C_{prod}\right)$ should be as low as possible, thus it is possible to work with these 2 quantities; the company can decide to make maintenance when the price of electricity is very low or when the cost or production is very high (or both of them at the same time) or anyway any mix of these 2 quantities which make the opportunity costs high.

The introduction of opportunity costs offers a more precise way to estimate costs and thus a better instrument choice.

In the fourth and last step this model is applied in a real energy plant with real data.

The thesis offers interesting results, the case study shows the following:

- Cost of acquisition have a strong impact but not as much as the utilization costs;
- Cost of utilization are more than the 50% of the total lifecycle costs;
- Opportunity costs are not high but still not negligible, it’s important anyway to say that they are not high also because in this plant they installed new equipment and moreover the plant is located in Russia where the cost of electrical energy is lower than in Europe; the same study conducted in Europe would have shown different results;
- Capital repairs have a strong impact on the total costs, that’s why it is interest of the company to minimize stops for repairs and maintenance, also there are some studies now which are showing that when turbines don’t work in regime but have peak and stops, they suffer some erosion activities, especially related to vibration of blades and to asynchronous behavior;

It’s possible to conclude that, it’s well known that LCC are not precise systems, in energy equipment this problem is even bigger than in other sectors as they have a very long life and there are a lot of factor for which it is impossible to make a precise prevision for a so long period of time; some of these factors are:

- Price of electrical energy;
- Fuel price;

- Price of lubrication oil and other materials;
- Exchange ratios;
- Real failure ratios.

They are anyway very useful when it is necessary to make a choice between different maintenance policies or between different equipment.

Finally, as cost of utilization and cost of maintenance are so important and have a so big impact on total costs it is necessary to introduce new systems in the market which are able to manage them. Moreover it is a heuristic fact that data supplied by producers are usually very different from real data, so these systems should be able to keep into account this fact and eventually there should be feedback information between the 2 companies (producer and user of energy equipment) in order to improve energy equipment using real data.

The thesis described has been presented in the international conference "Международная конференция студентов, аспирантов и молодых учёных «Ломоносов»" (International conference for students, PhDs and young scientists" in the university MGU im. Lomonosov of Moscow. Moreover an articles with title "PARTICULARS AND IMPACT OF TECHNOLOGY ON THE OIL & GAS BUSINESS" have been written about this thesis in the electronic journal "МОЛОДЕЖНЫЙ НАУЧНО-ТЕХНИЧЕСКИЙ ВЕСТНИК" (young science-technical news) which is a journal which collects the best projects, theses, PhD theses and scientific researches coming from all the university of Russia. Finally an article with title "Модель стоимости жизненного цикла (LCC) для энергетического оборудования" (Lifecycle costing model for energy equipment) has been written in the journal "Известия вузов. Машиностроение. – 2013. – № . 8" (News from university education. Section of "machine construction" – 2013. – № . 8).

Abstract

Il business energetico sta alla base di tutti gli altri business e della vita di tutti i giorni, un'insufficienza di energia può comportare gravi problemi a molti soggetti della società, per

questa ragione le stretagie PLM (Product lifecycle management) devono garantire affidabilità alle macchine enrgetiche in modo tale da garantire una costante fornitura di energia, allo stesso tempo devono garantire profittabilità visto che il business energetico, esattamente come tutti gli altri settori, deve risultare profittevole per i propri investitori.

L'obiettivo di questo lavoro di tesi è quello di trovare modelli e strumenti i quali permattono alle aziende energetiche di raggiungere i due obiettivi precedentement descritti.

I lavoro è svolto in 4 passi:

- Analisi dei concetti e delle strategie PLM (Capitolo 1) in modo da identificare quali modelli sono correntemente disponibili sul mercato e in che modo essi funzioano;
- Analisi del business energetico (Capitolo 2), necessaria al fine di comprendere le puculiarità di questo tipo di business;
- Applicazione del PLM nei sistemi energetici (Capitolo 3) e sviloppo di un modello corretto;
- Applicazione del modello in un caso reale (Capitolo 4);

Il primo passo di questo lavoro mostra chiaramente che, al momento, nel mercato sono presenti modelli e sistemi (come CAD,CAPP,CRM, ERP ecc.) che supportano le aziende in sede di sviluppo concetuale del prodotto, progettazione e produzione ma non nelle fasi di utilizzo e smaltimento del prodotto finito.

I macchinari energetici sono caratterizzati da un ciclo di vita molto lungo (in alcuni casi oltre i 50 anni), pertanto la minimizzazione dei costi durante la fase di utilizzo del macchinario riveste un'importanza capitale.

Al momento esisitono 2 modelli utili a questo scopo:

- Modelli FMECA (Failure Mode, Effect and Criticality Analysis) i quali supportano la gestione dei guasti e, conseguentemente, aiutano nella definizione di una politica di manutenzione atta alla minimizzazione dei costi legati alla riparazione e ai guasti;
- LCC (Lifecycle Costing) che è un paradigma che consiste nel considerare fin dalle prime fasi tutti i costi che avranno luogo nel corso di tutta la vita del prodotto.

Il secondo passo della tesi è estremamente importante in quanto permette di comprendere a fondo il business energetico. Questo settore e’ carattarizzato da regole proprie, da una peculiare struttura, da processi specifici ecc.
E’ pertanto importante capire le seguenti cose:

- Struttura di business;
- Livello di concorrenza;
- Soggetti di business;
- Strutture proprietarie;
- Struttura e regole di mercato;
- Profittabilità;
- Effetto della tecnologia;
- Responsabilità sociali;
- Rischi;
- Restrizioni ecologiche e controllo delle emissioni;
- Indicatori di performance;

Con il terzo passo della tesi vengono analizzati 2 modelli FMECA che sono stati sviluppati dalla professoressa Alla Efimovna Brom (MGTU im Baumana) esattamente per i macchinari energetici, entrambi i modelli si basano su:

- identificazione di ogni singolo componente;
- conseguete identificazione della funzione che essi svolgono;
- identificazione dei guasti a quali possono essere soggetti
- Valutazione della probabilità e criticità di ogni singolo guasto.

Questi modelli sono utili in modo da individuare la giusta politica di manutenzione per ogni singolo elemento.
A valle dell’FMECA è possibile calcolare il LCC della macchina con la seguente formula:

$$LCC = C_{buy} + C_{use} + C_{O\&M} + C_{CR} + C_{DIS}$$

Dove:

LCC= Life cycle cost [Rubli];

C_{buy}= Prezzo della macchina [Rubli];

$C_{O\&M}$= Costo totale di manutenzione (composto da manutenzione programmata e manutenzione a guasto) [Rubli];

C_{CR}= Costo totale di riparazioni capitali [Rubli];

C_{DIS}= Costo totale di smaltimento [Rubli];

Nel capitolo 3 sono presenti tutte le formule e i calcoli di ogni singola voce del LCC.

Il contributo di questa tesi è la aggiunta dei costi opportunità.

Nel caso di macchinari energetici i costi opportunità mostrano la perdita di denaro che la compagnia subisce a valle della mancata vendita di energia al cliente finale, che a sua volta e causata dal mancato lavoro delle macchine (dovuto a guasti, manutenzione programmata ecc.)

La formula, includendo i costi opportunità, diventa:

$$LCC = C_{buy} + C_{use} + C_{O\&M} + C_{CR} + C_{DIS} + C_{OP}$$

E i costi opportunità sono calcolati come di seguito:

$$C_{OP} = (p_{EE} - CV) * P * h_{stop}$$

Dove:

C_{OP}= Costi opportunità [Rubli];

p_{EE}= Prezzo dell’energia elettrica [$\frac{Rubli}{kWh}$];

CV= Costi variabili [$\frac{Rubli}{kWh}$];

P= Potenza elettrica effettiva [kWh];

h_{stop}= Numero di ore nelle quali non viene prodotta energia [h];

I costi opportunità hanno delle implicazioni interessanti.

E’ possibile notare che è ovviamente più economico, dal punto di vista dell’azienda, effettuare riparazioni quando i costi opportunità sono bassi, questo implica che la quantità $(P_{EE} - C_{prod})$ deve essere la più bassa possibile. Per far ciò è possibile lavorare con queste 2 quantità: la compagnia può decidere di far manutenzione quanto il costo dell’energia è molto basso o quando i costi variabili sono alti (o entrambi allo stesso tempo) o in ogni caso qualsiasi mix delle 2 vairiabili che rende i costi opportunità alti.
L’introduzione di costi opportunità offre una più precisa stima dei costi e quindi il modello risulta migliore ai fini di scelta.
Infine come ultimo step è stato calcolato il LCC delle 3 turbine a gas installate nella centrale elettrica di “Kolomenskoe” a Mosca; si tratta di una centrale cogenerativa a ciclo a gas semplice: 136MW elettrici e 171 Gcal/h termici.
La tesi offre alcuni risultati interessanti, il caso di studio mostra i seguenti risultati:

- I costi di acquisto hanno un forte impatto sui costi totali ma minore rispetto ai costi dei utilizzo;
- I costi di utilizzo sono più del 50% del totale;
- I costi opportunità non sono alti ma comunque non trascurabili, la spiegazione risiede nel fatto che le turbine sono nuove e che l’impianto si trova in Russia dove il costo dell’energia elettrica e sensibilmente inferiore rispetto all’europa. Lo stesso studio condotto in Europa avrebbe mostrato risultati differenti;
- Le riparazioni capitali hanno un forte impatto sui costi totali, ecco perchè è interesse della azieda cercare di minimizzarne i costi; inoltre sono stati fatti degli studi che mostrano che quando la turbina non lavora a regime, ma a fermate e picchi, essa è soggetta a vibrazioni e comportamenti asincroni che provocano erosione e danneggiamenti.

E’ possibile concludere che, come noto, il LCC è poco preciso, per le apparecchiature energetiche questo problema è ancora più evidente in quanto il loro ciclo di vita è estremamente lungo e per molte variabili che influiscono sul risultato finale non è possibile effetuare una previsione accurata in tempi così estesi. Le principali sono:

- Prezzo dell’energia elettrica;

- Prezzo del combustibile;
- Prezzo dell’olio lubrificante a altri materiali;
- Tassi di cambio;
- Tasso di guasto reale;

Il LCC è comunque utile nel caso in cui sia necessario fare una scelta: per esempio tra diverese strategie di manutenzione o tra diverse tecnologie.

Inoltre, siccome i costi di utilizzo hanno una tale influenza sui costi totali è necessario introdurre nuovi sistemi, che nel mercato non sono a oggi presenti, che aiutino a gestire questa fase del ciclo di vita.

Inoltre è un fatto euristico che i dati di performance reali sono sensibilmente diversi rispetto ai dati forniti dai venditori, pertanto è necessario che questi nuovi sistemi tengano conto di dati reali e siano in grado di gestirli, con il consiglio inoltre di dare un feedback al produttore del macchinario in modo tale promuovere il miglioramento continuo per entrambi.

La tesi appena descritta è stata presentata nella conferenza iternazionale “Международная конференция студентов, аспирантов и молодых учёных «Ломоносов»” (International conference for students, PhDs and young scientists” in the university MGU im. Lomonosov di Mosca. Inoltre su questa tesi è stato scritto un articolo dal titolo “PARTICULARS AND IMPACT OF TECHNOLOGY ON THE OIL & GAS BUSINESS**”** nel giornale elettronico “МОЛОДЕЖНЫЙ НАУЧНО-ТЕХНИЧЕСКИЙ ВЕСТНИК” (young science-technical news) che è un giornale che colleziona i migliori progetti, tesi, tesi di dottorato e ricerche scientifiche provenienti da tutte le università russe. Infine è stato scritto un articolo dal titolo “Модель стоимости жизненного цикла (LCC) для энергетического оборудования” (Lifecycle costing model for energy equipment) nel giornale “Известия вузов. Машиностроение. – 2013. – № . 8” (News from university education. Section of “machine construction” – 2013. – № . 8)

1 Characteristics' analysis of PLM for science intensive products

1.1 Product Lifecycle Management – PLM

The term Product Lifecycle Management has been introduced for the first time in the 70's studying the ecological compatibility of industrial products, the aim was to emphasize that products should be thought, designed and realized respecting the environment, considering all the phases of his lifecycle **[NIE02] [VER99].** Then in the 90's the meaning changed and PLM has been considered as the management of traceability of the whole product-system. **[SOG99]**

Nowadays it is possible to find a lot of definitions, for example:

- Daratech, define it with this acronym the evolution of Digital Manufacturing without any distinction **[DAR03]**;
- QAD defines PLM as a tool to control product's performances, physical and functional features. The attention is not kept to the technology but more on functionalities related to PLM, such as planning, coordination and control **[QAD02]**;
- For ARC Advisor Group a PLM solution is a tool which helps producers to obtain the right product in the right moment and in the right place, so for ARC product lifecycle management is not a specific product but a strategy **[ARC03]**;
- CimData defines PLM has a strategic business approach which applies a big number of IT solutions to support the collaborative creation/design, the use and management of information connected to the product definition from the concept to the end of the lifecycle. Also CimData thinks that PLM is not just a technology but an approach where processes are more important than data. **[CIM02];**

- According to the definition by Kenneth McIntosh, engineering data management – EDM (currently the appropriate acronym would be PLM) is a systematic way to design, manage, direct, and control all the information needed to document the product through its entire lifespan: development, planning, design, production, and use. **[MCI95];**

Yet a real definition is not worldwide accepted but it's possible to define PLM in the following way:

PLM is a new integrated business approach, supported by information technologies and useful for cooperative and collaborative management of all the product information which are spread along all the lifecycle phases. Thus PLM includes:

- Strategic orientation to value creation "on" and "through" the product;
- The application of a collaborative approach for the evaluation of core-competences of different actors;
- The use of a big number of IT solutions to realize the coordinate, integrate and safe management of all necessary information for the value creation **[TGB12]**.

In daily business, the problems of product lifecycle management typically become evident in three different areas:

- The concepts, terms and acronyms within the area of product lifecycle management are not clear and not defined within companies. This means that the information content connected to certain terms is not clear and the concepts how to utilize to the product related information are even fuzzier. (for example the definition: what is product lifecycle and what are its phases);
- The use of the information and the formats in which it is saved and recorded varies a lot. Information has usually been produced for different purposes or in some other connection but it should still be possible to utilize it in other contexts than in the task for which it was produced, in a different locality or even in a separate company;
- The completeness and consistency of information produced in different units, departments or companies cannot be guaranteed. This problem arises when the product data is produced and stored in different data bases or even as paper

documents, and also when the subjects involved have different approaches to information protection and handling. However, shortcomings in the processes, standards, and tools for information, production and management can cause some erosion of the operations model. People and organizations begin to update the same information on their own storage and they share information from there. Nobody knows for sure whether the latest version is located in the agreed place. Nowadays, product lifecycle management is, in practice, carried out almost without exception with the help of different information processing systems. However, it does not always have to be like this. In many companies, simple actions can be taken to develop information management without a special and dedicated information processing system. An agreement, an operations model, or a set of common practices and standards for information handling can be the basis of development work. The creation and following of common modes of action is the key to improvements in the creation and analysis of information. It is possible to solve many of the problems and situations described above using information-processing systems that support. product lifecycle management. Information processing systems have evolved quickly during the last few years; and yet it has not been possible to remove all problems. The worst problems, at a practical level, result usually from different modes of operation, the wide spectrum of different software used to produce the information, functional differences in software, and the numerous inter faces between different information processing systems. Product lifecycle management is above all the management of processes and large totalities. How and at what level each company carries out its own product lifecycle management always depends upon the viewpoint from which problems are examined as well as company objectives and strategies in this area. It is therefore extremely important that the operation and core business processes of the company be described in depth before implementing a PLM concept and IT-system. In practice, this means that the required specifications of the TO BE of future processes as well as the PLM concept framework must be set to match the high-level objectives of the business and the future visions of the company. In addition to careful selection of requirements for product lifecycle management, business processes must be described in detail. The resulting product lifecycle management solutions differ considerably as they are based on the individual strategy and business architecture of each company. They reflect different objectives and priorities and emphasize different areas and functions of PLM. **[ALY12]**

Product lifecycle management systems

A product lifecycle management or PLM system (what is usually meant by the term PLM) is ideally an information processing system or set of IT-systems that integrates the functions of the whole company. This integration is done through connecting, integrating and controlling the company's business processes and produced products by means of product data. At the practical level, the adoption of PLM is still too often restricted to only certain areas of certain business processes, such as product design and development. Kenneth McIntosh has proposed that PLM can be the operational frame of CIM (*Computer Integrated Manufacturing*) – one of the isms's of industrial business. In other words, it is a system or set of systems, which integrate the functions of the whole company with the help of information technology. PLM is above all a connecting technology, not an individual technology islet or information processing system like a CAD (*Computer Aided Design*) system. A specialized IT-system can be very efficient in its own area but such systems usually cause bottlenecks elsewhere in the company's data flows and at the level of practical implementation in corporate IT-systems. The most important business processes, product processes and the order-delivery processes, in manufacturing industry are cross-functional and cross organizational. The task of PLM, in one sense, is to provide the necessary conditions for connecting separate information data systems, processes and automation. Additionally, PLM should control a wide variety of information systems and thus give birth to integrated totalities. Commanding the totality of various processes brings considerable value to companies by seamlessly integrating information from organization-wide processes using different information processing systems. **[MCI95]**

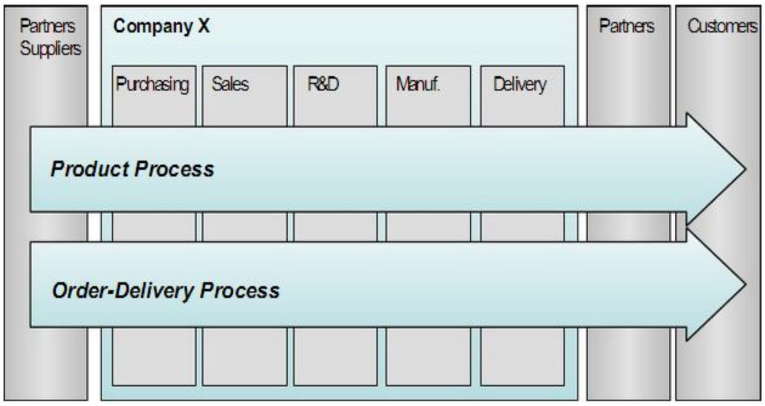


Figure 1.1 The core processes and functional verticals of an industrial enterprise. **[ALY12]**

Figure 1.1 illustrates how a PLM system is positioned as a common and central databank within the field of operation of the process oriented manufacturing enterprise, the PLM system often creates a wide totality of functions and properties with which supports the different processes involved in the creation, recording, updating, distribution, utilization, and retrieval of information as shown in **figure 1.2**. **[BUY99]**

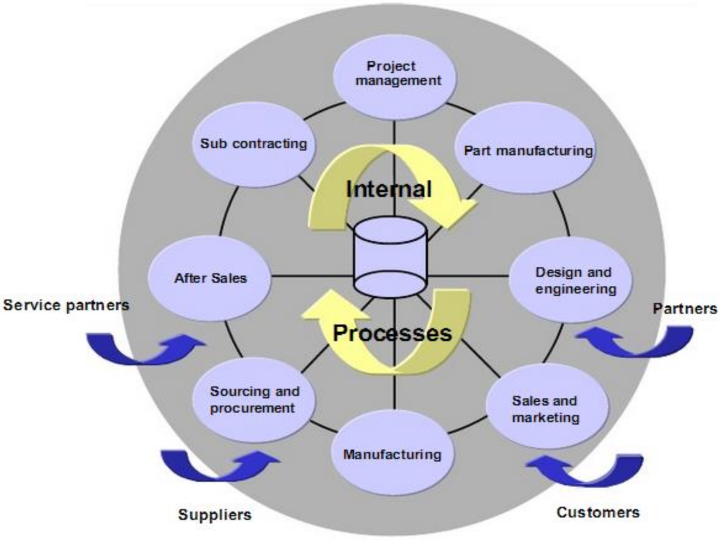


Figure 1.2 PLM connects all company's processes **[BUY99]**

Typical features of such systems include:

- Item management: The system controls the information on the item and the status of the item as well as processes related to the creation and maintenance of items;
- Product structure management and maintenance: the PLM system identifies individual information and its connections to other pieces of information with the help of the product structure, which consists of items hierarchically connected together;
- User privilege management: the PLM system is used to define information access and maintenance rights. PLM system defines the people who can create new information or make, check and accept changes, and those who are allowed only to view the information or documents in the system;
- Maintenance of the state or status of documents and items: the system maintains information about the state and version of each document and item, and about changes made to them: what, when, and by whom;
- Information retrieval: one of the main tasks of a PLM system is information retrieval. PLM systems intensify and facilitate the retrieval of information so that:
    - It is possible to utilize existing information better than before when creating new information. All the existing information on a given subject, such as a particular product, can be easily accessed: documents, components, perhaps a design solution of proven quality;
    - It is easy to find out how a given piece of information is related to other information, for example to find out where else a given design solution, part or component is used;
- Change management: it is a tool with which the latest valid information about changes, such as version changes to a product or component, are recorded in documents or items, which are then made available in the right place and at the right time;

- Configuration management varying the physical properties of similar products and switching inter-changeable assemblages or components. Configuration management allows products to be customized according to customer wishes;
- The management of tasks (messages), also known as work flow management, is one of the basic properties of a PLM system. The communication and division of tasks is carried out through graphical illustration of the chain of tasks and by e-mail or a task list. The management of tasks makes possible the radical intensification of communication in the organization, especially in a decentralized even global environment;
- File/document management involves index information on files contained in the system. In other words, it is a question of metadata information about what information is located where;
- Information loss during updating is avoided. The PLM system controls the copying of files and ensures that the master copy is preserved until the files have been successfully updated;
- Backup management – the system automatically logs backup copies;
- History / System log – a database of events which ensures that that all measures such as updating documents or changing component items made within the sphere of PLM management can be tracked, if necessary (Product process traceability);
- File vault (electronic vault). The system also includes a file vault, or storage place for files. It is the place where files the actual data or file attachments are recorded. The file vault is usually located near the group of persons who create, update and administer the files. In practice, the vault is a file server on the same LAN (Local Area Net-work). The files on the PLM system file server are managed by the system so that correct and controlled overhauling principles, user privileges and information maintenance are maintained. Geographical and network architecture restrictions usually lead to the actual file servers being decentralized over the whole company network, so that files can be delivered quickly to the users and applications that need them most. In such cases, the PLM system must also be distributed over several file

servers, all of which must always have the same version of each file. This can be achieved for example by copying large files to all the servers at quiet times – at night, for instance when the network load is low. The PLM system is typically based on one or several physical servers, which use the PLM application and metadata base to control other databases and file services. The company's or the partner's employee – i.e. the end user of the system can access product data from servers in different parts of the information network containing the actual information and files. A file located on a device other than the users own workstation or PC is obtained physically from the source server as a copy or as a so called virtual copy. When a file is fetched as a copy, a copy is normally created for the user and the original file is returned to its original location. When the file is fetched as a virtual copy, it is not copied onto a workstation or PC; instead, pointers are created to the original file. Sometimes the most efficient solution, especially for large files, is to make working copies on the user's own PC, thus avoiding time-consuming file transfers in the data networks. **[AYR92] [BEL] [BUY99]**

Product lifecycle management systems are implemented in different companies for different reasons. These will vary according to which branch of the company is involved, what products it produces, and above all, what the user wants the systems to do. The PLM system brings extremely useful problem-solving tools and methods for every-day product information and product lifecycle management problems. However, it is wrong to expect the system itself to solve data management problems. For one company a PLM system is no more than a tool to improve the effectiveness of daily business. To others it is an investment, which will help the company to take over international markets. Product lifecycle management continues to be developed while, at the same time, more and more companies are implementing it. This is caused by the complexity and the large amount of data involved in creating, maintaining and delivering products. Ever increasing global competition requires that products be produced more quickly, more economically, and with more custom tailoring according to the customer's wishes. Companies must always be looking for new ways to solve their daily problems. Customers expect ever better and more advanced properties from products. For this reason the products themselves and their production processes have become more complicated even though it has often been possible to simplify the products by developing processes and industrial design, for example through standardization, and with the help of group technologies. Complex products have forced companies to specialize, with large groups of specialists being tied up in product design and planning. The management of the design networks of hundreds of companies with units scattered all over the globe requires new technologies. Developing the quality of products and their production processes is necessary in international competition; scrap and bad quality can't be tolerated. Increased quality requirements demand planning and a product development process in which information is effectively and reliably handled, recorded and utilized. Most of the time needed to bring a product to market, in other words time to market is used in the product planning and development phase. If a company wants significantly to shorten the time to market of its products, development efforts must be concentrated on the planning stage, where the most significant savings and best results can be obtained. These development operations have brought, among other things, CE (Concurrent Engineering), and the idea that the functions of the company can be integrated using CIM, in other words with the help of information technology. PLM is a valuable tool in this development. The trend in manufacturing industry during the last few years has been to concentrate on the company's own expertise, its core business. This has meant that areas of operation beyond the core of the business strategy have been transferred to outside parties or organizations. They have been out sourced. Subcontracting chains, alliances, partnership relations and companies specialized in some narrow field of business, such as contract manufacturing, marketing, or documentation of workshop drawings, have been created. The operations model in which companies concentrate on their own core expertise and core business and outsource other necessary expertise as external parts, products and services is called network economy. The cooperating companies form a network, every part of which commands a certain special area. Efficient management of this kind of network requires advanced information technology solutions because the network economy hugely increases the need for data transfer and management. One solution can be to use a PLM system. Companies operating in a heavily networked business environment must be able to make product changes and find required information quickly. Reliable and efficient communication is a condition of life. **[COO96] [ALY12]**

1.2 Lifecycle costing

Definitions

Some LCC definitions are:

- Life cycle cost is the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and/or decommission; **[SAE99]**
- LCC are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced in annual time increments during the project life with consideration for the time value of money. The objective of LCC analysis is to choose the most cost effective approach from a series of alternatives to achieve the lowest long-term cost of ownership. LCC is an economic model over the project life span. Usually the cost of operation, maintenance, and disposal costs exceed all other first costs many times over. The best balance among cost elements is achieved when the total LCC is minimized. **[LAND96]**

Businesses must summarize LCC results in net present value (NPV) format considering depreciation, taxes and the time value of money. Government organizations do not require inclusion of depreciation or taxes for LCC decisions but they must consider the time value of money. **[BAR03]**

Use of LCC

LCC helps to change provincial perspectives for business issues with emphasis on enhancing economic competitiveness by working for the lowest long term cost of ownership which is not an easy answer to obtain.

Consider these typical problems and conflicts observed in most companies:

1. Project Engineering wants to minimize capital costs as the only criteria;
2. Maintenance Engineering wants to minimize repair hours as the only criteria;
3. Production wants to maximize uptime hours as the only criteria;
4. Reliability Engineering wants to avoid failures as the only criteria;
5. Accounting wants to maximize project net present value as the only criteria;
6. Shareholders want to increase stockholder wealth as the only criteria.

Management is responsible for harmonizing these potential conflicts under the banner of operating for the lowest long term cost of ownership. LCC can be used as a management decision tool for harmonizing the never ending conflicts by focusing on facts, money, and time.

1.2.1 LCC Data and models

The basic tree for LCC starts with a very simple tree based on the costs for acquisition and the costs for sustaining the acquisition during its life as shown in **figure 1.3**.

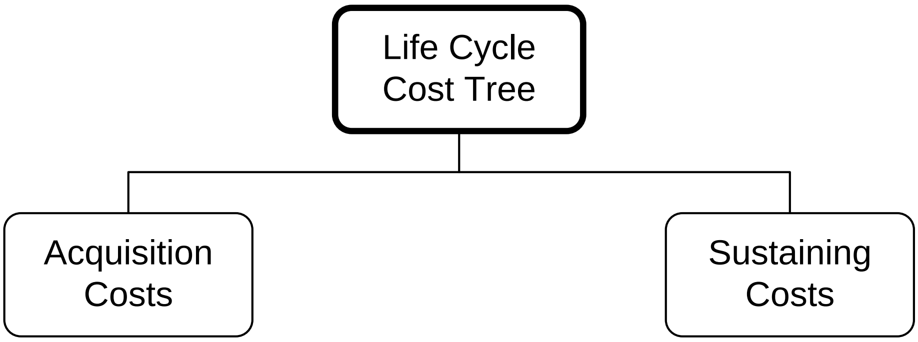


Figure 1.3 Top levels of LCC tree **[BAR96]**

LCC can also be seen as an iceberg, as shown **in figure 1.4,** where the acquisition costs represent only the spike while sustaining costs are the biggest and hidden part. **[ROD10]**

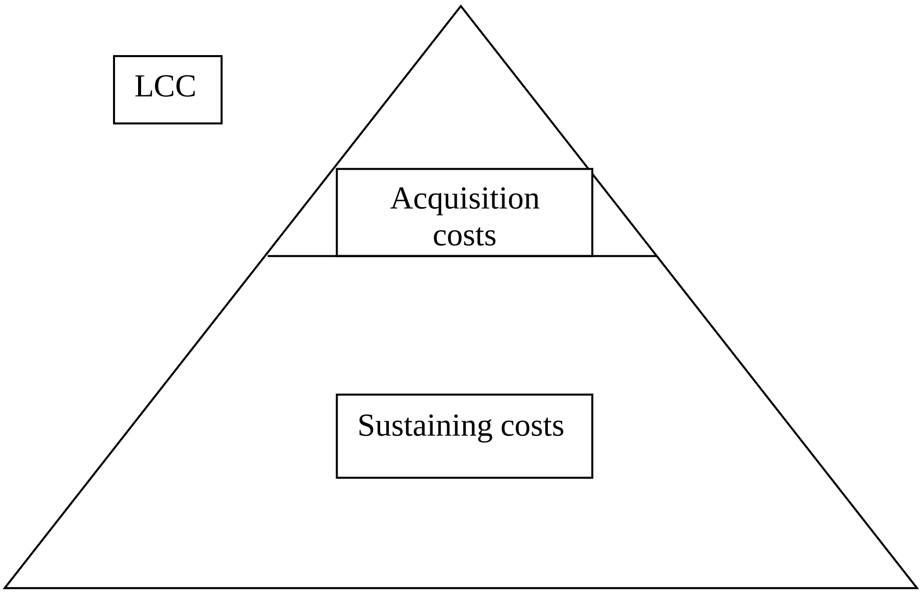


Figure 1.4 LCC Iceberg **[ROD10]**

Acquisition and sustaining costs are not mutually exclusive. If you acquire equipment or processes, they always require extra costs to sustain the acquisition, and you can't sustain without someone having acquired the item. Acquisition and sustaining costs are found by gathering the correct inputs, building the input database, evaluating the LCC and conducting sensitivity analysis to identify cost drivers.

Acquisition costs have several branches for the tree as shown in **figure 1.5**.

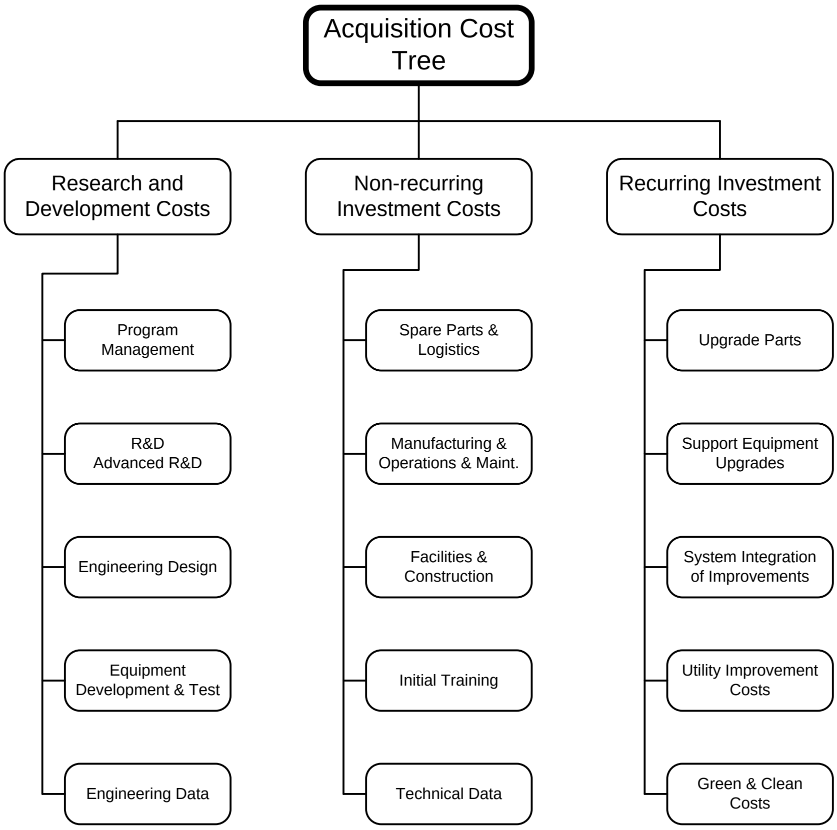


Figure 1.5 Acquisition Cost Tree **[BAR96]**

Sustaining costs have several branches for the tree as shown in **figure 1.6**

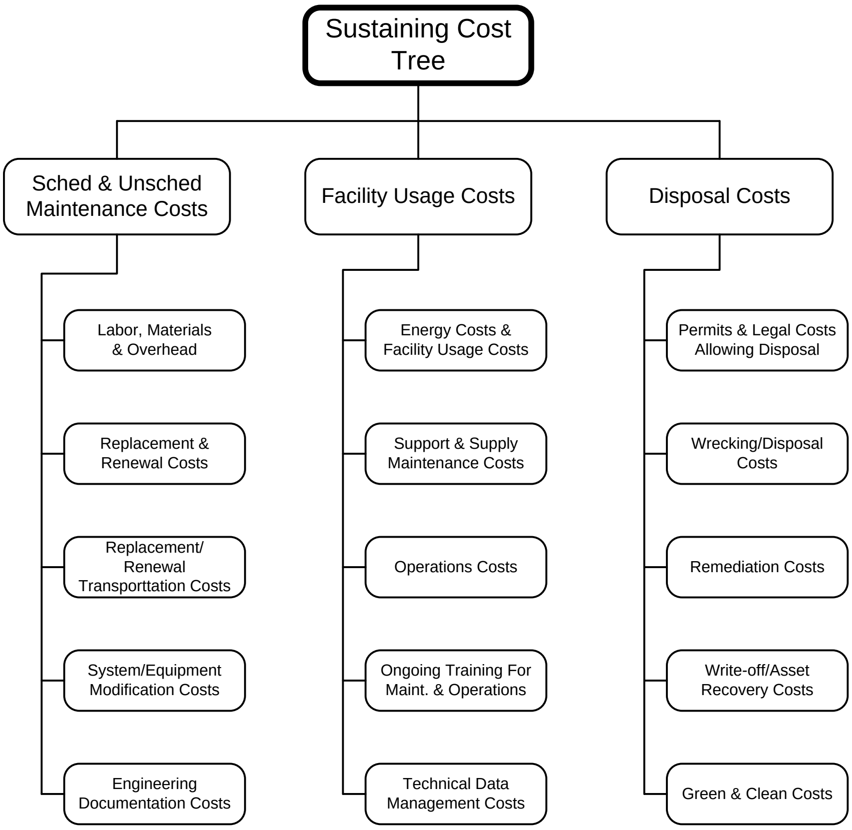


Figure 1.6 Sustaining Cost Tree **[BAR96]**

What cost goes into each branch of the acquisition and sustaining branches? It all depends on the specific case and is generally driven by common sense. Include the appropriate cost elements and discard the elements which do not substantially influence LCC. **[BAR96] [BAR03]**

Consider these alternative LCC models as described by:

1) LCC = non-recurring costs + recurring costs;
2) LCC = initial price + warranty costs + repair, maintenance, and operating costs to end users;
3) LCC = manufacturer's cost + maintenance costs and downtime costs to end users. **[RAH91]**

SAE also has a LCC model directed toward a manufacturing environment:

4) LCC = acquisition costs + operating costs + scheduled maintenance + unscheduled maintenance + conversion/decommission. As shown in **figure 1.7 [SAE93]**

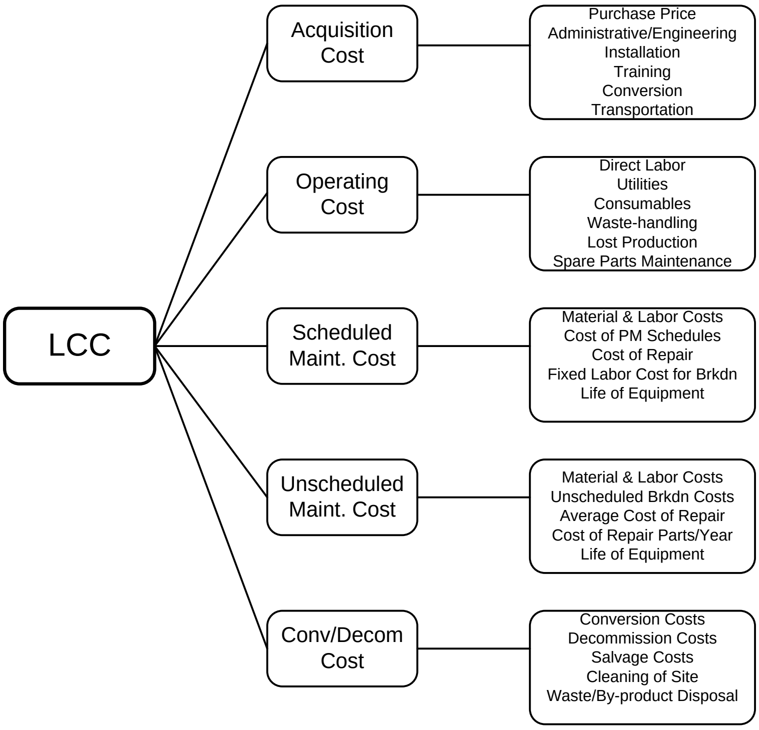


Figure 1.7 SAE Model of LCC **[SAE93]**

1.2.2 Phases of a LCC

Figure 1.8 Phases of LCC **[SAE93]**

As shown in **figure 1.8** Life Cycle Costing is a six-staged process. The first four stages comprise the Life Cost Planning phase with the last two stages incorporating the Life Cost Analysis phase. The six stages are:

- Stage 1: Plan LCC Analysis
- Stage 2: Select/Develop LCC Model
- Stage 3: Apply LCC Model
- Stage 4: Document and Review LCC Results
- Stage 5: Prepare Life Cost Analysis
- Stage 6: Implement and Monitor Life Cost Analysis

All stages may be performed iteratively as needed. Assumptions made at each stage should be rigorously documented to facilitate such iterations and to aid in interpretation of the results of the analysis.

Plan LCC analysis

The Life Cycle Costing process begins with development of a plan, which addresses the purpose, and scope of the analysis. The plan should:

- Define the analysis objectives in terms of outputs required to assist management decisions. Typical objectives are:
  - Determination of the LCC for an asset in order to assist planning, contracting, budgeting or similar needs
  - Evaluation of the impact of alternative courses of action on the LCC of an asset (such as design approaches, asset acquisition, support policies or alternative technologies)
  - Identification of cost elements which act as cost drivers for the LCC of an asset in order to focus design, development, acquisition or asset support efforts.
- Delineate the scope of the analysis in terms of the asset(s) under study, the time period (life cycle phases) to be considered, the use environment and the operating and maintenance support scenario to be employed.
- Identify any underlying conditions, assumptions, limitations and constraints (such as minimum asset performance, availability requirements or maximum capital cost limitations) that might restrict the range of acceptable options to be evaluated.

- Identify alternative courses of action to be evaluated. The list of proposed alternatives may be refined as new options are identified or as existing options are found to violate the problem constraints.
- Provide an estimate of resources required and a reporting schedule for the analysis to ensure that the LCC results will be available to support the decision-making processes for which they are required.

The plan should be documented at the beginning of the Life Cycle Costing process to provide a focus for the rest of the work. Intended users of the analysis results should review the plan to ensure their needs have been correctly interpreted and clearly addressed.

Select LCC model

Stage 2 is the selection or development of an LCC model that will satisfy the objectives of the analysis.

The model should:

- Create or adopt a cost breakdown structure (CBS) that identifies all relevant cost categories in all appropriate life cycle phases. Cost categories should continue to be broken down until a cost can be readily estimated for each individual cost element. Where available, an existing cost breakdown structure may provide a useful starting point for development of the LCC breakdown structure.
- Identify those cost elements that will not have a significant impact on the overall LCC of the asset(s) under consideration or those that will not vary between alternatives. These elements may be eliminated from further consideration
- Select a method (or methods) for estimating the cost associated with each cost element to be included in the model.
- Determine the data required to develop these estimates, and identify sources for the data.
- Identify any uncertainties that are likely to be associated with the estimation of each cost element.

- Integrate the individual cost elements into a unified LCC model, which will provide the LCC outputs required to meet the analysis objectives.
- Review the LCC model to ensure that it is adequate to address the objectives of the analysis.
- The LCC model including all assumptions should be documented to guide and support the subsequent phases of the analysis process.

Apply LCC model

Application of the LCC Model involves the following steps:

- obtain data and develop cost estimates and their timing for all the basic cost elements in the LCC model.
- validate the LCC model with available historical data if possible.
- obtain the LCC model results from each relevant combination of operating and support scenarios defined in the analysis plan.
- identify cost drivers by examining LCC model inputs and outputs to determine the cost elements that have the most significant impact on the LCC of the asset(s).
- quantify any differences (in performance, availability or other relevant constraints) among alternatives being studied, unless these differences are directly reflected in the LCC model outputs.
- categorize and summarize LCC model outputs according to any logical groupings, which may be relevant to users of the analysis results (eg. fixed or variable costs, recurring or non-recurring costs, acquisition or ownership costs, direct or indirect costs).
- conduct sensitivity analyses to examine the impact of variations to assumptions and cost element uncertainties on LCC model results. Particular attention should be focused on cost drivers, assumptions related to asset usage and different discount rates.
- review LCC outputs against the objectives defined in the analysis plan to ensure that all goals have been fulfilled and that sufficient information has been provided to

support the required decision. If the objectives are not met, additional evaluations and modifications to the LCC model may be required.

- the LCC analysis (including all assumptions) should be documented to ensure that the results can be verified and readily replicated by another analyst if necessary.

Document and review result

The results of the LCC analysis should be documented to allow users to clearly understand both the outcomes and the implications of the analysis along with the limitations and uncertainties associated with the results. The report should contain the following:

- Executive Summary: a brief synopsis of the objectives, results, conclusions and recommendations of the analysis.
- Purpose and Scope: a statement of the analysis objective, asset description including a definition of intended asset use environment, operating and support scenarios, assumptions, constraints and alternative courses of action considered.
- LCC Model Description: a summary of the LCC model, including relevant assumptions, the LCC breakdown structure and cost elements along with the methods of estimation and integration.
- LCC Model Application: a presentation of the LCC model results including the identification of cost drivers, the results of sensitivity analyses and the output from any other related analyses.
- Discussion: discussion and interpretation of the results including identification of uncertainties or other issues which will guide decision makers and users in understanding and using the results.
- Conclusions and Recommendations: a presentation of conclusions related to the objectives of the analysis and a list of recommendations along with identification of any need for further work or revision of the analysis.

A formal review of the analysis process may be required to confirm the correctness and integrity of the results, conclusions and recommendations presented in the report. If such a requirement exists someone other than the original analysts should conduct the review (to ensure objectivity).

The following elements should be addressed in the review:

- the objectives and scope of the analysis to ensure that they have been appropriately stated and interpreted
- the model (including cost element definitions and assumptions) to ensure that it is adequate for the purpose of the analysis
- the model evaluation to ensure that the inputs have been accurately established, the model has been used correctly, the results (including those of sensitivity analysis) have been adequately evaluated and discussed and that the objectives of the analysis have been achieved
- all assumptions made during the analysis process to ensure that they are reasonable and that they have been adequately documented.

Prepare Life Cost analysis

The Life Cost Analysis is essentially a tool, which can be used to control and manage the ongoing costs of an asset or part thereof. It is based on the LCC Model developed and applied during the Life Cost Planning phase with one important difference: it uses data on nominal costs.

The preparation of the Life Cost Analysis involves review and development of the LCC Model as a "real-time" cost control mechanism. This will require changing the costing basis from discounted to nominal costs. Estimates of capital costs will be replaced by the actual prices paid. Changes may also be required to the cost breakdown structure and cost elements to reflect the asset components to be monitored and the level of detail required.

Targets are set for the operating costs and their frequency of occurrence based initially on the estimates used in the Life Cost Planning phase. These targets may change with time as more accurate data is obtained, either from the actual asset operating costs or from benchmarking with other similar assets.

Implement Life Cost Analysis

Implementation of the Life Cost Analysis involves the continuous monitoring of the actual performance of an asset during its operation and maintenance to identify areas in which cost savings may be made and to provide feedback for future life cost planning activities.

For example, it may be better to replace an expensive building component with a more efficient solution prior to the end of its useful life than to continue with a poor initial decision. **[NSW04]**

Effectiveness

One helpful tool for easing LCC calculations involving probabilities is the effectiveness equation which gives a figure-of-merit for judging the chances of producing the intended results. The effectiveness equation is described in several different formats where each element varies as a probability and the issue is finding a system effectiveness value which gives lowest long term cost of ownership:

System effectiveness = Effectiveness/LCC

Effectiveness is a measure of value received and effectiveness varies from 0 to 1:

Effectiveness = availability*reliability*maintainability*capability

=availability*reliability*performance (maintainability*capability)

=availability*dependability(reliability*maintainability)*capability

Availability

Availability deals with the duration of up-time for operations and is a measure of how often the system is alive and well. It is often expressed as (up-time)/(up-time + downtime) with many different variants.

Up-time refers to a capability to perform the task and downtime refers to not being able to perform the task. Also availability may be the product of many different terms such as:

$A = A_{hardware} * A_{software} * A_{humans} * A_{interfaces} * A_{process}$

Reliability

Reliability deals with reducing the frequency of failures over a time interval and is a measure of the probability for failure-free operation during a given interval, i.e., it is a measure of success for a failure free operation. It is often expressed as:

$R(t) = \exp(-t/MTBF) = \exp(-\lambda t)$

where λ is constant failure rate and MTBF is mean time between failure. MTBF measures the time between system failures and is easier to understand than a probability number. For exponentially distributed failure modes, MTBF is a basic figure-of-merit for reliability (and failure rate, λ, is the reciprocal of MTBF). Also reliability may be the product of many different reliability terms such as:

$R = R_{utilities} * R_{feed\text{-}plant} * R_{processing} * R_{packaging} * R_{shipping}$

Maintainability

Maintainability deals with duration of maintenance outages or how long it takes to achieve (ease and speed) the maintenance actions compared to a datum. The datum includes maintenance (all actions necessary for retaining an item in, or restoring an item to, a specified, good condition) is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance. Maintainability characteristics are usually determined by equipment design which set maintenance procedures and determine the length of repair times.

The key figure of merit for maintainability is often the mean time to repair (MTTR) and a limit for the maximum repair time. Qualitatively it refers to the ease with which hardware or software is restored to a functioning state. Quantitatively it has probabilities and is measured based on the total down time for maintenance including all time for: diagnosis, trouble shooting, tear-down, removal/replacement, active repair time, verification testing that the repair is adequate, delays for logistic movements, and administrative maintenance delays. It is often expressed as:

$M(t) = 1 - \exp(-t/MTTR) = 1 - \exp(-\mu t)$

where μ is constant maintenance rate and MTTR is mean time to repair. MTTR is an arithmetic average of how fast the system is repaired and is easier to visualize than the probability value.

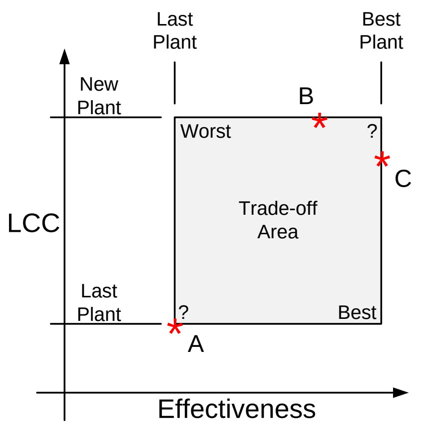
It is frequently expressed in exponential repair times rather than the more accurate but very cumbersome log-normal distributions of repair times describing maintenance times which are skewed to the right.

Capability

Capability deals with productive output compared to inherent productive output which is a measure of how well the production activity is performed compared to the datum. This index measures the systems capability to perform the intended function on a system basis. Often the term is the synonymous with productivity which is the product of efficiency multiplied by utilization. Efficiency measures the productive work output versus the work input. Utilization is the ratio of time spent on productive efforts to the total time consumed. **[BAR96]**

System effectiveness

System effectiveness equations (Effectiveness/LCC) are helpful for understanding benchmarks, past, present, and future status as shown in **Figure 1.9** for understanding trade-off information.



Parameter	Last Plant	New Plant	Best Plant
Availability	0.95	0.95	0.98
Reliability	0.3	0.4	0.6
Maintanability	0.7	0.7	0.7
Capability	0.7	0.8	0.6
Effectiveness	0.14	0.22	0.25
LCC	80	100	95

Figure 1.9 Benchmark Data Shown In Trade-Off Format **[Wei 96]**

The lower right hand corner of **Figure 1.9** brings much joy and happiness often described as "bang for the buck". The upper left hand corner brings much grief. The remaining two corners raise questions about worth and value. **[WEI96]**

The system effectiveness equation is useful for trade-off studies as shown in the attached outcomes in **Figure 1.10**. **[BRE85]**

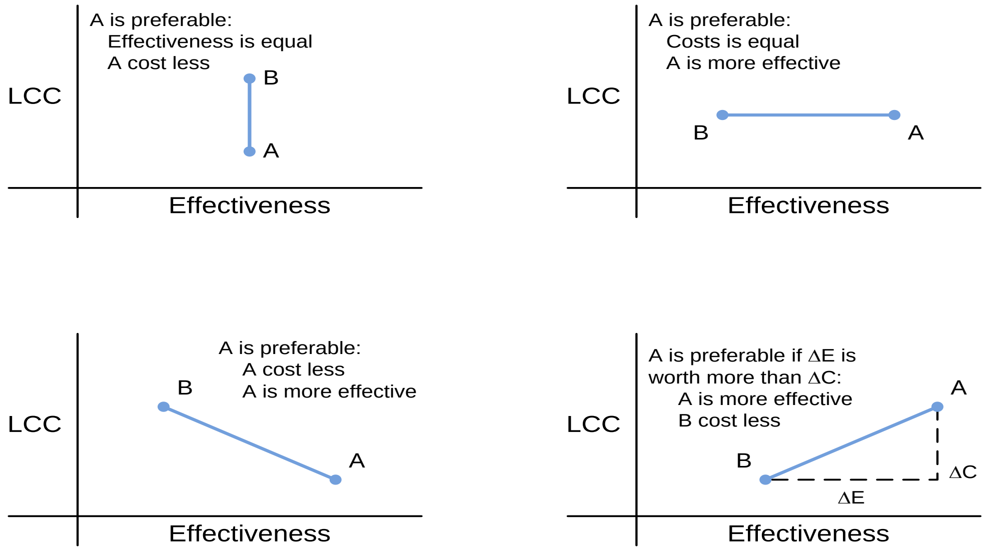


Figure 1.10 Some Possible Outcomes From Trade-Off Studies **[BRE85]**

System effectiveness equations have great impact on the LCC because so many decisions made in the early periods of a project carve the value of LCC into stone. About 2/3's of the total LCC are fixed during project conception **[FOL95] [YAT95]**

Even though expenditure of funds will flow at a later time, and the chance to influence LCC cost reductions grows smaller as shown in **Figure 1.11**. **[BLA91]**

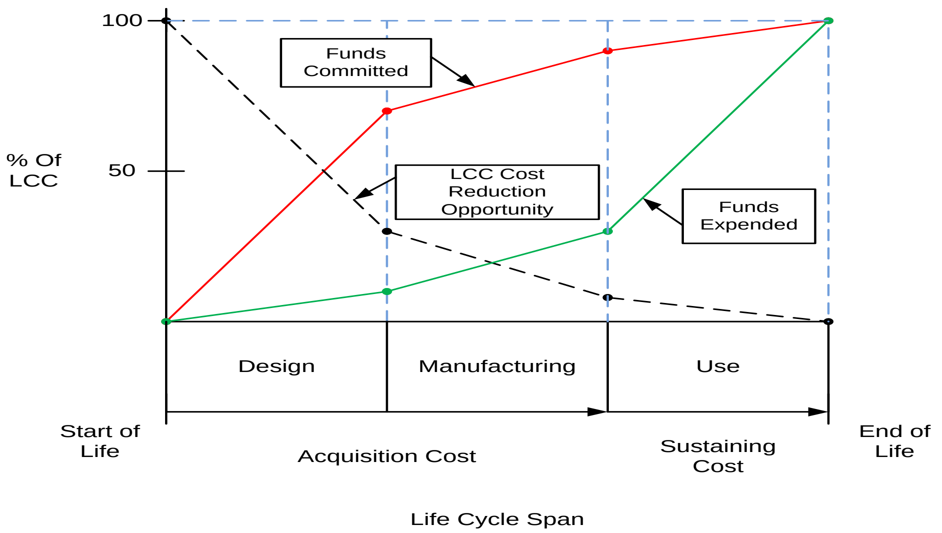


Figure 1.11 Funding Trends by Commitment and Expenditure **[BLA91]**

1.3 Application problem of PLM for the Lifecycle management of science-intensive products

As already said above there are a lot of phases during a product's lifecycle: concept definition, design, manufacturing, utilization, decommissioning ex.

In the market there are a lot of applications available but most of them are mostly concentrated on the first phases **[BRO07]**., in **figure 1.12** are shown the most common PLM tools **[TER12]**, it's easy to figure out that most of them are useful for manufacturing companies, they don't really help the company to manage the products during the central and the last phases of its life, so basically utilization and decommissioning **[BRO07]**.

Science-intensive products are characterized of a very long exploitation time (in some cases even more than 50 years) and their acquisition costs are just a little part of the whole costs (the iceberg's spike as shown in **figure 1.4**), for this reason it is important to find models or tools which can help the company to manage these products during the last phases of their life: from the utilization to the decommissioning.

In **figure 1.13** are shown the most important PLM models and the way the influence the different phases of product's life. It's easy to notice that LCC keeps in consideration all the phases of the product's life, the other one is FMEA/FMECA; these are 2 models which really help the company to manage science-intensive products during their exploitation and their decommissioning. **[BRO07]**

For these reasons this work will mostly concentrate in these 2 models

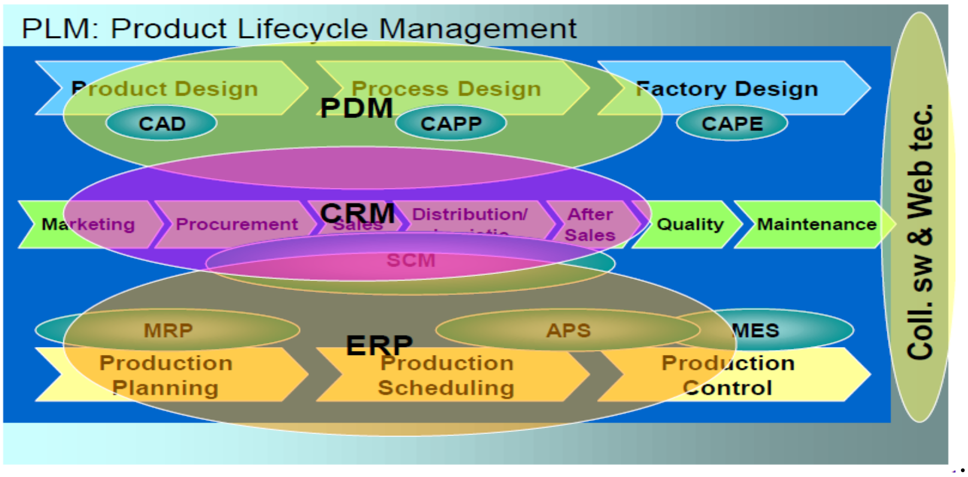


Figure 1.12 PLM tools during the product's phases **[TER12]**

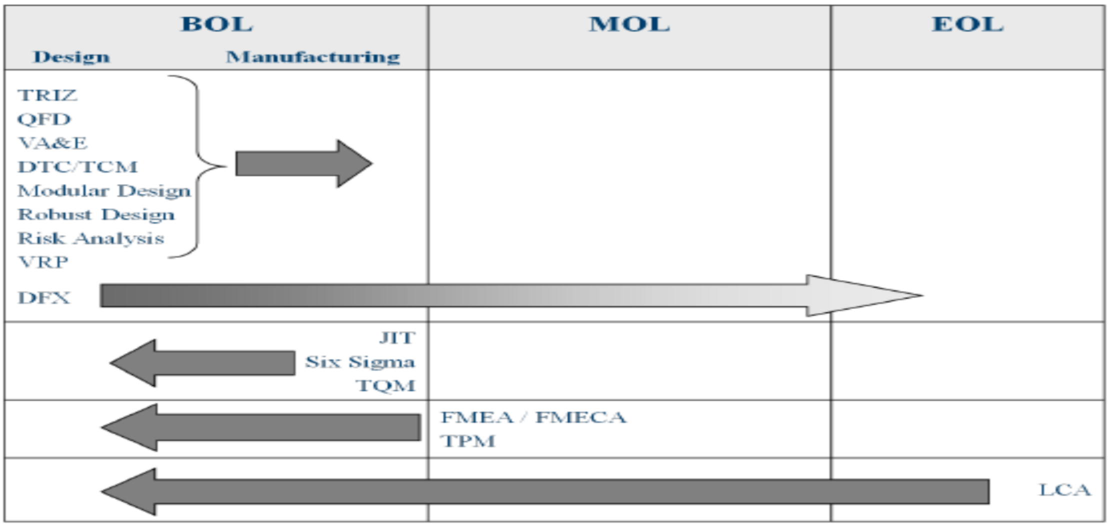


Figure 1.13 PLM models and their effect to the product's phases **[TER12]**

2. Investigation of energy business specifics

2.1 Definition & Products

It is considered “Energy” any form of energy commercially available including: electric energy, natural gas (liquid natural gas included),liquefied petroleum gas, any kind of fuel for heating or refreezing, coal and lignite, peat, automotive fuel (excluding aircraft fuel) and biomasses.

An energy business is any commercial activity which allows people or firms to make profit in any energy areas including fossil fuel usage.

The final results of the energy business are energy products divided into goods and services. **[D.L.25.6.08]**

As said above the energy products can be divided in 2 categories:

- Energy provision: includes all the supply and transport activities. The transport is divided in 2 types:
  - Transmission: is the transport of big energy quantity (or energy source) through dorsal nets of countries ;
  - Distribution: is the transport through the smaller nets which transport energy from the dorsal net to final customers;
- Services: are all those activities which support the main activities of an energy firm like activities which support energy generation or transport, maintenance, energy efficiency, modernization. **[D.L.25.6.08]**

2.2 Strategic analysis of energy business

In order to have a better idea concerning the energy business it’s necessary to understand the attractiveness of the business, which are the competitors and the most common business model of the biggest oil & gas companies.

A good instrument to analyze the attractiveness of a business is the **“Porter’s 5 forces model”** (**figure 2.1**), this model analyze the business basing on 5 features:

- **Competitive rivalry:** it says how strong is the competition between companies inside the business; it is influenced by:
  - Number of companies which operate inside the business;

- Market growth ratio;
- Product differentiation;
- Conversion costs;
- Fix cost influence;
- Exit barriers;

- **Threat of new entries:** it says how easy/hard it is for a new company to enter into business and start to make profit with it; it is influenced by:
  - Demand elasticity;
- **Threat of substitution:** it says how is it easy/hard it is to find or create a different product which gives the same performance of the business product; it is influenced by:
  - Entrance barriers;
  - Scale economies;
  - Learning economies;
  - Product fidelity of costumers;
  - Financial needs;
  - Conversion costs;
  - Access to distribution channels;
- **Supplier power:** it says how easy/hard it is for suppliers to drive up prices; it is influenced by:
  - Number of suppliers compared to the number of companies inside the business;
  - Conversion costs;
  - Product differentiation;
  - Supplier's features;
- **Buyer power:** it says how easy/hard it is for buyers to drive prices down; it is influenced by:
  - Number of suppliers compared to the number of companies inside the business;
  - Conversion costs;
  - Product differentiation;
  - Buyer's features; **[AZB07].**

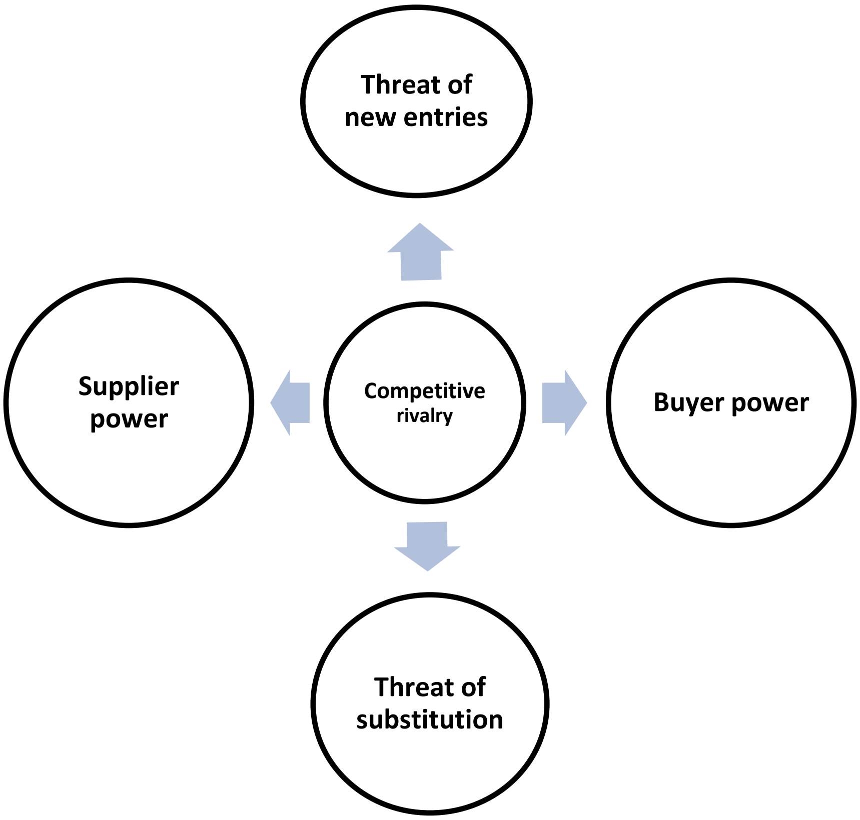


Figure 2.1: Scheme of the Porter's "5 forces model" **[ChiOG].**

Applying the model to the Oil & Gas sector we can find as following:

- **Competitive rivalry:** the competitive rivalry is very high because of the following reasons:
    - ➢ This sector ruled by very big companies, usually with an high level of vertical integration and with great advantages obtained by the scale effect;
    - ➢ There are strong exit barriers especially because of the very expensive assets which are difficult to reconvert or to sell;
    - ➢ Very high fix costs;
    - ➢ In the recent year in the oil & gas market took place the development of the NOC (National Oil Companies) which are state controlled companies based in those

countries which have a big quantity of natural resources (Saudi Arabia, Iran, Russia). The government of these states, to protect the country's interest, allows these companies to have the absolute control of the natural resources. This fact made the rivalry become even stronger inside this business;

- The product is considered as a "**commodity**" so all the competitive advantage is related to the efficiency of the processes;

- **Threat of new entries:** the threat of new entries is very low because of the following reasons:
  - Huge entrance barriers such as: enormous initial investments, necessity of budget for R&D, necessity of financial availability, scale economies etc;
  - Necessity of license and agreements for the extraction processes;
- **Threat of substitution:** it's low in the short term but high in the long term the substitution products of the oil and gas are the alternative energy sources; at the moment they are still too expensive but in the future they will take the place of the traditional fossil sources.
- **Supplier power:** the suppliers have a strong power because they are a very few company with a very differentiated product portfolio. Some oil & gas companies solved this problem with a vertical integration in the first phases of their spinneret. It's important to don't forget that these companies have to work a lot with governments and in fact often it's very difficult to manage all laws and rules of different countries.
- **Buyer power:** it is very law because the number of customers is extremely high and so they have a very low power; **[ChiOG].**

2.3 Business model

To analyze the business model of energy companies we have to consider 2 main aspects:

- **Vertical integration:** a company which is very integrated is a company which invests in all the phases of its spinneret, the more phases are done by the company the more the company is vertical integrated.

  Vertical integration has advantages and disadvantages:

  - *Advantages:*
    - Low fluctuation of profits inside the spinneret;
    - Possibility to take advantages from the synergies between one phases and the previous/next one;
    - Strong position and high entrance barriers;
  - *Disadvantages:*
    - Strong dependence from the taxation of the countries which own the highest number of natural reserves;
    - Strong competition coming from the NOC;
    - Risks related to the public opinion because of the global size of the company;
- **Differentiation:** it's related to the quantity of different products/services offered by the company; the more they are, the more the company has a differentiated portfolio. For the oil & gas company we can identify 2 types of portfolio:
  - **Focused:** when the company concentrate all its effort in the core business, this solution has advantages and disadvantages:
    - *Advantages:* better possibilities to switch supplier (still low in absolute level);
    - *Disadvantages:*
      - Strong exposition to fluctuation coming from the phases of the spinneret;
      - Great dependence from producer;
      - Usually low profits;
  - **Differentiated:** when the company sell products or service which are not only the ones of their core competence. This solution has advantages and disadvantages:

- *Advantages:* they have the same advantages of integrate company and also:
    - Better business opportunities;
    - Risks partially lower;
    - Better exploitation of synergies;
- *Disadvantages:* they have the same disadvantages of integrate company and also:
    - Highest management complexity; **[AZB07] [SPI08] [ChiStr].**

Focused portfolio	ERG.
Differentiated portfolio	Royal Dutch Shell.
Integrated companies	ENI; Exxon Mobil, BP Amoco, Chevron Conoco Phillips, Total.

Table 2.1: Most popular oil & gas companies divided by their business model **[ChiOG].**

Group	**Primary activity**	**Engineering and services**	**Chemistry**	**Others**
Petro China				
Exxon Mobil				
Petrobras				
BP				
Royal Dutch Shell				
Chevron				Electric Energy
Gazprom				
Total				Electric Energy
Sinopec				
Eni				Electric energy + retail distribution

Table 2.2: Most popular oil & gas companies and the differentiation of their portfolio. **[ChiOG]**

2.4 Subjects of energy business and form of ownership

There are 3 main actors in the energy business: government, owner and top management, but a very important role is played also by the regulator.

It’s possible to determinate different form of ownership basing on the power of each of these actors.

State owned companies

It’s the case when the company is owned by the state.

Basing on economic models the best situation for the common interest is the perfect competition, so a lot of small private companies completely identical and the competition is based on the efficiency, in this way the prices are as low as possible and the community has the biggest profit.

Not always it is possible to realize a competitive market, the most important cases of impossibility are:

- **Monopoly:** it’s the case when the whole market is controlled by only one company. There are 3 types of monopoly:
  - **Natural monopoly:** it’s the case when the monopoly is the only convenient market form, the most common natural monopolies are the energy networks (gas and electric networks);
  - **“De iure” monopoly:** It’s when the monopoly condition is established by the law;
  - **“De facto” monopoly:** It’s when there are no laws or natural conditions which make the monopoly necessary but there is a company which is better than the others and it actually rules the market;
- **Public goods:** they are goods which have 2 important features:
  - **Non-rivalry:** it means that the good, used by someone, can be used in the same proportion by someone else. The usage of a user doesn’t compromise the usage of another person who can thus use it in the same quantity or proportion;
  - **Non-excludability:** it means that the usage of a good by someone doesn’t impede the others to use the same good. It’s impossible (or enormously expensive) to exclude someone from the usage of the non-excludable goods;

	Non-rival	**Rival**
Non-excludable	Pure public goods (weather, sun light)	Common property goods (forests, sea fauna)
Excludable	"Club" goods (specific knowledge, cultural products)	Private goods (cars, pc, tickets)

Table 2.3: Types of goods basing on rivalry and excludability **[GAR11].**

- **Distribution reasons:** to warranty equity for example create jobs in rural places or reduce the unemployment ratio;
- **Strategic sectors:** for example space industry, army, weapon and missile industries;

In these cases state-owned companies are preferred to private ones.

The main problem of this solution is the high inefficiency level, it has been studied and proved in fact that private companies are usually more efficient than public ones. There are 2 theories to explain this fact: the first one says that the reason is because the government doesn't have the same interest of people and so they use public companies in order to achieve their own targets (usually their targets is to give advantages to their group of electors in order to be elected again), the second one says that the reason is the public top managers who have the task to manage public companies, they pursue their own interest which are not always the same interests of people **[STI03]**.

Private companies

The privatization process is a process in which the state gives some of his assets to private firms; there are many levels of privatization:

- **Real privatization:** give the state property to privates;
- **Outsourcing:** delegate some operative functions or operations to privates;
- **Partnership:** share strategic control with privates;
- **Horizontal subsidiarity:** recognize autonomous subjects which deliver public services;

The privation itself can also be done 2 ways: the first one is via bilateral contract between the state and a private and the second is via public auction.
As said before the private companies usually have a higher efficiency level, but this is not always true; in fact it depends on what kind of market the companies are making their business; for this reason it is important to distinguish between liberalized market and regulated market **[STI03]**.

Liberalized market

When the market is not a natural monopoly it's better to have a competitive market, in this way the companies will compete basing on their efficiency and trying to improve their skills day by day in order to make more profit, in this way they make people's interests.
Unfortunately the perfect competitive market doesn't exist; in reality there are always groups of companies which are bigger and stronger than the others especially in the energy business.
For this reason it is important to introduce in the market a controller which has the task to warranty the respect of competition between companies, this function is done by the Antitrust, the most common non respectful activities are:

- **Abuse of dominant position:** The dominant position is a condition in which there is a company which is much bigger and stronger than others and so it can use its size to eliminate the competitors from the market (ex. reducing a lot the prices, contracts which restrict the actions of competitors);
- **Anti-competitive agreements:** These are agreements between the biggest and strongest companies in order to eliminate the other competitors from the market (ex. geographical division of market, joint price fixation) **[STI03]**.

Regulated market

In case of natural monopoly it is still possible to have a privatization but it's necessary to have a **regulator**; the regulator is an actor which has the task to control the activities of monopolists, in particular the regulator has to warranty the same conditions to all the customers and suppliers of the monopolist; basically the monopolist has to give the same contract conditions to everyone.

In case of natural monopoly but with not big “sunk investments” the most convenient market form is the “**competition for the market**” which is also a monopoly but the company which wants to be the monopolist have to win a tender, the company who offers the lowest prices wins the tender and became the only monopolist (still controlled by the regulator) **[STI03]**.

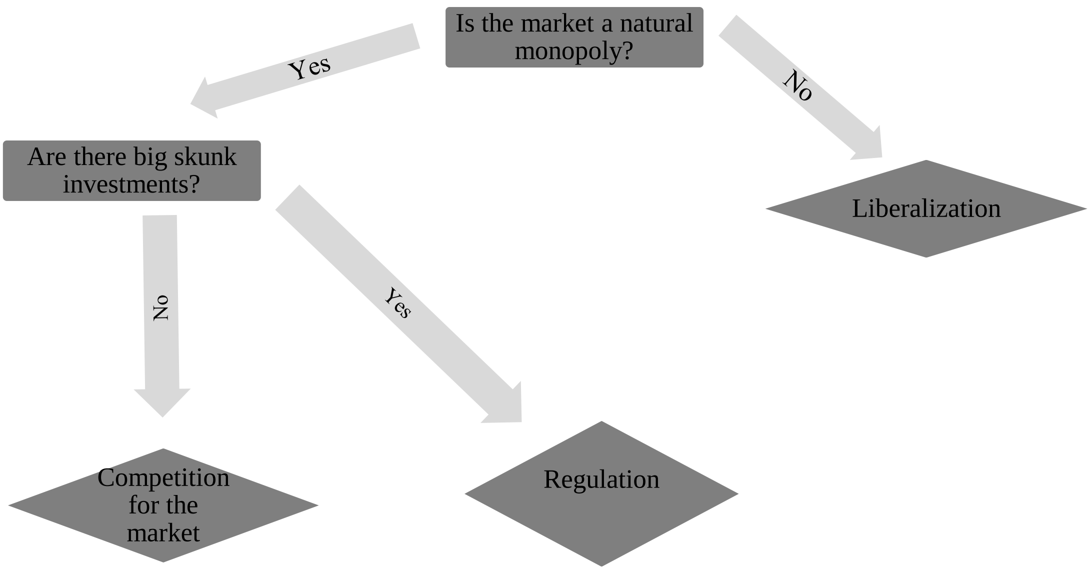


Figure 2.2: Criteria of ownership form choice based on the market situation. **[GAR11]**

Municipalities

Municipalities are an ownership form in which the local government is the owner and it chooses the partners which build the plant; the choice is done via public auction, in this way, if the auction is correctly and legally done, it is possible to obtain efficiency through lowest investment cost.

At the same time the municipalities have the great advantage to have a good influence in the territory, for this reason it will be easier to get permission and to have people trust.

They have the same disadvantages of the public companies **[STI03]**.

2.5 Technology influence

The energy production business is deeply influenced by technology, there are many kinds of technological solutions which can be chosen in order to produce electricity and heat, a lot of aspects must be taken in consideration during the choice of technology (such as geographical and weather conditions, expected efficiency, public opinion etc.)

It will be very long and complicated to list and discuss all the solutions and all the impacts they will have on the finance of the company but it's important to keep in mind that technology mainly influence the following aspects:

- Investments costs;
- Maintenance times and costs;
- Efficiency;
- Performances;
- Emissions (which, especially in the European countries, are translated into costs);

As previously said it's impossible to talk about all the solutions and all the impacts they have but it's important to talk about the main aspects.

Simple gas cycle

In **figure 2.3** it's shown the scheme of a simple gas cycle.

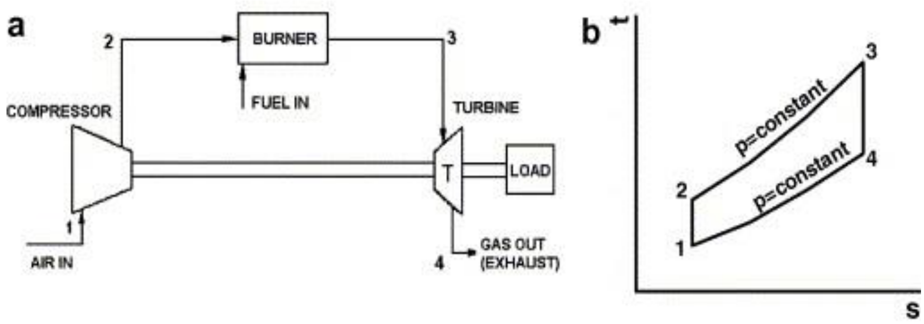


Figure 2.3: Scheme of simple gas cycle **[UBG]**

It's possible to demonstrate that the cycle efficiency **η** and the specific work **l** are dependant from the **β** which is the compression ratio ($\frac{p_2}{p_1}$ in **figure 2.3**) of the compressor and the maximum temperature of the cycle as shown in **figure 2.4**

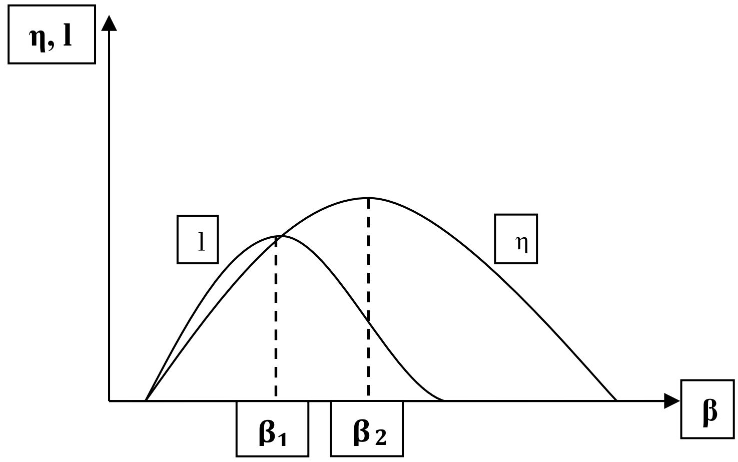


Figure 2.4 Graph which shows the impact of the β on performances. **[UPV]**

As it's possible to see there are 2 values of optimum compression ratio β_1 and β_2, the first one optimizes the specific work while the second one optimizes the efficiency.
At this point the management should decide which is the best value of β to adopt, obviously an higher value of β means higher investments costs, for these reason the choice is taken basing on the working hours of the plant: if the plant will work many hours it's better to choose β_2 in order to save fuel otherwise (it's the case of plants which are created to satisfy the peaks in demands) it's better to choose β_1 in order to have lower investment outgoings.**[UBG] [UPV] [NAP96] [MAN]**
There are 3 main ways to increase efficiency and specific work of a simple gas cycle: Regeneration, inter-cooling and reheat.

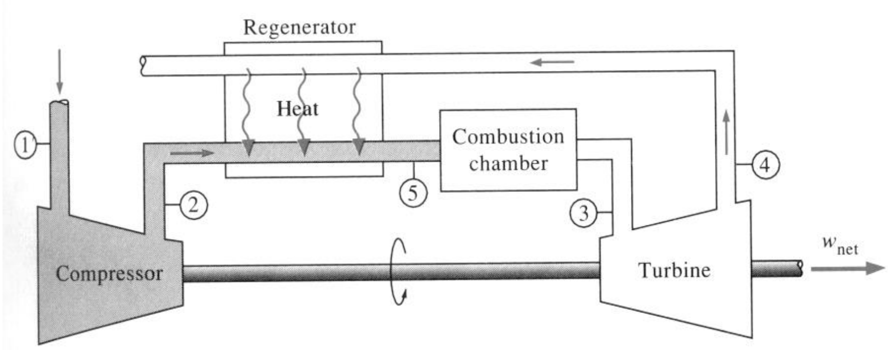


Figure 2.5 Regeneration**[UBG]**

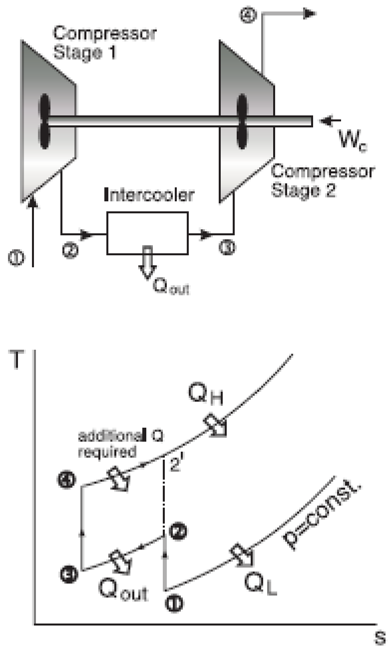


Figure 2.6: Inter-cooling **[UBG]**

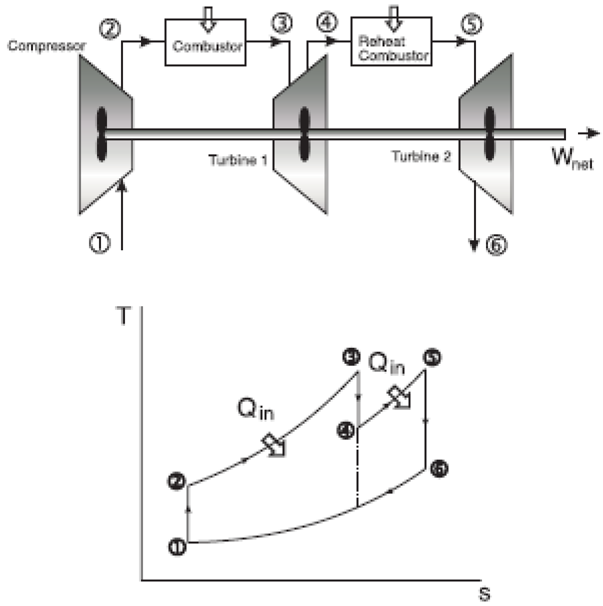


Figure 2.7 Reheat **[UBG]**

These models will not be detailed explained as this is not the target of this thesis, it's anyway important to know that they can be used all together or it's possible to use only some of them, with any mix; the management has to choose the best mix keeping in mind that any additional tool involve higher investments, higher maintenance costs and higher cycle complexity. **[LAN96] [UBG][NAP96] [MAN]**

Combined cycle

At the end of the gas cycle the exhaust gases are still very hot with a high level of enthalpy, it's possible to take advantage of this fact introducing a steam cycle alimented by these gases which will improve the efficiency of the cycle.

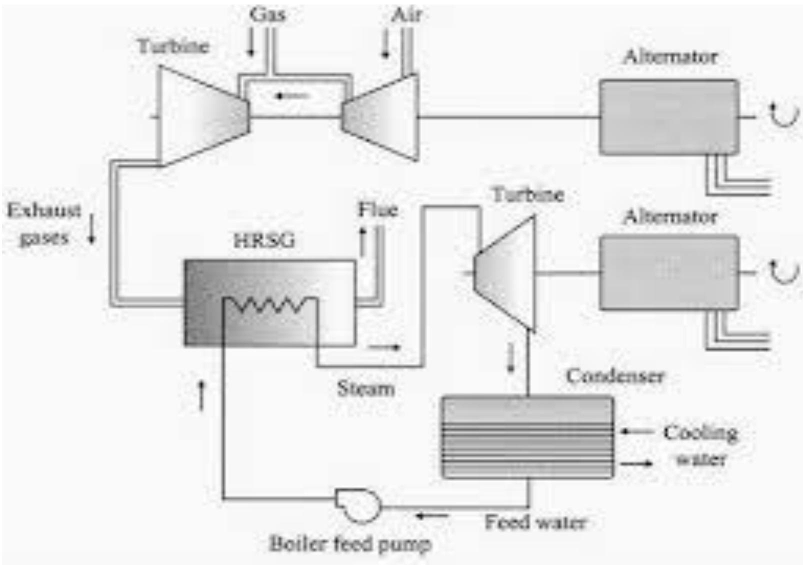


Figure 2.8 Scheme of combined cycle **[RAM12]**

Again the introduction of a steam cycle increases the cost of investments, the complexity of the plant and the cost of maintenance, also the steam cycle has its own efficiency improvement criteria (ex. steam expanded in turbine with 3 pressure levels). **[RAM12] [UPV] [MAN]**

CHP gas cycle and CHP combined cycle

Another solution is the cogeneration which consists in the joint production of heat and power. For the gas cycle it's possible to adopt 2 solutions the first is shown in **figure 2.9** and it is the CHP gas cycle;

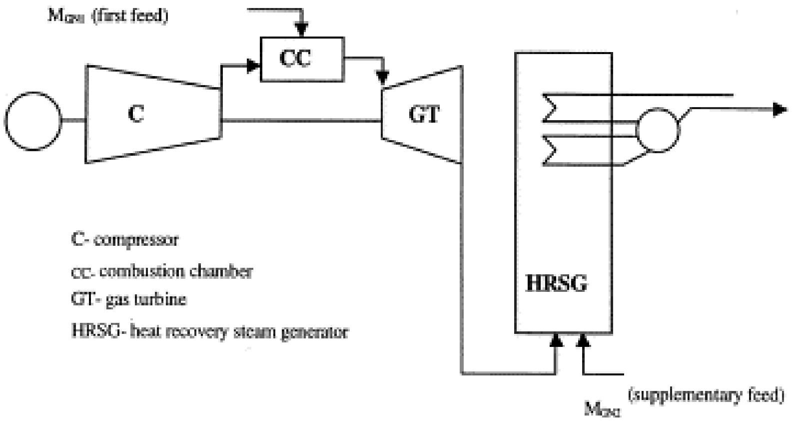


Figure 2.9 Scheme of CHP gas cycle **[RAM12]**

The second one is shown in **figure 2.10** and it's the CHP combined cycle

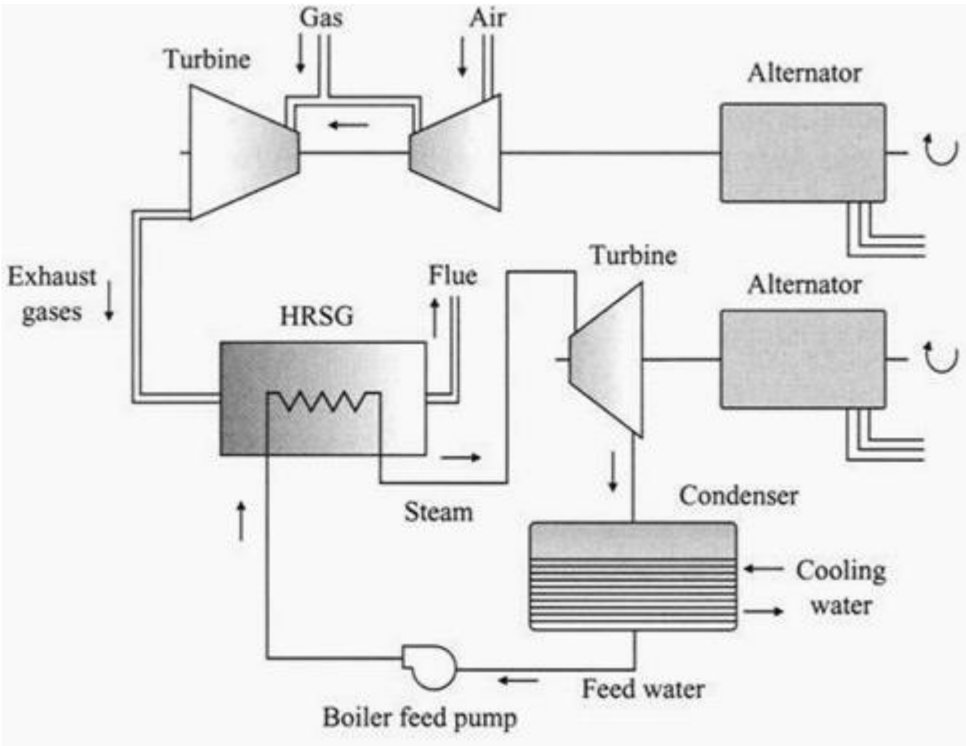


Figure 2.10 Scheme of CHP combined cycle **[RAM12]**

Both the configurations allow to exploit the thermal energy produced by the fuel combustion, but of course, compared to the standard configurations, they have a lower electrical efficiency.

It is possible to put some additional tools on the CHP cycles in order to increase the flexibility and the heat production (ex. post-firing, 3-ways valves).

The management has a difficult job to do with CHP plants because the production is made to satisfy 2 different users: electricity users and heat users. It's very important to size the plant in order to have the best economical profit, keeping in mind all the factors and all the features they are characterized of. **[MAN]**

Cost & Performance Characteristics[4]	System 1	System 2	System 3	System 4	System 5
Electricity Capacity (kW)	1,150	5,457	10,239	25,000	40,000
Basic Installed Cost (2007 $/kW)[5]	$3,324	$1,314	$1,298	$1,097	$972
Complex Installation wth SCR (2007 $/kW)[6]	$5,221	$2,210	$1,965	$1,516	$1,290
Electric Heat Rate (Btu/kWh), HHV[7]	16,047	12,312	12,001	9,945	9,220
Electrical Efficiency (percent), HHV	21.27%	27.72%	28.44%	34.30%	37.00%
Fuel Input (MMBtu/hr)	18.5	67.2	122.9	248.6	368.8
Required Fuel Gas Pressure (psig)	82.6	216	317.6	340	435
CHP Characteristics					
Exhaust Flow (1,000 lb/hr)	51.4	170.8	328.2	571	954
GT Exhaust Temperature (Fahrenheit)	951	961	916	950	854
HRSG Exhaust Temperature (Fahrenheit)	309	307	322	280	280
Steam Output (MMBtu/hr)	8.31	28.26	49.10	90.34	129.27
Steam Output (1,000 lbs/hr)	8.26	28.09	48.80	89.8	128.5
Steam Output (kW equivalent)	2,435	8,279	14,385	26,469	37,876
Total CHP Efficiency (percent), HHV[8]	66.3%	69.8%	68.4%	70.7%	72.1%
Power/Heat Ratio[9]	0.47	0.66	0.71	0.94	1.06
Net Heat Rate (Btu/kWh)[10]	7,013	5,839	6,007	5,427	5,180
Effective Electrical Efficiency (percent)[11]	49%	58%	57%	63%	66%

Table 2.4 Typical performance parameters and costs in commercially available CHP gas turbines **[EPA08]**

Emissions Characteristics	System 1	System 2	System 3	System 4	System 5
Electricity Capacity (kW)	1,000	5,000	10,000	25,000	40,000
Electrical Efficiency (HHV)	21.9%	27.1%	29.0%	34.3%	37.0%
NO_x, ppm	42	15	15	25	15
NO_x, lb/MWh[22]	2.43	0.66	0.65	0.90	0.50
CO, ppmv[23]	20	25	25	25	25
CO, lb/MWh[23]	0.71	0.68	0.66	0.55	0.51
CO_2, lb/MWh	1,877	1,440	1,404	1,163	1,079
Carbon, lb/MWh	512	393	383	317	294

Table 2.5 Gas turbine emissions characteristics without heat recovery or exhaust control options **[EPA08]**

Cost Component	*System 1*	System 2	System 3	System 4	System 5
Nominal Turbine Capacity (MW)	1	5	10	25	40
Equipment (Thousands of 2007 $)					
Combustion Turbines	$1,015	$2,733	$6,102	$12,750	$23,700
Electrical Equipment	$411	$540	$653	$1,040	$1,575
Fuel System	$166	$177	$188	$251	$358
Water Treatment System	$74	$180	$293	$370	$416
Heat Recovery Steam Generators	$508	$615	$779	$1,030	$1,241
SCR, CO, and CEMS	$0	$0	$0	$0	$0
Building	$0	$0	$0	$0	$0
Total Equipment	$2,173	$4,246	$8,015	$15,440	$27,290
Construction	$769	$1,402	$2,568	$4,947	$8,744
Total Process Capital	$2,942	$5,648	$10,583	$20,387	$36,034
Project/Construction Management	$271	$402	$664	$1,279	$2,260
Shipping	$47	$89	$164	$317	$559
Development Fees	$217	$425	$802	$1,544	$2,729
Project Contingency	$116	$177	$276	$532	$940
Project Financing	$230	$431	$799	$1,540	$2,721
Total Plant Cost	$3,822	$7,172	$13,288	$25,598	$45,243
Actual Turbine Capacity (kW)	1,150	5,457	10,239	23,328	46,556
Total Plant Cost per net kW (2007 $)	$3,324	$1,314	$1,298	$1,097	$972

Table 2.6 Estimated capital costs for typical gas turbine-based CHP systems **[EPA08]**

O&M Costs[16]	System 1	System 2	System 3	System 4	System 5
Electricity Capacity, kW	1,000	5,000	10,000	25,000	40,000
Variable (service contract), $/kWh	0.0060	0.0060	0.0060	0.0040	0.0035
Variable (consumables), $/kWh	0.0001	0.0001	0.0001	0.0001	0.0001
Fixed, $/kW-yr	40	10	7.5	6	5
Fixed, $/kWh @ 8,000 hrs/yr	0.0050	0.0013	0.0009	0.0008	0.0006
Total O&M Costs, $/kWh	0.0111	0.0074	0.0070	0.0049	0.0042

Table 2.7 Gas turbine non-fuel operation and maintenance costs **[EPA08]**

2.5.1 Technology influence to costs

It is possible to express the cost to produce energy from a power plant with this formula:

$$COE = \frac{\frac{C_{inv} * CCC + C_{O\&M} + C_{ins} + C_{hr}}{P}}{h_{eq}} + \frac{C_{fuel}}{\eta}$$

Where:

COE= Cost of electricity [$\frac{€}{MWh}$];

C_{inv}= Cost of investment [$\frac{€}{year}$] ;

CCC= Capital carrying charge [%];

$C_{O\&M}$=Operation and maintenance costs[$\frac{€}{year}$];

C_{ins}= Insurance costs [$\frac{€}{year}$];

C_{hr}= Personnel costs [$\frac{€}{year}$];

C_{fuel}= Fuel cost [$\frac{€}{MWh}$]; ;

h_{eq}= Hours equivalent [$\frac{h}{year}$];

η= Efficiency [%];

P=Plant power [MW];

This formula is a simple way to show the relationship between technology and costs.
It's important to say that investment costs depend on the plant size, the more the plant is big the more the investment for power unit is low, this fact is related to scale economies. The situation is very similar for personnel costs. **[MAN]**
The hours equivalent are related to the operation and maintenance policy, the more hours are spent for the maintenance the lower will be the hours equivalent but at the same time if the failure time will be very high it will influence the hours equivalent; for these reasons it's very important to choose the best maintenance policy.
The cost of fuel is very specific for every country and for each fuel type, it can be as well influenced by the plant size as it's possible to get big discounts in case of big amount of fuel purchased.
The efficiency of the plant is related to investment costs and to O&M costs (if the plants is very complex, with a high number of components which allow a higher efficiency, for sure it has big investment and maintenance cost).
The COE is finally influenced by the useful life of the plant, the longer the life is the more the investments will be spread during the years and so the COE will be lower (the CCC will be lower in the formula if the life is long).
This model doesn't contain all the variables which influence the COE, it is possible to improve it introducing other 2 very important factors, the cost of auxiliaries and the carbon tax (which will be probably be introduced soon). The model so becomes:

$$COE = \frac{\frac{C_{inv} * CCC + C_{O\&M} + C_{ins} + C_{hr} + C_{aux}}{P}}{h_{eq}} + \frac{C_{fuel}}{\eta} + \frac{CO_2}{\eta} * CT$$

Where:

COE= Cost of electricity [$\frac{€}{MWh}$];

C_{inv}= Cost of investment [$\frac{€}{year}$] ;

CCC= Capital carrying charge [%];

$C_{O\&M}$=Operation and maintenance costs[$\frac{€}{year}$];

C_{ins}= Insurance costs [$\frac{€}{year}$];

C_{hr}= Personnel costs [$\frac{€}{year}$];

C_{fuel}= Fuel cost [$\frac{€}{MWh}$]; ;

h_{eq}= Hours equivalent [$\frac{h}{year}$];

η= Efficiency [%];

P=Plant power [MW];

C_{aux}= Cost of auxiliaries [$\frac{€}{year}$];

CO_2= Production of carbon dioxide [$\frac{KG_{co2}}{MWh}$];

CT = Carbon tax [$\frac{€}{KGco2}$];

For both these new elements it is possible to exploit the scale effect, which means that the bigger the plant is, the lower the cost per MW will be. **[MAN]**

ITALY

Type of plant	**COE [$\frac{€}{MWh}$]**
COMBINED CYCLE	43,9
GAS TURBINE HD TYPE	57,9
GAS TURBINE AD TYPE	53
STEAM CYCLE GAS ALIMENTED	55,7
STEAM CYCLE COAL ALIMENTED	42,1
INTEGRATED GASIFICATION COMBINED CYCLE	52,3
CHP COMBINED CYCLE	30,7

Table 2.4 Italian costs of electricity for the different types of plant **[MAN11]**

2.6 Demand and prices

The big peculiarity of electrical market is that electrical energy can't be stored, for this reason in every moment it is necessary to produce exactly the same quantity which customers request.

Obviously the energy requests is not the same every moment, it changes a lot during the year and during the day, the **figure 2.11** shows an example of demand curve during the 3rd Wednesday of December 2011, in this way it is possible to see how demand changes during the day; the pink curve represents the demand of energy while the grey curve represents the Italian production, the difference between the 2 curves represents the energy which Italy buys from foreign countries, the red curve represents the energy produced by traditional fuel sources and all the other curves represent the energy produced by renewable sources.

Looking at the **figure 2.12** it is possible to see how the energy demand has been increasing during the last 41 years: the black curve shows the Italian energy demand, the grey line shows the Italian production while the orange space between the 2 curves represents the energy bought from foreign countries; the trend settled during the last 4 years probably because of the world crisis.

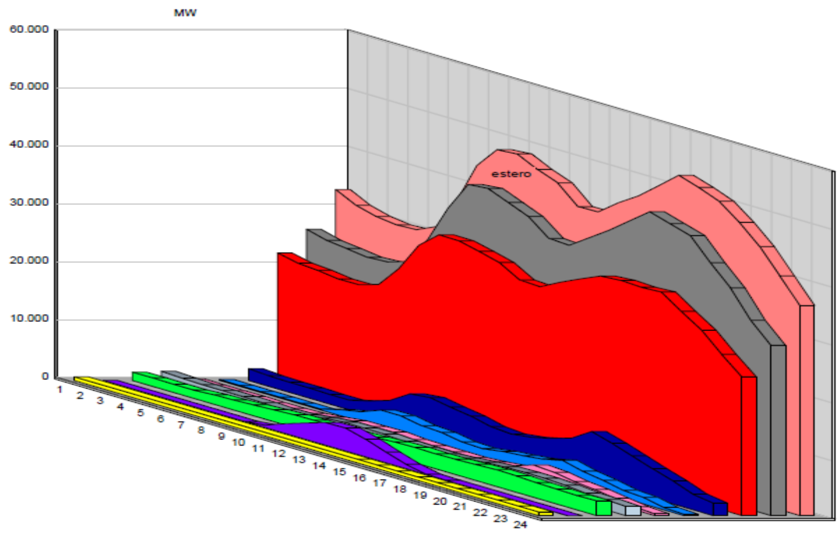


Figure 2.11 Electrical energy demand and production during the 3rd Wednesday of December 2011 **[Terna]**

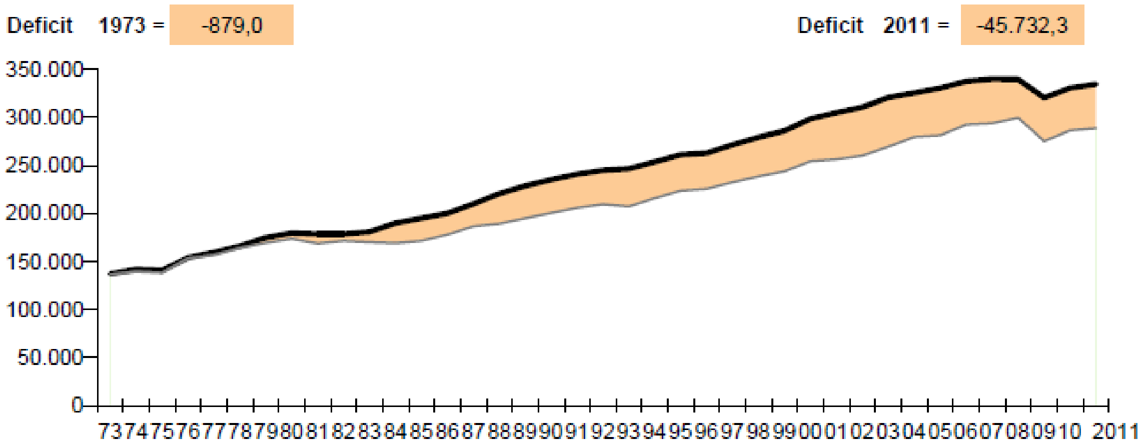
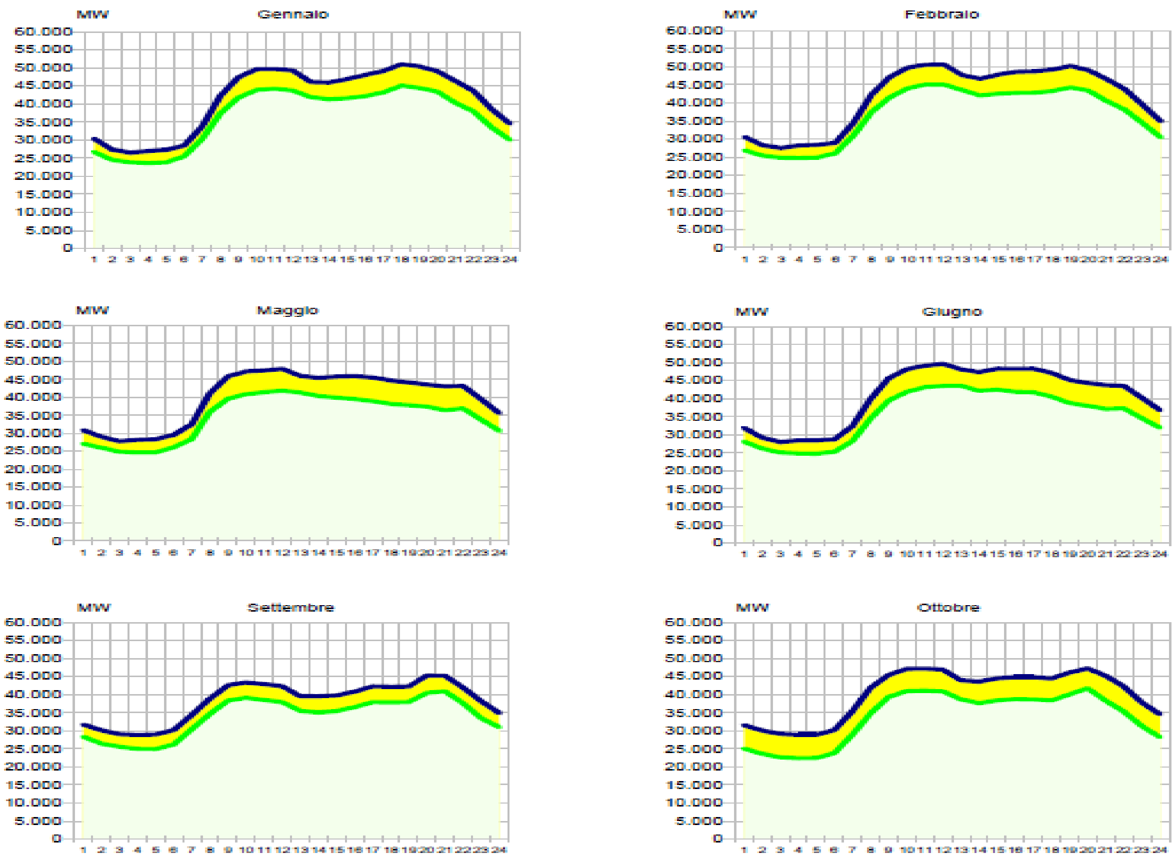


Figure 2.12 Italian electrical energy demand in the last 41 years **[Terna]**



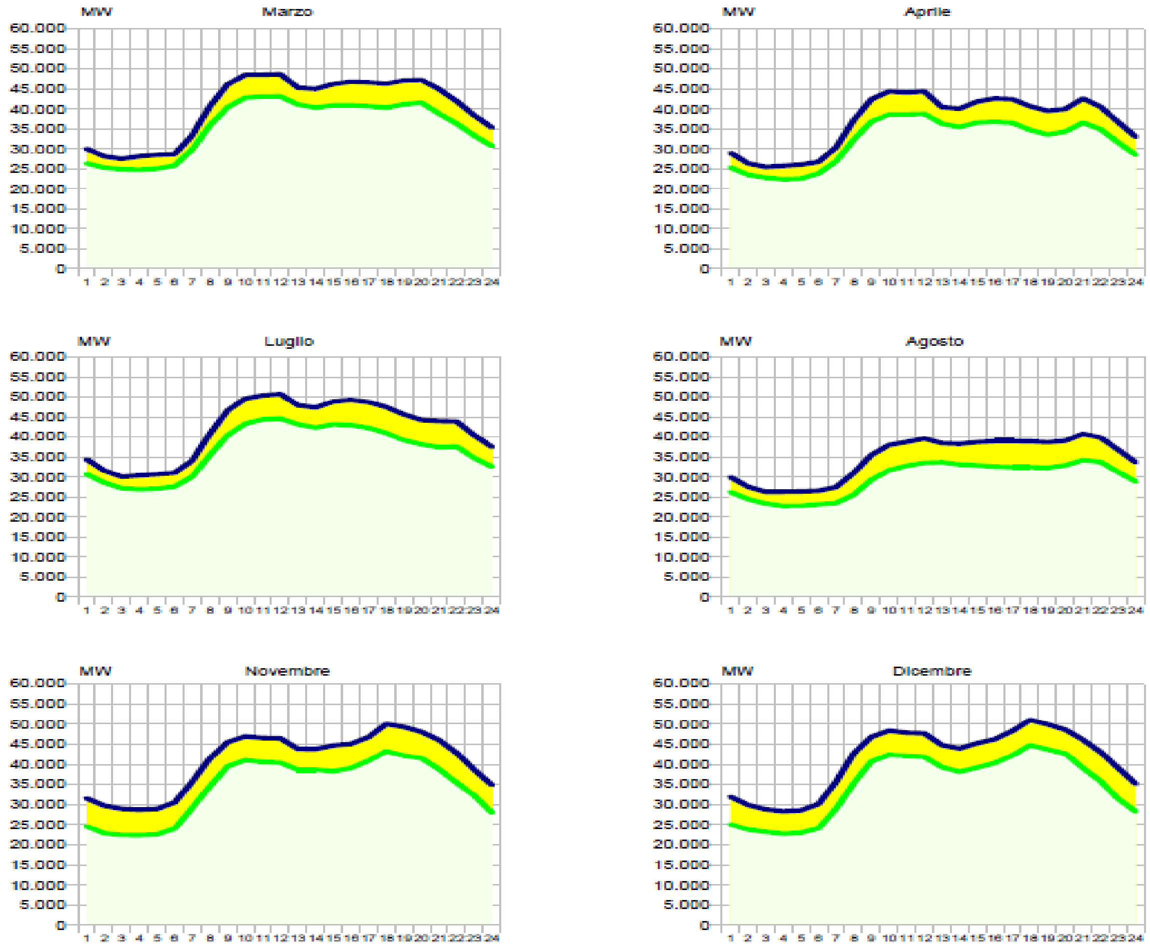


Figure 2.13 Italian electrical energy demand during the 3rd day of every month in 2011**[Terna]**

The **figure 2.13** shows the 3rd shows the Italian electrical energy demand during the 3rd Wednesday of every month of the year 2011: the blue line represents the demand, the green one represents the Italian energy production while the yellow space between the 2 curves represents the energy bought from foreign countries.

As shown in the last 3 figures, the demand changes a lot during the day, during the year and from one year to the next one, for these reasons it is necessary to think about a system which allows to know the energy demand in every moment.

In Italy the **Gestore del Mercato Elettrico GME** (in English electrical market manager) has the following tools which solve this problem:

- **Mercato del giorno prima:** in English “market of the day before”, customers ask for the quantity of energy which they are going to need the day after with the maximum price they are willing to pay, at the same time producers make their offers with the minimum price they are willing to accept. At the end of the day the GME accept the offers ordered from the cheapest to most expensive one; at this point the GME decide the optimum price, divided per geographical area, creating the demand and offer curve and intersecting them.
- **Mercato di aggiustamento:** In English “market of adjustment”, it’s a tool which allows to modify the quantity of energy decided in the mercato del giorno prima with the same criteria.
- **Mercato dei servizi di dispacciamento:** in english “market for dispatching services”, it’s a tool used by Terna, the company which manage the electrical network, to purchase the tools to manage the dispatching. **[GME] [Terna] [MAN2]**

2.7 Profitability

The amount of profit which is possible to get from one unit of money invested depends on different factors which will be explained in the following points.
These factors has been studied by **Martin Boyer** and **Didier Filion** from the Universite’ de Montreal **[BOY06]**, they created a regression model which has as dependent variable the stock return and the independent variables are the interest rate return, the exchange rate return, the crude oil price return and the natural gas price return:

$$r_{i,t} = \alpha + \beta_{ir} r_{ir,t} + \beta_{er} r_{er,t} + \beta_m r_{m,t} + \beta_{oil} r_{oil,t} + \beta_{gas} r_{gas,t} + \text{э}_t$$

Where:

- $r_{i,t}$= excess return of each stock after 1 month;
- $r_{ir,t}$= interest rate return;

- $r_{er,t}$= exchange rate return;
- $r_{m,t}$= market excess return after one month;
- $r_{oil,t}$= crude oil price return;
- $r_{gas,t}$= natural gas price return;

α is the constant, $э_t$ are the residuals and all the β are the constants associated to every variable.

$$r_{i,t} = \alpha + \beta_{ir} r_{ir,t} + \beta_{er} r_{er,t} + \beta_m r_{m,t} + \beta_{oil} r_{oil,t} + \beta_{gas} r_{gas,t} + D1\gamma_{ir} r_{ir,t} + D2\gamma_{er} r_{er,t} + D3\gamma_m r_{m,t} + D4\gamma_{oil} r_{oil,t} + D5\gamma_{gas} r_{gas,t} + э_t$$

The only difference between the 2 equations is the introduction of the Dummy variables D1, D2, D3, D4 which are equal to 1 when the firm is integrated and 0 when the firm is an independent producer, the β are common for all the types of companies while the γ are unique to the integrated firms.

The first model can be improved with the introduction of new independent variables:

$$r_{i,t} = \alpha + \beta_{ir} r_{ir,t} + \beta_{er} r_{er,t} + \beta_m r_{m,t} + \beta_{oil} r_{oil,t} \beta_{drill} r_{drill,t-1} + \beta_{gas} r_{gas,t} \beta_{drill} r_{drill,t-1} + \beta_{cf} r_{cf,t-1} + D1\beta_{res} r_{res,i,t-1} + \beta_{prod} r_{prod,i,t-1} + \beta_{debt} r_{debt,i,t-1} + э_t$$

Where:

- $r_{drill,t-1}$= variation in drilling success;
- $r_{cf,t-1}$= variation in cash flows;
- $r_{res,i,t-1}$= variation in reserves;
- $r_{prod,i,t-1}$= variation in production volume;
- $r_{debt,i,t-1}$= variation in debts;

The results which this model, applied to a big number of companies, shows can be very different from country to country in fact geographical positioning influences the profit in many ways:

- Geo-political factors of the area (also including the presence of oil & gas reserves which is a very important factor);
- Taxation and fiscal rules applied, especially concerned to the resource extraction from the subsoil;
- Technologies: in many location it's necessary to use advanced technologies to extract sources from the subsoil which influence directly the costs of the company;

Anyway it is possible to understand the main factors which influence the oil & gas companies' revenues:

- Most of their value is driven by the price of the commodity they produce, a price upon which no firm has any impact;
- One surprising result is that firms that increase their production of crude oil and/or of natural gas experience a lower stock return on the market. This result is surprising considering that more production should increase the firm's available cash flows. This theory stipulates that firms hold a portfolio of options on the assets of the firm to expand production (or reduce it). These options are exercised whenever the value of the underlying asset is sufficiently high. When these options are exercised, the risk of the firm is reduced because an option on the assets is always riskier than the asset itself. It is quite possible that an increase in production signifies that the firm has exercised its options so that risk is reduced and return should be reduced as well;
- Interest exchange rate has a negative influence on the revenues;
- According to the correlation between energy tariffs and capital intensity of energy machines, profitability in electric and heat energy field is usually lower than in other sectors. Anyway, there are differences also inside the sector because it depends on the type of plant; for example in Russia nowadays profitability can be higher for small gas and steam turbines than for the big ones. Direct selling of fuel is much more profitable than power generation. **[BOY06]**

Oil price return and the natural gas return have a greater impact on producers than on integrated firms. Although this difference may not be significant, producers appear more affected by variations in oil and gas prices than integrated firms. Different is the impact of each common factor on integrated firms compared to producers. Integrated firms are significantly positively affected by a depreciation of the local money compared to USA dollar whereas producers are significantly negatively affected. Furthermore, crude oil prices have a significantly larger impact on producers than on integrated companies. **[BOY06]**
Interestingly, crude oil price returns had a greater impact on the stock market return than natural gas price returns. There are two possible explanations. First, since the production of crude oil is on average greater than the production of natural gas, crude oil prices should have a more important impact on the revenues and the profits of energy firms (and on their stock price) than natural gas prices. Second, energy firms are more likely to hedge against the volatility of natural gas prices than the volatility of oil prices. The impact of the market return is not the same on crude oil intensive firms as on natural gas intensive firms. In fact, the sensitivity of natural gas firms is twice as large as that of crude oil firms, natural gas intensive firms are twice as sensible to stock market variations as oil intensive firms. **[BOY06]**

2.8 Social Responsibilities

The energy business is a very important sector for people every-day-life and it is already a social responsibility itself, people could not live without energy.
To understand the social responsibility of the energy business it's useful to analyze the study done by the Russian researchers **Gidelman** and **Ratnikov** and then published in their book "**Energeticheskij Biznes**" (in English "Energy Business") **[GIT06]** ; their motto regarding this topic is: "Owners and managers of energy companies should do everything according to the society or at least not against it".
Their study is based on 3 hypotheses:

- The government is benevolent and all its actions and decisions are taken in order to help the society;
- There is always demand of heat and electrical energy in the market;
- The system is based on reliable, safe and ecological respectful energy supply, with minimal exploitation of fuel and natural sources;

The first hypothesis is very strong, there are a lot of studies which shows that public managers and government have their own objective function which is not the same function of the society, they pursue their own interests and targets which are different from the society's ones. The authors say that the solution would be to create a government system which can stimulate social responsibility with energy programs of different levels, compensations and incentives and also fines for people who break laws.

The second hypothesis is always true. It's very difficult to find a reality where there is no energy demand; if it is not always true, it is for sure true in EU and Russian Federation.

The third hypothesis is true in Europe, has the European governments, companies and customers are very sensible to this factors, in Russia it's still not completely true but becoming every day closer to reality.

Departing from these 3 hypotheses, authors found 6 main rules which, if respected, allow the market and the system to be completely social responsible:

- Companies must respect all the laws for 100%;
- Energy production, transport and distribution has to be a non-stop process and with non-stop innovation;
- In order to avoid long-timed network overloads it is necessary to have a reliable system, for this reason companies have to keep equipment in good conditions, avoiding failures and long-timed stops; good maintenance policies are needed.;
- Companies have to take part to national, regional and provincial energy programs which are created to develop the country energy system. This is important in order to cooperate for social interests with proactive suggestions and joint projects;
- Network connection of a new user has to be done respecting the rule of social priorities. This problem is much more important in Russia than in Europe as the huge

territory makes the network connection a very important problem, especially in terms of priorities;

- Companies have to understand that it's more important to invest in order to achieve a long-term economic safety and stability while think about short-term financial result;

Even with these rules it's not completely sure to realize a total social responsible business, in literature it's possible to find other norms and rules, mandatory and recommended, but there is always a trade-off which is necessary to manage, this is the choice between ethic and economics.

Authors say that ethic is the result of a long-term development of market relationships and it represent the main characteristic of the civilized business nowadays. The consideration of this factor doesn't have to be neglected but at the same time it doesn't have to be over-considered. Economics is connected to much more pragmatic factors.

Another problem that owners and managers have to choose is the right amount of money they should invest for social causes, this is another trade-off because from one side it's a cost to invest in social responsibility and in the other side it improves the social image, in this way customers and government will trust the company much more, this allows to have direct and non-direct advantages.

The right amount of money to invest depends also on the people social conscience of each country.

The last thing which authors noticed is that the social policy of energy companies shouldn't influence the prices, in this kind of business prices must be the natural consequence of the "demand-offer" law. **[GIT06]**

2.9 Risks

The book "**Energeticheskij Biznes**" of **Gidelman** and **Ratnikov** is again useful to analyze risks of energy business. The authors identified 5 main types of risks and for each of them they found a solution in order to minimize them.

The 5 main risks of energy business are:

- **Investments:** it consists on all the risks which are connected to don't get enough profits after the investments. In case of small plants or equipment the risk is much lower than for big plants as sunk investments are much lower.
  For the authors the only way to control the risk in case of big investments is to receive warranties from the state.
- **Prices:** in energy business price change every day and also they change many times during the day, this happens because of the organization of the electric burse. As a result it is really difficult to organize a production plan even in the short-term. To control this risk it's necessary to develop a powerful market which is not related to the burse: bilateral contract and price risk insurance policies. Finally it's important to say that this risk is strongly related to the raw material prices, to minimize this risk companies can buy financial options.
- **Financial:** it's the risk connected to the fact that final customers don't pay.
  Companies have to fight against losses and against people who steal energy.
  This problem is very important in Russia, in fact they created a new paradigm exactly to fight against it. This paradigm is called **"Nadezhnost kak uslug"** (in English "Reliability as a service"), it consists in seeing the reliability which a company offers to another one and for which the other company wills to pay money. In the practice it is done in this way: the company which sells divides its customers in groups based on their paying reliability, then they will make difference prices for each of these groups, the most reliable ones will receive a lower price while the less reliable ones will have a higher price. At the same time this practice can be seen as a form of insurance from the company which sells energy. It's also recommended to have an insurance policy, especially for the less reliable company.
- **Technical:** it's related to the equipment and it consists in all these problems which impede the normal flow of energy to the final customers, the most important examples are: failures, decreasing of reliability in energy supply, stops in energy

supply. The equipment reliability and process flow are very important for this reason it's necessary to have high qualified personnel (which is expensive) and good maintenance policies. Moreover energy business is connected with many other areas (such as construction, geology ex.) which imply a huge number of contracts and often also strict quality requirements; all these features make energy business more risky than other sectors.

To minimize this risk it is important to have qualified personnel, qualified technical management, a good maintenance policy and finally it is recommended to have an appropriate insurance policy.

- **Regulation: Gidelman** and **Ratnikov** take in consideration also the risk related to unexpected or bad actions by the regulator. It can take place not only into regulated markets but also into competitive market (Antitrust authority) and it regards many aspects, such as final prices, ecology, taxes, standards exc. This problem can influence a lot the revenues.

  In this case there is nothing which the company can do to solve this problem. But if the first hypothesis is valid the government should give the money, lost because of the regulator, back to the company.

  The authors also defined 3 external features which will allow the companies to minimize their risks:

- The government has to benevolent and create laws, incentives, fines and other mechanisms in order to help companies to minimize their risks;
- Financial warranties for investors have to be included in the system structure;
- The regulator and antitrust have to be benevolent and work out of the parts, respecting the laws and helping companies to control risk. **[GIT06]**

2.10 Emission control

After the Kyoto Protocol (1997), where nations of the whole world decided to reduce the emissions per 5,2% compared to the value of 1990**,** the EU decided to create the 20-20-20 packet, the target of this agreement is to reduce the emissions of the 20%, increase the power production from renewables of the 20% and increase the energy efficiency of the 20% compared to the value of 1990 before the year 2020.

For these purposes the EU created some energy plans with specific targets for every country and for certain periods, then every single country create an own energy plan declining the targets to regions, provinces, commons and finally single factories.

For the purpose of this job it is not necessary to analyze in detail all this action plans, their targets, their limits and all their features; it is just necessary to understand which are the main pollutants which are necessary to control and the main control systems in order to understand their impact to the company's revenues. **[ChiSos][D.E.23.10.01]**

	SOx (kton)	**NOx (kton)**	**Particulate (kton)**
ITALY	475	990	1159
EU	3850	6519	6510

Table 2.5 Exemple of energy plan: First European energy plan, emission targets to reach until 2010.

[D.E.23.10.01]

The European Union created an emission trading emission, it consists on the possibility to buy and sell certificates. Every company has a an emission saving target to respect, all the units of emission saved give the permission to receive a certificate (which is then taken from the EU and paid), so a company can decide to invest and reduce the emissions by itself or buy the certificates on the market depending on what is more convenient for it. If at the end of the year the company doesn't have all the certificates it needs it will have to pay a fine. **[ChiSos]**

2.11 Main pollutants and pollution containment systems

Particulate

They are liquid or solid particles with variable diameter. They are very dangerous and they mainly attack the respiratory system, the smaller the particles are the deeper they can penetrate in the respiratory system (the biggest ones are stopped in the nose or in the mouth. **[ULS]**

There are many technologies which allow the reduction of particulate emissions:

- **ESP electrostatic precipitator**: it's composed by 2 metal plates, one is negatively electrically charged and the other one is positively electrically charged. A potential difference is applied in order to create an electrostatic flow. The particles electrically charged will be attracted by the plates.

  The particles will be accumulated on the plate, this is a problem because with time the precipitator efficiency will decrease, for this reason it is necessary to provide a system to clean the plates without turning off the precipitator. The system is very easy and it consists in beating the plates with a kind of hammer. The efficiency of this system decreases when the particle size decreases as shown in **figure 2.17**. **[UPD] [SHA09]**

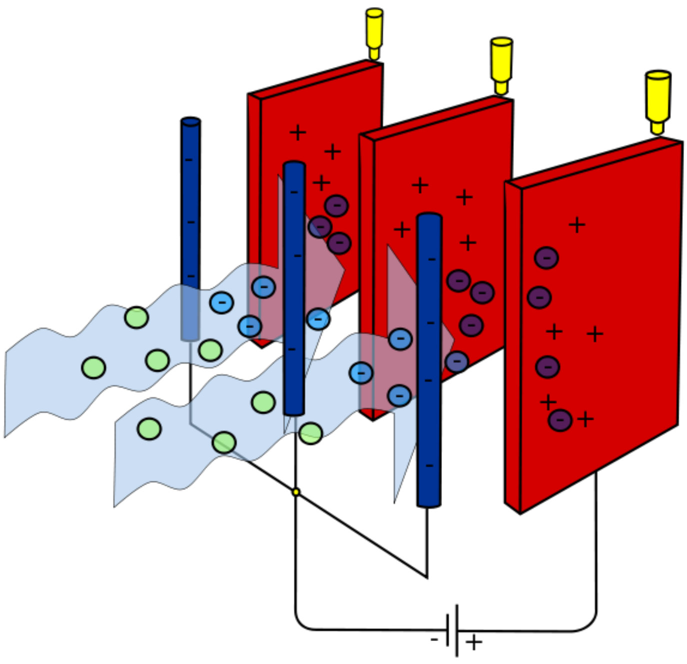


Figure 2.15 Electrostatic precipitator **[SHA09]**

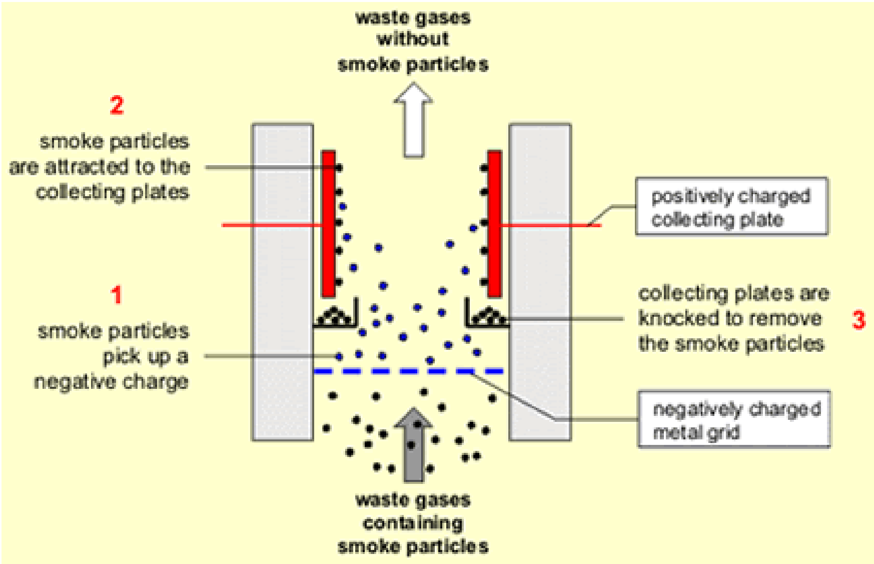


Figure 2.16 Electrostatic precipitator working mechanism **[SHA09]**

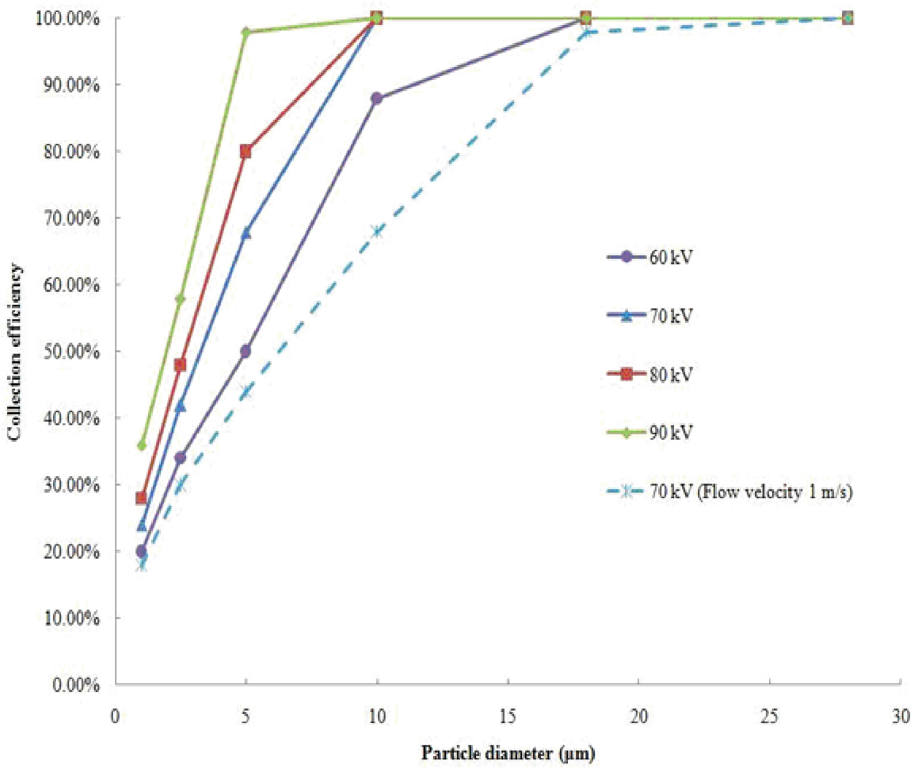


Figure 2.17 Electrostatic precipitator efficiency **[SHA09]**

- **Cyclones:** they use the centrifugal force to separate the particles from the exhaust gas, the particles are deposited to the wall of the machine while the gas continue to run They have high efficiency for particles bigger than 5 μm as shown in **figure 2.19**. They are widely used. **[UPD] [SOU12]**

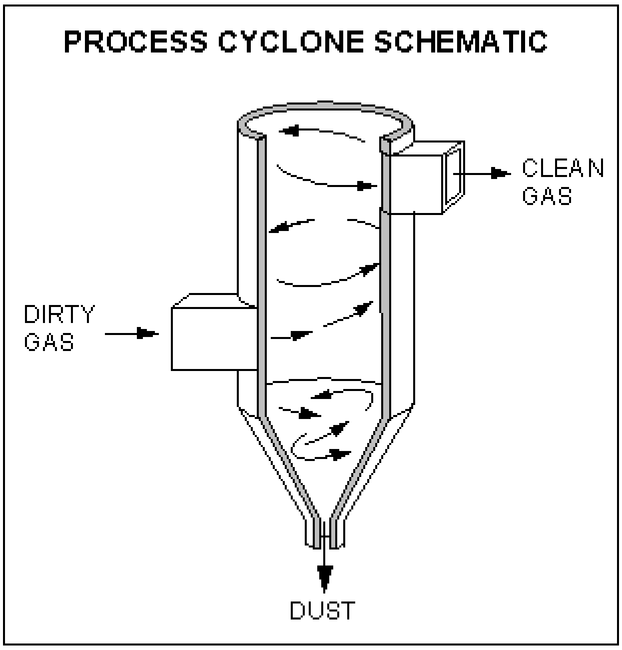


Figure 2.18 Cyclone **[SOU12]**

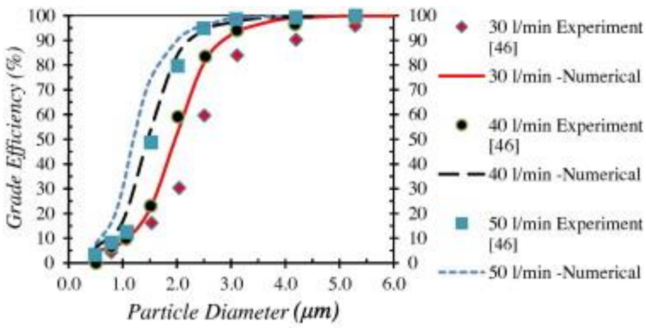


Figure 2.19 Cyclone efficiency depending on the gas speed and on the particle size **[SOU12]**

- **Scrubber and Venturi scrubber:** they consist on spraying water on the exhaust smokes in order to mix the particulate with water, in this way the particles will fall down instead of following the smokes. They always need water to don't stop the process.

The difference between the standard scrubber and the Venturi scrubber is that the second one has a sort of funnel where both water and exhaust smokes are concentrated. This increases the efficiency of the scrubber. **[UPD]**

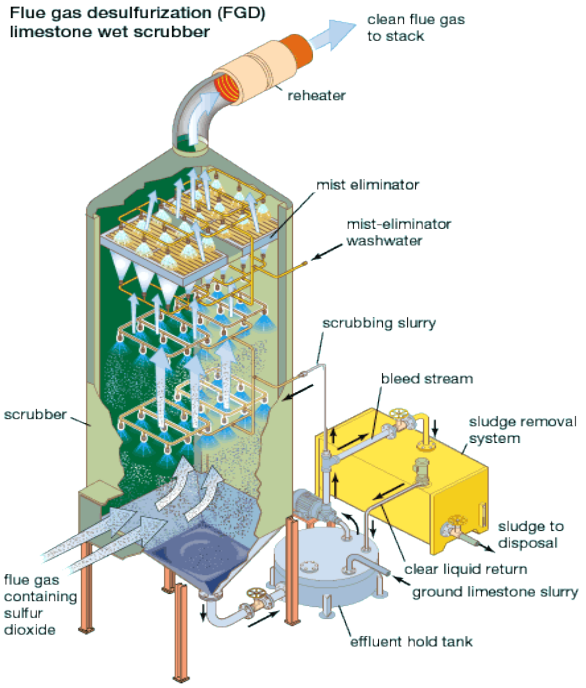


Figure 2.20 Scrubber **[SOU12]**

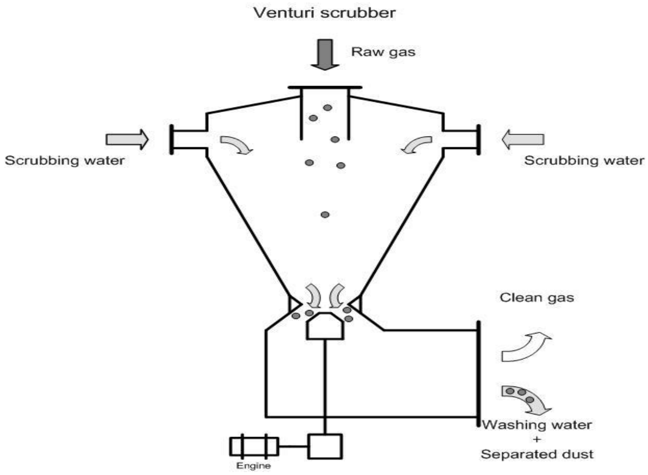


Figure 2.21 Venturi Scrubber **[SOU12]**

- **Sleeve filter:** It’s a filter composed of many texture sleeves (it’s a particular material which is able to resist to temperature over 200 °C).The exhaust gas enter inside this filter and it pass through sleeves. These sleeves have holes which allow gas but not particles to pass through them. Only the particles which are smaller than these holes can pass through the filter. It has a very high efficiency also with small particles. Also for this application it is important to have a cleaning system in order to don’t jam the gas, the way to clean it is very easy and it consists in airflow in the opposite direction of the gas one. One sleeve per time is cleaned in order to don’t stop the production. **[UPD]**

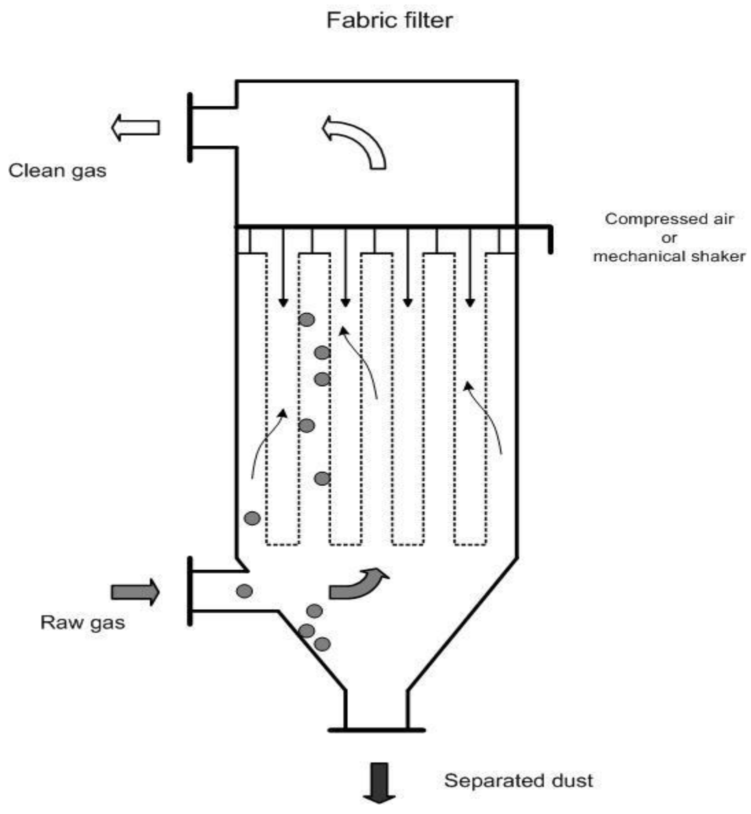


Figure 2.22 Sleeve filter **[SOU12]**

It's possible to use more than one of these applications in series in order to increase the efficiency of the particulate emission control.

	Application field	**Advantages**	**Disadvantages**
Cyclone	Removes big particles, >10μm, efficiency 85%.	Low costs and small size, easy to use.	Low efficiency, risk of corrosion, erosion and jam.
Electrostatic precipitator	Removes particles, >0,0001 μm, efficiency 99%.	High efficiency, big operational range, low operational costs, low load losses.	High investments costs, expensive maintenance, risk of fire.
Sleeve filter	Low dust concentration, >0,5 μm, efficiency 99%.	High efficiency and small size.	High investments costs, high management costs, risk of fire and jam.
Scrubber & Venturi scrubber	>3 μm, efficiency 95%.	High efficiency, low load losses, reduces fire risks.	High management costs, difficult to dispose mud.

Table 2.6 Features of the different particulate reduction technologies.

NOx

Are considered NOx all the chemical components which are composed with nitrogen and oxygen. The most dangerous is the nitrogen dioxide (NO_2) which is very dangerous for the mucosa.

There are 3 main kinds of NOx emission control, in this thesis only the main ones will be treated:

- **Two steps combustion:** the combustion is divided in 2 steps, in the first step the combustion takes place with lack of oxygen in order to limit the production of NOx, in the second step (the probability of NOx production in the second step is much lower) the combustion takes place with an oxygen excess in order to complete the process. This solution has a very low efficiency, around the 30% and also it reduces the efficiency of the heater.
- **Selective non catalytic reduction:** it consists on spraying ammonia directly to the fire. That's because without a catalyst the following chemical reaction needs from 870°C to 1150°C to take place:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$
$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$
$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

  The efficiency of this system is about 70%.
- **Selective catalytic reduction:** in this case the ammonia with the catalyst can be sprayed in the exhaust gases, the reaction can take place at 300-400°C arriving at the efficiency of more than 95%.**[UPD] [CON05] [ULS]**

SOx

For Sox are commonly considered $SO_2$and SO_3.

There are a lot of technologies which can be used to control the SOx emission, they are divided in 3 types: wet, dry and semi-dry.

The most used ones (about the 90% of the total) are the wet ones so we will discuss about these ones only, it is called flue gas desulphurization FGD.

The exhaust gases are treated with water first and with calcium carbonate after, in order to trigger the 2 chemical reactions which are following explained in order to obtain calcium sulfite; finally the oxygen react with it and the result is calcium sulfate (plaster) which will be sold to construction industry. **[UPD] [CON05] [ULS]**

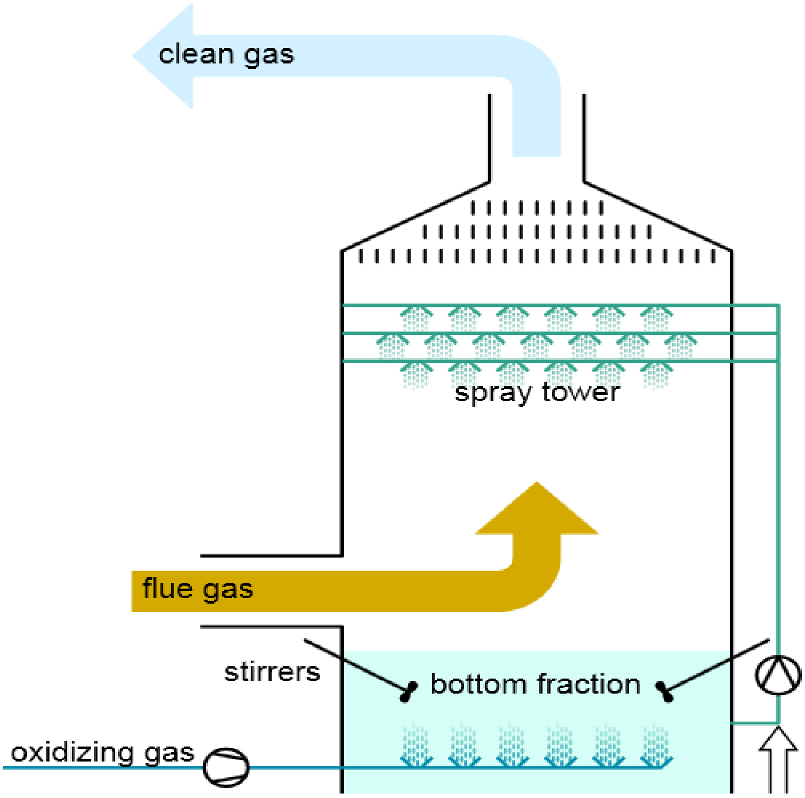


Figure 2.23 Flue gas desulphurization **[SOU12]**

Layout configuration

The layout depends on the position of the SCR, there are 3 main types of configuration:

- **High dust:** In the case of high-dust configuration, the SCR reactor is installed right at the rear of the economizer, and this location becomes the front of the air pre-heater. The biggest benefit of this structure is the fact that there is no separate pre-heating required to insert gas into the SCR reactor. Generally, the inserted gas is 300-430°C. The basic advantage of a high-dust system is the low initial investment cost and the savings in operational costs but the volume is bigger and the catalyzer life is shorter

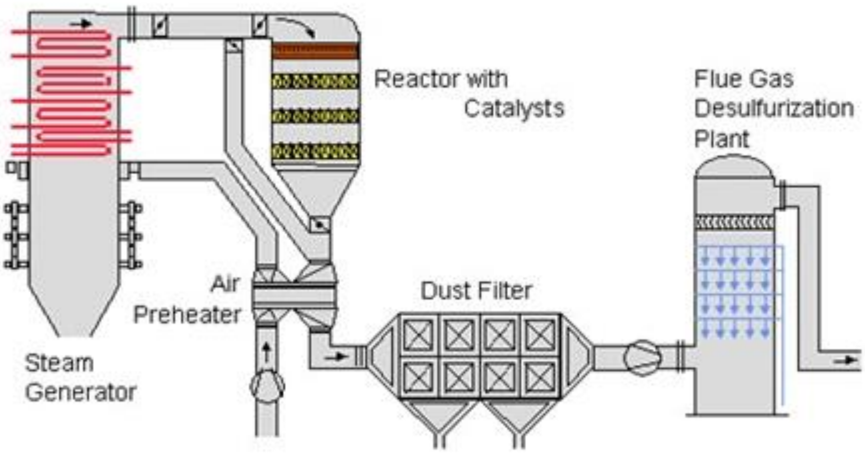


Figure 2.24 High dust configuration. **[SOU12]**

- **Low dust:** In this arrangement, the catalyst is placed in the rear of the electrostatic precipitator or the bag-filter. Since the gas at the rear of the electrostatic precipitator is inserted into the SCR reactor, extremely small particles of dust are inserted; on the other hand, a lot of SO2 is also inserted. Since the temperature of emission gas does not reach the reactive temperature of the NOx Catalyst, in many cases it requires an extra temperature-raising system and also this system needs to treat particulate with high temperature. The volume is smaller than the High dust.

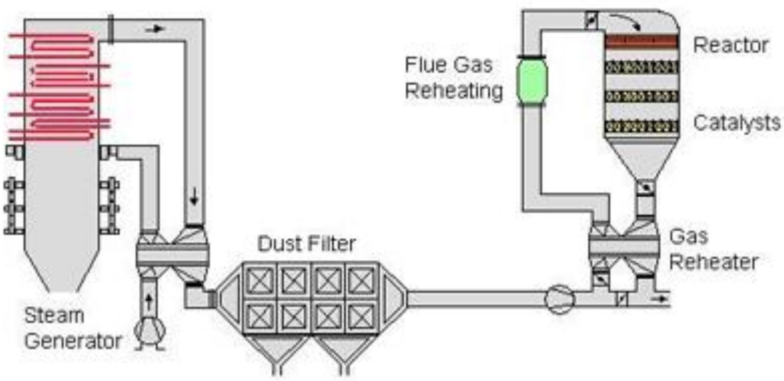


Figure 2.25 Low dust configuration **[CON05]**

- **Tail End:** This structure is widely being applied in Western Europe. The SCR facility is installed at the very rear of other emission gas treatment facilities. Since there is a very small amount of dust or SO2 in the emission gas, exposure of catalyst to catalyst toxin may be prevented. Since the temperature of emission gas does not reach the reactive temperature of the NOx Catalyst, in many cases it requires an extra temperature-raising system. High energy consumption, small volume and best protection for the catalyzer. **[CON05]**

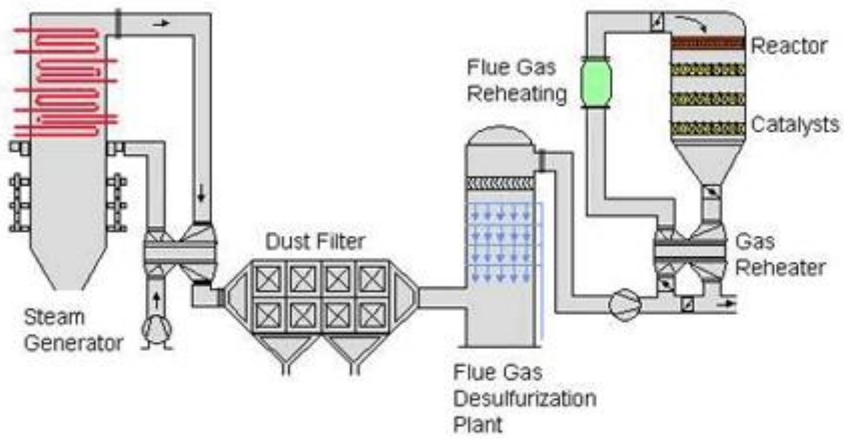


Figure 2.26 Tail end configuration **[CON05]**

CO_2

The carbon dioxide is probably the most important and the most discussed pollutant nowadays as it is considered the main responsible of the greenhouse effect, the way to control the CO_2emission is the Carbon Capture and Storage **CCS**, it consists in capture the CO_2 produced and then transport it and stock it.

The capture of CO_2 is economically achievable only with high concentration of CO_2, there are 3 approaches for the capture:

- Post-combustion separation: it consists on spraying liquid solvents on exhaust gases in order to capture a little percentage of CO_2 (between 3 and 15%);

- Pre-combustion separation: the primary source has to be processed in a reactor with steam and oxygen in order to produce a mixture of carbon monoxide and hydrogen, then in a second reactor the carbon monoxide reacts with and steam in a second reactor in order to obtain CO_2; the result is a mixture of hydrogen and CO_2 which can be captured. This solution is more complex and more expensive but it allows higher efficiencies (between 15% and 60%);
- Oxygen combustion: in this case the combustion takes place with pure oxygen and not with air. In this case the exhausting gases are composed only by CO_2 and steam, the concentration of CO_2 in this case is higher (80%) and the steam is removed cooling the exhaust gas. For this application it is necessary a system which separates oxygen with 90-95% of purity from the air, there are already some of these machines in the market but the sector is still in research.

The choice of the technology depends on the choice of the technology depends on the operational conditions, it is important to know that the CO_2 capture systems need the 10-40% more energy than a normal plant, this obviously reduces the efficiency of the whole plant.

It has been estimated that the production costs increase between 20-80% with a CO_2 capture system, it depends on the type of plant. **[MAN3] [UPD]**

Activity	**Min**	**Max**	**Rrepresentative value**
Emissions without capture [$\frac{Kg_{CO_2}}{kWh}$]	78	174	137
Emissions with capture [$\frac{Kg_{CO_2}}{GJ}$]	7	28	17
% reduction of CO_2 emission per GJ	72	96	86

Plant efficiency with CO_2 capture	52	68	60
% increasing of energy needs	4	22	8
Cost of net CO_2captured [$\frac{USD}{t_{CO_2}}$]	2	56	15

Table 2.7 CO_2 capture costs **[MAN3]**

There are also some formulas to calculate the CO_2captured, CO_2 captured and the Specific Energy Consumption for CO_2avoided **SPECCA**.

The first one is the CO_2captured compared to the case of normal combustion:

$$CCR=\frac{CO_{2,fuel}-CO_{2,emit}}{CO_{2,fuel}}$$

Where:

CCR= CO_2 captured [%];

$CO_{2,fuel}$= CO_2 in case of normal fuel combustion [$\frac{kg}{s}$];

$CO_{2,emit}$=CO_2 emitted with capture system [$\frac{kg}{s}$];

The second one represent the specific emissions avoided compared to reference case:

$$CO_{2,}\text{ avoided} = \frac{E_{ref}-E_{capt}}{E_{ref}}$$

Where:

$CO_{2,}$ avoided [%];

E_{ref}= CO_2 emissions in the plant without capture system;

E_{capt}=CO_2 captured;

The third one identifies the primary energy which necessary to capture the CO_2

$$SPECCA = \frac{HR - HR_{ref}}{E_{ref} - E} = \frac{3600 * (\frac{1}{\eta} - \frac{1}{\eta_{ref}})}{E_{ref} - E}$$

Where:

SPECCA= Specific Energy Consumption for CO_2avoided;

HR= Hours equivalent;

HR_{ref}= Hours equivalent in the plant without capture system;

η= Plant efficiency with capture system;

η_{ref}= Plant efficiency without capture system;

E_{ref}= Emissions without capture system;

E= Emissions with capture system; **[MAN3]**

Finally it is possible to calculate the cost of CO_2 avoided with the following formula:

$$COE_{CO2avoided} = \frac{COE_{catt} - COE_{ref}}{E_{ref} - E_{catt}}$$

Where:

$COE_{CO2avoided}$= Cost of CO_2avoided;

COE_{catt}= Cost of electricity of the plant with capture system;

COE_{ref}= Cost of electricity of the plant without capture system;

E_{catt}= Emission of the plant with capture system;

E_{ref}= Emission of the plant without capture system; **[MAN3]**

2.12. Performance

As for all the production sectors, also for the energy sector it's very important to consider the performances of processes and the efficiency of all components.

The main performances for an energy plant can be resumed as in **figure 4.1**

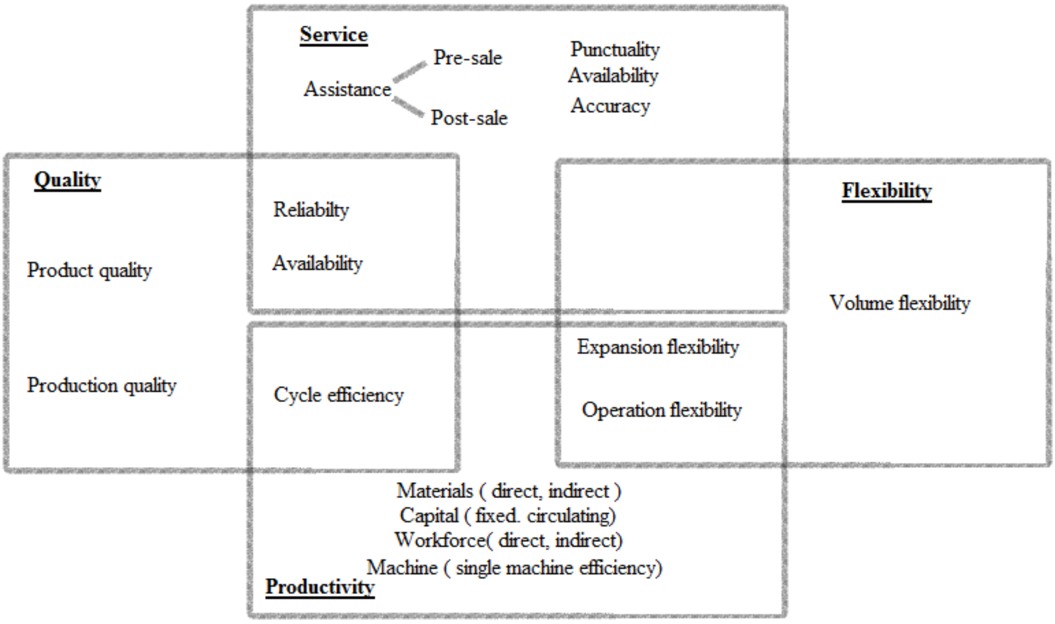


Figure 2.27 Most important performances for the energy sector **[BRA07]**

It is important now to understand the importance of these performances and show some indicators to value them, the indicators have the function to monitor these features in order to have a management tool, useful to create a strategy, value the work of personnel and take decisions. **[BRA07]**

Service

It's very complicated to talk about service in energy business because the energy sale is already a service itself in any case it's possible to understand how the mechanism work and introduce some indicators:

- **Pre-sale and post-sale assistance:** the assistance consists in all those operations which are connected to the customer satisfaction like maintenance especially in case of fails or in case of impossibility to supply energy. Unfortunately it's impossible to create an indicator which can measure the customer satisfaction, for this purpose are usually used surveys or questionnaires.

It's by the way possible to create indicators to control the quality of the assistance interventions:

$$Assist_{Del} = \frac{N_{del}}{N_{tot}}$$

$$Del_{AVE} = \frac{\sum_{i=1}^{n} Del_i}{N_{tot}}$$

$$Rep_{good} = \frac{N_{rep}}{N_{tot}}$$

Where:

$Assist_{Del}$= Percentage of delayed assistance [%];

N_{del}= Number of delayed interventions;

N_{tot}= Total number of interventions;

Del_{AVE}= Average delay time [days];

Del_i= Delay time referred to intervention i [days];

i= index referred to the intervention;

Rep_{good}= Percentage of intervention solved in only one time;

N_{rep}= Number of interventions repaired in only one time;

The choice of the indicator is very important because the people will behave in a different way basing on the indicator which is used to value them.

- **Punctuality, availability and accuracy**: these 3 performances are usually considered separately for traditional manufacturing companies, in the case of energy companies it's nonsense to do it because of the features of electrical energy, the product in fact has to be supplied in real time and the offer has to be exactly the same of the demand in every moment, for these reason it’s nonsense to divide these 3 which will collapse in just one indicator;

- **Reliability:** The reliability of power supply represents how much the company is able to purchase energy to customers without leaving them without it.

This is very important because a lack of energy from the costumer means a lack of production, this has a bad impact to the energy company in 2 ways:

  - **Penalties and fines:** the energy company probably has to pay a penalty because of this lack;
  - **Imagine:** if this happens many times it will negatively impact on the name, brand and reputation of the energy company;

It’s very difficult to find good indicators for the reliability of power supply but the Italian government found 2 very interesting indicators which are useful to monitor this performance:

$$D_{tot} = \sum_{i=0}^{n} D_i$$

$$N = \sum_{i=0}^{n} i$$

Where:

D_{tot}= Total duration of all the periods when energy is not supplied;

D_i= Duration of the single period when energy is not supplied;

i= Index of the period when energy is not supplied;

N= Total number of periods when energy is not supplied;

The Italian government use separate indicators for low voltage, medium voltage and high voltage because in Italy there is a very different behavior for each of this type, of course it depends on the context, it might be not necessary to do create this separation.

From these 2 indicators it is possible to create a new indicator:

$$D_{ave=}\frac{D_{tot}}{N}$$

Where:

$D_{ave=}$ Average duration of the periods when energy is not supplied;

The others are the same as before. **[AZZ11] [BRA07]**

Flexibility

It's first of all very important to say that it is useful to talk about flexibility only in a differential way, it means that it makes sense only to compare 2 or more plants and value which one is the most flexible.

As the energy companies have only one product (or two in case of CPH) the only flexibility it is important to consider is the volume flexibility which is the skill which a plant has to fast change the production volume.

The main problem in the power plants is the turn on, these plants are usually very inertial and they need hours to turn on.

The turn-on time can change a lot between the different types of plants.

Usually the simple gas cycles are the fastest ones while the CPH-combined ones are the slowest ones, that's the why the first ones are used to cover the demand peak and the second ones usually works for 24 hours every day (also because they save primary energy).

The regulation in order to increase or decrease the volume of energy produced (when the plant is already working) is usually not a critical problem because it is done by 3-way valves and decreasing the mass flow of fuel (the first one quickly reduce the production while the second one slowly, they are usually both used depending on the necessity) or increasing the mass flow of the fuel (to increase the production).

As the decreasing is immediate (obviously the efficiency decreases if it is necessary to decrease the production quickly and so using the valves) it's important to know how much time it is necessary to increase the production.

It is possible to create 2 indicators:

$$TO_{ave} = \frac{\sum_{i=1}^{n} TO_i}{n}$$

$$TI_{ave} = \frac{\sum_{i=1}^{m} TI_i}{m}$$

Where:

TO_{ave}= Average turn on time;

TO= Single turn on time;

i= Index;

n=Total number of turn-ons;

m=Total number of production increasing;

TI_{ave}= Average production increasing time;

TI_i=Single production increasing time; **[AZZ11] [BRA07]**

Production

It has been already discussed a lot about production and its importance but it is important to introduce some indicators in order to monitor all the parts of the plant:

- **Machines:** about the machines it is important to define the availability which represents the time when the machine is available compared to the total time when the plant is working. The availability influences the equivalent hours which influence the costs as already explained in the **chapter 2.5.2**

$$A = \frac{T - O - F - PS}{T}$$

Where:

A= Availability;

T= Total time when the plant is opened;

O= Time when the plant doesn’t work because of organizational problems;

F= Failure time (included the time to repair);

PS= Planned time;

For the machines which work continuously it is usually used the following equation:

$$A = \frac{MTBF}{MTBF + MTTR}$$

Where:

MTBF= Mean time between failures;

MTTR= Mean time to repair;

For the energy plants it is also very important to understand the efficiency of the machines which are involved in the energy cycle, that's because the efficiency of every single machine influences the efficiency of the whole cycle.

In order to calculate the efficiency it is necessary to distinguish from machines which absorb energy in order to increase fluid pressure (ex. compressors and pumps) and machines which produce energy (ex. turbines).

For the first type the isentropic efficiency is defined by the following expression:

$$\eta_{iso} = \frac{W_{id}}{W_{re}}$$

Where:

η_{iso}= isentropic efficiency;

W_{id}= Ideal work;

W_{re}= Real work;

For the second type the expression will be exactly the opposite:

$$\eta_{iso} = \frac{W_{re}}{W_{id}}$$

This difference is related to fact that real compressors or pumps waste more energy than the ideal ones while real turbines create less energy than the ideal ones: this is due to hydraulic wastes (wastes of the fluid during is flow), volumetric wastes (wastes related to the different mass flow between the entrance and the exit of the machine) and mechanical wastes (related to frictions inside the machine);

- **Workforce:** about the workforce there is basically no difference from a normal manufacturing plant, the most common indicator to show the workforce efficiency is the following:

$$WE = \frac{h_{EP}}{h_{paid}}$$

Where:

WE= Workforce efficiency;

h_{EP}= Hours of effective production;

h_{paid}= Hours paid;

This indicator shows how good the workforce performs;

- **Materials:** are considered to be all the tools which support the main process. This is because there is only one raw material used for the production which is the fuel. There are a lot of indicators and models which can be used to monitor the materials, the main one is the Kraljc Matrix, in this work it will not be explained as it is not the main target of this project; **[AZZ11][BRA07]**

2.13 Factors which influence the revenue

After the analysis about business, technology and emissions it is possible to individuate the factors which influence the revenue of energy companies.

It is possible to divide these factors into 2 groups: the ones which can’t be influenced directly by the company and the ones which can be influenced directly by the company.

Factors influenced non-directly

In this group are included all those factors which are not decided by the company but by third people, in the energy business these factors are very important, the main ones are:

- **Geo-political factors:** energy companies are strongly influenced by laws and political decisions such as: laws to control emissions or pollution, wars, monopolies, taxes;
- **Raw material price:** as explained in the chapter 2.7, energy companies are directly influenced by the fuel price.
- **Exchange ratio:** as previously explained in chapter 2.7 are influenced by the exchange ratio;

Factors influenced directly

This group is much more interesting from the company's point of view, here we can find all the factors which are determined by the choice of the company:

- **Choice of the location:** this is a very important choice, the company has to choose the best place to build an energy plant basing on many factors:
    - **Geological features of the area;**
    - **Political situation;**
    - **Emission limits and environmental restrictions;**
    - **Taxes;**
    - **NIMBY effect;**
    - **Building costs:** influenced by the workforce cost, material cost, geological structure of the area;
    - **Personnel cost;**
    - **Energy demand and its features;**
    - **Electrical energy price;**
    - **Presence of water in the nearest area:** in order to aliment the condenser, in this choice it is also included the choice of which type of condenser it is better/necessary to use (air, water or evaporative tower);
- **Choice of the size:** another very important choice for the company is the choice of plant size. The top management has to consider the following factors in order to take the right choice:

- ➢ **Energy demand and its features;**
- ➢ **Efficiency:** usually the cycle efficiency increases when the plant size increases;
- ➢ **Corporate budget;**
- ➢ **Debt possibilities;**

- **Choice of the environmental policy:** As explained in chapter 3 the environmental restrictions are extremely important. The tools to contain the emissions are expensive and they need maintenance. The company needs to manage a trade-off between costs of emission controls and cost of emissions.

As shown in **figure 2.28** if the company invests more in emission control systems the emission costs (the cost which the company should pay if it pollutes more than the allowed limit) decrease but the emissions control costs increase. The target of the company is to find the optimal level of investments for these systems.

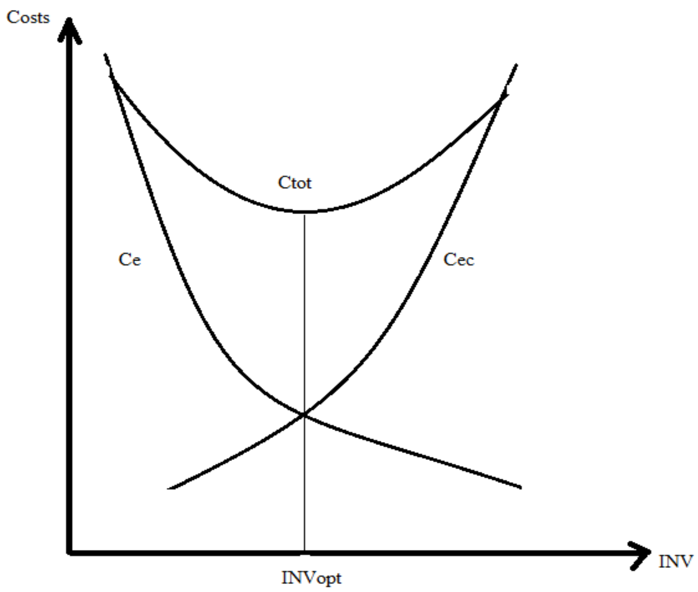


Figure 2.28 Trade-off between emission costs and emission control costs.

- **Choice of the debt structure:** the way to finance the project is extremely important. There are many ways to finance an energy plant, the most important is the **project**

financing. The leverage strongly influences the profitability, it is be impossible to analyze the way to finance an energy project as it is a very wide topic and it is not the target of this project.

It is important to know that the higher the debt is, the lower will be the tax burden as demonstrated by **Modigliani & Miller** in their model; but at the same time if the debt is very high, also the interest ratio will be very high.

It's important to take the right choice in order to have the best compromise between taxes and interest ratio.

- **Choice of the right insurance policy:** useful to control risks and to help the company with social imagine as explained in **chapters 2.8** and **2.9**.

- **Choice of tools and machineries:** it's probably the most important and difficult choice.

Looking at the expressions of the plant power it is possible to understand the impact which every part has on the whole plant:

Power of the simple gas cycle

$$P_{SGC=}\left(\dot{m}_{EG}\,\Delta h_{turb}\,\eta_{org} - \frac{\dot{m}_{air}\,\Delta h_{pump}}{\eta_{mecc}}\right)\eta_{alt} - P_{aux}$$

Where:

$P_{SGC=}$ Simple gas cycle power;

$\dot{m}_{EG}$ = Flow mass of exhaust gases;

Δh_{turb}= Enthalpy variation in the turbine;

η_{org} = Organic efficiency of the turbine;

$\dot{m}_{air}$ = Air flow mass;

Δh_{pump}= Enthalpy variation in the pump;

η_{mecc}= Mechanic efficiency of the pump;

η_{alt}= Efficiency of the alternator;

P_{aux}= Power of auxiliaries;

Power of steam cycle

$$P_{SC} = (\dot{m}_{HP}\Delta h_{turbHP} + \dot{m}_{MP}\Delta h_{turbMP} + \dot{m}_{LP}\Delta h_{turbLP})\eta_{org}\,\eta_{alt} - \frac{\dot{m}_{Pump}\Delta h_{pump}}{\eta_{mecc}} - P_{aux}$$

P_{SC}= Steam cycle power;

$\dot{m}_{HP}$= Flow mass in the high pressure turbine;

$\dot{m}_{MP}$= Flow mass in the medium pressure turbine;

$\dot{m}_{LP}$= Flow mass in the low pressure turbine;

Δh_{turbHP}= Enthalpy variation in the high pressure turbine;

Δh_{turbMP}= Enthalpy variation in the medium pressure turbine;

Δh_{turbLP}= Enthalpy variation in the low pressure turbine;

$\dot{m}_{Pump}$= Flow mass in the high pump;

Combined cycle power:

$$P_{CC} = \left(\dot{m}_{EG}\,\Delta h_{gas-turb}\,\eta_{org.gas.turb} - \frac{\dot{m}_{air}\,\Delta h_{air-pump}}{\eta_{mecc.air.pump}}\right)\eta_{alt} + (\dot{m}_{HP}\Delta h_{turbHP} + \dot{m}_{MP}\Delta h_{turbMP} + \dot{m}_{LP}\Delta h_{turbLP})\eta_{org.steam.turb}\,\eta_{alt} - \frac{\dot{m}_{Steam.Pump}\Delta h_{Steam.Pump}}{\eta_{mecc.steam.pump}} - P_{aux}$$

Where:

P_{CC}= Combined cycle power;

$\dot{m}_{EG}$ = Flow mass of exhaust gases;

$\Delta h_{gas-turb}$= Enthalpy variation in the gas turbine;

$\eta_{org.gas.turb}$ = Organic efficiency of the gas turbine;

$\dot{m}_{air}$ = Air flow mass;

$\Delta h_{air-pump}$= Enthalpy variation in the air pump;

$\eta_{mecc.air.pump}$= Mechanic efficiency of the air pump;

η_{alt}= Efficiency of the alternator;

$\dot{m}_{HP}$= Flow mass in the high pressure steam turbine;

$\dot{m}_{MP}$= Flow mass in the medium pressure steam turbine;

$\dot{m}_{LP}$= Flow mass in the low pressure steam turbine;

Δh_{turbHP}= Enthalpy variation in the high pressure steam turbine;

Δh_{turbMP}= Enthalpy variation in the medium pressure steam turbine;

Δh_{turbLP}= Enthalpy variation in the low pressure steam turbine;

$\eta_{org.steam.turb}$ = Organic efficiency of the steam turbine;

$\dot{m}_{Steam.Pump}$= Mechanic efficiency of the steam pump;

$\Delta h_{Steam.Pump}$= Enthalpy variation in the steam pump;

$\eta_{mecc.steam.pump}$= Mechanic efficiency of the steam pump;

P_{aux}= Power of auxiliaries;

- **Maintenance policy:** this is another very important point. In the energy business the maintenance plays a very important role as explained in chapter 2.5.2. For this reason this work will try to look for the best maintenance policy for business plants.

3. Development of PLM strategies for energy companies

3.1 Functional analysis and FMECA – Reliability principles for energy companies

FMECA (Failure Mode, Effect and Criticality Analysis) is a very useful model in order to choose the best maintenance policy and minimize LCC.

It was proposed and developed for the reliable design of aerospace applications and other products with high risk for human life, then its application has been extended to define maintenance policies.

FMECA is a tool which applies the approach “forward”, for this reason it is necessary to have a deep knowledge of the process or of the tool the model is applied for. A very important role is played by all components, which must be identified and detailed.

For every component it is necessary to identify the manufacturing phases, all the possible defects or failures and their effect to the system.

Finally the FMECA is completed with an evaluation of criticality of every defect/failure.

FMECA has to be done from the first phases in order to influence all the choices which allows to analyze products in a more complete and precise way.

It is based on the analysis of possible failures, their consequences and causes by which are generated, for this reason it allows to choose the best maintenance policies and to plan maintenance identifying the necessary resources (competences, structures, spare parts, tools exc.).

FMECA finally allows to find critical points of products.

The analysis is done in 4 steps:

- Identify all possible defects or failures of the system;
- For every defect identify the possible causes;
- For every defect identify the possible effects;
- For every effect identify the possible way to reduce them;

The criticality is evaluated with a Risk Priority Index **RPI**

RPI=P*S*D

P= Probability of failure;

S= Severity of effects;

D= Detection easiness;

After these first steps it is necessary to define a score scale of these 3 parameters. **[TER11]**

Alla Brom professor of MGTU im Baumana applied FMECA model to science-intensive equipment.

The analysis is done in some steps:

- First of all it is necessary to identify all the components of the equipment which are relevant for the study, usually it is better to use graphs and charts in order to be easier to read;
- At this point it is necessary to identify all the basic functions of the equipment. Starting from the most aggregated and finishing with the most detailed ones;
- Associate to every function the physical element which provide that function;
- Identify all the possible failures;
- Define a scale of occurrence probability and criticality level of failures, for gas turbines are usually used the standards in **table 3.1 and 3.2**;

Level of failure probability	Description
A	Frequent failure: it occurs more than 20% of the plant working time
B	Probable failure: it occurs between 10% and 20% of the plant working time
C	Possible failure: it occurs between 1% and 10% of the plant working time
D	Rare failure: it occurs between 0,1% and 1% of the plant working time
E	Unlikely failure: it occurs less than 0,1% of the plant working time

Table 3.1 Levels of failure probability **[VLA12]**

Criticality level	Description
I	Catastrophic failure: it can cause equipment death or destruction.
II	Critical failure: It can cause serious damages to the equipment.
III	Medium failure: It can cause medium sized damages to the equipment

IV	Border line failure: It can cause minor priority injuries or damages to the equipment
V	Slight failure: does not cause injury, not inflicting damage and does not affect execution of the mission, but leading to the need for unscheduled maintenance or minor repairs the final product

Table 3..2 Criticality level of failures **[VLA12]**

- For all of them identify the criticality of their impact and the probability of occurrence;
- W it is possible to create a matrix combining occurrence probability and criticality level of failures in order to choose the best maintenance strategies for all groups, as shown in **table 3.3**;

	Criticality level				
Level of failure probability	V	IV	III	II	I
A					
B					
C					
D					
E					

Table 3.3 Matrix failure level- criticality level **[VLA12]**

It is possible to notice 3 areas, the darkest one is the most critical one as in this area are located the most probable failures with the most critical effects. Usually it is necessary to choose a maintenance strategy based on technical condition or a planned one in case the first one is too expensive or impossible. In the white area are located the failures with low criticality and low probability of occurrence, for these elements it is usually used a failure-based strategy (the parts are replaced only in case of failure). In the middle area it is possible to use a mixed, planned or a based-on-condition strategy depending on the situation.

It is also possible to use another tool which is less precise but easier to use. It consists in 3 criticality levels, every element has its criticality level and the maintenance policy is chosen basing to the technical characteristics of the product and its criticality. In table 3.4 is shown the table with the maintenance policy usually used for every criticality level **[BRO08] [BRO09] [BRO10].**

Elements, Parts	Category of criticality	Maintenance based on technical conditions	Planned Maintenance	Repair when failure occur
	A Active, responsible of basic-critical performances. A stop of this element of involves a decrease of safety until a critical level, leads to significant losses of efficiency and power capacity. It involves full equipment stop or destruction of the product.	X		
	B Active, supports primary production (or primary critical parts). A stop in this element reduces production, reduce safety until a potentially dangerous level or can require other actions (switching, change of work regime, turn on reserve equipment.	X	X	
	C Non-core asset Останов этого узла практически никак не			

	отразится на основном производстве или снижении безопасности и надежности изделия. A stop of this element basically doesn’t have any effect in the primary production or in the product reliability.			X

Table 3.4 Table of criticality levels and maintenance policies **[BRO10]**

3.2 Strategy of utilization and maintenance of energy equipment

Talking about LCC applied to energy systems it’s a common mistake to consider only energy producers as actors which influence the LCC, because the role played by energy equipment suppliers is actually very important and critical.

For this reason it is extremely important to consider also the point of view of energy machines producers. We can so define 2 main actors:

- **Energy producers:** they are the users of energy equipment. For them LCC is useful to reduce equipment exploitation costs, O&M costs keeping an high level of performances;
- **Energy equipment producers:** they are considered as producers and suppliers of energy equipment;

Suppliers of energy equipment

The 2 actors are very related to each other, in fact it is impossible to find an optimal LCC solution for the energy company if its supplier doesn’t pursue any LCC policy. Not considering the supplier is nowadays one of the main mistakes which occur in Energy LCC.

For these reasons it’s important to follow some rules:

- The company should introduce PLM and LCC tools and models which allow to increase reliability, maintainability, manufacturability and product attractiveness in the market and consequently allow to achieve bigger sales volume and to improve economic indicators;

- The company has to offer appropriate and not expensive solutions to potential clients concerning the exploitation and maintenance of the equipment they sell, including a rational system of spare parts in order to allow their costumers to adopt a correct maintenance policy and efficient replacement of broken parts;
- If the main product has a long life and composed by different parts which have a substantial shorter life (which is very common in energy business) and the company produce these spare parts (or outsources this activity but still can supply them to their costumers), than the company should also produce (or anyway supply) the tools which allow their clients to perform all the maintenance activities;

At this point, if the company respect these 3 rules it is possible to calculate their incomes in a very simple way.

The model has 4 main hypotheses:

- The discount ratio is not considered;
- The tools to change which are used to change broken parts are not considered;
- The life of equipment and spare parts are deterministic and known;
- The time which is necessary to produce the equipment is deterministic and known;

The following quantities are considered:

Leq= Life of the final product (equipment) which the company sells [Years];

Nsp_i= Number of spare parts contained in the final product [#];

Lsp_i= Life of spare parts [Years];

Psp_i=Average price of spare parts [Rubles];

K= The amount of different kinds of spare parts [#];

t_{eq}= Time which is necessary to produce one unit of final product (equipment) [Years];

N_{eq}= Total units of final product (equipment) which are produced every year [$\frac{\#}{years}$];

Departing from these data it’s possible to calculate the following quantities:

- Zsp_i= Number of spare parts of “i” type which are necessary during the whole life of the equipment [#];

$$Zsp_i = \frac{Leq}{Lsp_i}$$

- I= Total incomes from the sales of final products (equipment) [Rubles];

$$I = \sum_{i=1}^{K} Zsp_i \, Nsp_i Psp_i = Leq \sum_{i=1}^{K} \frac{Nsp_i Psp_i}{Lsp_i}$$

- I_{year}= Total income in one year [Rubles];

$$I_{year} = \frac{I}{Leq} = \sum_{i=1}^{K} \frac{Nsp_i Psp_i}{Lsp_i}$$

- If it's considered that the production of final products is done for a limited time T_{prod} [Years] (because after that the product will be obsolete and will be replaced with the launch of a new product) we can calculate the time in which there are costumers which are using the final products T_{work}

$$T_{work} = T_{prod} + Leq$$

- At this point it's possible to find the average number of final products used every year N_{ave} [$\frac{\#}{years}$];

$$N_{ave} = \frac{N_{eq} T_{prod} Leq}{T_{prod} + Leq}$$

- It's finally possible to calculate incomes coming from the spare parts I_{sp}[Rubles];

$$I_{sp} = N_{ave} I_{year} = \frac{N_{eq} T_{prod} Leq}{T_{prod} + Leq} \sum_{i=1}^{K} \frac{Nsp_i Psp_i}{Lsp_i}$$

Users of energy equipment: Energy companies

As said above the LCC for energy companies is declined into the choice of the best O&M choice in order to get the best trade-off between costs and performance.

It is possible to classify different maintenance strategies:

- **Planned maintenance:** it consists in all those maintenance operations which are planned in advance (there are many types, the difference is the frequency and work-volume), capital maintenance is included in this group;
- **Maintenance based on technical conditions:** the purpose of the maintenance is determined only by the technical conditions of the equipment. The repair-work is done only if the values which are controlled pass some decided limits;
- **Mixed strategies:** there is a standard frequency of maintenance which is decided in advance but the work-volume is done basing on the present conditions of the equipment;
- **Unplanned repairs:** repairs are done only in case of failure.

The equipment organization is usually independent from the strategy chosen, in case of mixed strategy or condition-based strategy there will be a big effort to monitor constantly the equipment conditions.

New Russian handbooks suggest, for power equipment, a mixed strategy. Repair-works based on conditions are recommended for spare parts of the main equipment and for auxiliary machines, while planned repair-works are assigned only to the most critical applications; unplanned repairs are assigned only to the parts with very low-value and to non-critical equipment.

The usage of control systems allows in some case to use condition-based strategies also for main equipment.

In case of new equipment it's cheaper to use a condition-based strategy than a planned strategy as it will be useless to loose time controlling a new machine (which maybe requires a stop in the production), at the same time if there is no control an accidental stop might occur.

In the non-stop energy production machines which are not redundant are only the biggest and most expensive machines, the other equipment, which are still important but not so expensive are usually duplicated. This redundancy is done in order to guarantee a higher level of availability to the main equipment which works non-stop (avoid stops caused by failures). In this case the duplicated machines are repaired using an unplanned or condition-based strategy.

The choice of the right strategy is related to some factors, if the equipment has a high level of:

- Criticality;
- Complexity;
- Uniqueness;
- Level of control by monitor systems;
- Costs;

than it will be better to choose a mixed or a condition-based strategy.

Anyway it is always necessary to value every single case.

Recent studies showed that capital repair-works and complex overhauls, as well as complex equipment installations, can be done in an appropriate way only by specialized companies.

Finally it is important to say that maintenance is not the core business of energy companies so in the recent years they usually outsource this operation.

3.3 LCC calculation in the stage of equipment utilization

In general it is possible to divide **O&M costs** into:

$$C_{O\&M} = C_{O\&M}^{pl} + C_{O\&M}^{un}$$

Where:

$C_{O\&M}$= Total O&M cost [Rubles];

$C_{O\&M}^{pl}$= Cost of planned O&M [Rubles];

$C_{O\&M}^{un}$=Cost of unplanned O&M [Rubles];

Are considered as unplanned O&M all those operation related to sudden failures or anyway to maintenance operations which were not planned in advance.

The planned O&M cost of the year "t" are calculated in the following way:

$$C_{O\&M}^{pl}(t) = \sum_{i=0}^{t} \sum_{j=1}^{K_i} N_{O\&M,j,i} C_{O\&M,j,i} D_i$$

Where:

$C_{O\&M}^{pl}(t)$= Planned O&M costs of the year "t" [Rubles];

j= type of O&M work;

i= year index;

$N_{O\&M,j,i}$= Number of operation of "j" type during the year "i" [#];

$C_{O\&M,j,i}$=Cost of the single repairs of "j" type during the year "i" [$\frac{Rubles}{repair-work}$];

D_i= Discount ratio of the year "i";

K_i=Number of O&M types planned for the year "i";

And the $C_{O\&M,j,i}$is calculated with the following formula:

$$C_{O\&M,j} = T_j C_{AVE,j} + C_{mat}$$

Where:

T_j= Hours necessary to complete the job "j" [hours];

$C_{AVE,j}$= Average hourly costs for the job "j" [$\frac{Rubles}{Hour}$];

C_{mat}= Average costs of material and spare parts for the job "j" [Rubles];

In this case **capital repairs** are not included in this formula, they are calculated in the following way:

$$C_{CR} = \sum_{i=0}^{n} (P_{CR} + 2C_{TR})\, D_i$$

Where:

C_{CR}= Total cost of capital repairs [Rubles];

P_{CR}=Price of a single capital repairs [Rubles];

D_i= Discount ratio of the year "i";

i= year index;

This model considers all the situations, if the repair is done by the company (or by a specialized company but without moving the equipment) the C_{TR} will be zero.

P_{CR} can be the price which the specialized company asks for this job or the costs which occurs to the energy company if it repairs the equipment by itself.

Then again it is possible to calculate the **cost of decommissioning (disposal):**

$$C_{DIS} = (P_{DEC} - V_{REZ} + C_{TR})D_t$$

Where:

C_{DIS}= Total cost of disposal/decommissioning [Rubles];

P_{DEC}= Price of decommissioning [Rubles];

V_{REZ}= Residual value of the item [Rubles];

C_{TR}= Transport cost [Rubles];

D_t= Discount ratio of the last year of the life of the equipment;

This model take in consideration all the circumstances: in Russia it's necessary to pay for equipment decommissioning but the company which do the decommissioning must give the money back to the company which is dismantling its product, the amount of money as to be exactly the same of the value of reusable parts contained in the equipment; obviously this value can be zero **[OOO12]**.
In other parts of the world decommissioning companies pay for used equipment, in this case the term P_{DEC} can be negative.
It might occur also the case where the whole term C_{DEC} is negative, in this case the company which is dismantling its equipment is earning money instead of loosing them; but of course this is a very rare case.
Finally we can calculate the LCC of the equipment as:

$$LCC = C_{buy} + C_{use} + C_{O\&M} + C_{CR} + C_{DIS}$$

Where:
LCC= Life cycle cost [Rubles];
C_{buy}=Price of the equipment when the company buys it [Rubles];
$C_{O\&M}$= Total O&M cost [Rubles];
C_{CR}= Total cost of capital repair-works [Rubles];
C_{DIS}= Total cost of disposal [Rubles];

In this case it's not specified how the $C_{use}$is calculated because it's very specific for every kind of equipment, so the formula strictly depends on what machine we are talking about, also the C_{buy} here is considered as a single amount of money at the beginning of the equipment's life. It's ot always like that, in fact it might happen that that the expenses are spread during some years, in this case the C_{buy} is calculated as following:

$$C_{buy} = \sum_{i=0}^{t} C_{buy,i}\, D_i$$

Where:

$C_{buy,i}$= Amount of money used to pay part of the equipment during the year “i” [Rubles];

D_i= Discount ratio of the year “i”;

t= Last year of equipment’s life;

3.3.1 Improvement of the model: Introduction of Opportunity Costs

Thinking about how electrical energy production works it’s not hard to understand that a stop in the gas turbine implies immediately a loss in the revenues, this is related to the fact that electrical energy has to be produced in the same moment when its demand occurs.

The introduction of Opportunity Costs allows to quantify exactly these losses and, most important, allows, in case it is necessary to choose between different maintenance policy, to take the choice which really minimize the LCC.

The opportunity cost of a good or of a process is what we are willing to renounce in order to get or do that ware or project **[SOL10].**

In this case the opportunity cost of maintenance is the lost sale in the energy market, in order to do maintenance it is necessary (in some cases) to stop the energy production; as the electrical energy has to be produced at the same time when demand occurs.

Opportunity costs are given from the formula:

$$C_{OP} = (p_{EE} - CV) * P * h_{stop}$$

Where:

C_{OP}= Opportunity costs [Rubles];

p_{EE}= Price of electrical energy [$\frac{Rubles}{kWh}$];

CV= Variable costs [$\frac{Rubles}{kWh}$];

P= Effective electrical power produced [kWh];

h_{stop}= Number of hours in which the gas turbine doesn't produce electrical energy [h];

Finally the opportunity costs are summed to the LCC, as shown in the next formula:

$$LCC = C_{buy} + C_{use} + C_{O\&M} + C_{CR} + C_{DIS} + C_{OP}$$

Where:

LCC= Life cycle cost [Rubles];

C_{buy}=Price of the equipment when the company buys it [Rubles];

$C_{O\&M}$= Total O&M cost [Rubles];

C_{CR}= Total cost of capital repair-works [Rubles];

C_{DIS}= Total cost of disposal/decommissioning [Rubles];

C_{OP}= Opportunity costs [Rubles];

To understand this concept better let's take for example 2 maintenance strategies, strategy A and strategy B. Calculating the life cycle costing in the traditional way (without considering opportunity costs) the output is that strategy A is cheaper than strategy B, let's say for example that LCC_A=1.500.000.000 rubles and LCC_B=2.000.000.000 rubles. But the first strategy needs to stop the production for 40.000 hours during the whole lifecycle while the second one only for 30.000 hours, let's assume that the average cost of electrical energy production is 2000 $\frac{Rubles}{MWh}$,the turbines produces 50 MW and the price of electrical energy in the market is 6000 $\frac{Rubles}{MWh}$.

LCC which includes opportunities costs shows the following results:

$$LCC_A^{OC} = LCC_A + (6000 - 2000) * 50 * 40.000 = \text{ 9.500.000.000 rubles}$$

$$LCC_B^{OC} = LCC_B + (6000 - 2000) * 50 * 30.000 = \text{8.000.000.000 rubles}$$

The problem of opportunity costs in energy management is that both production costs and price of electrical energy are not fixed but always changed so it is hard to have a precise esteem of them as it's not possible to know in advance when all stops take place.

Opportunity costs have very important implications.

First of all it is possible to notice that it is obviously cheaper for the company to make repairs when opportunity costs are lower, this means that the quantity $\left(P_{EE} - C_{prod}\right)$ should be as low as possible, thus it is possible to work with these 2 quantities; the company can decide to make maintenance when the price of electricity is very low or when the cost or production is very high (or both of them at the same time) or anyway any mix of these 2 quantities which make the opportunity costs high. This point is much more relevant in Italy or Europe than in Russia as the variable costs are much higher (this is mostly related to the cost of natural gas); anyway if the company for some reasons knows that opportunities costs are going to be lower, than it can decide to plan maintenance exactly in that period (some examples can be to make repairs during the night because the electricity cost is lower or during the winter because the price of natural gas is higher). It's necessary anyway to keep in mind that this is true only if all the other quantities don't change, in fact doing repair works during the night might be more expensive as the personnel cost might be higher and doing maintenance during the winter might be bad for the company's image as in winter the energy requests is higher than in summer with high peaks, customers might be disappointed if they don't receive all the energy they need.**[GIT06]**

3.4 Reliability indicators of equipment

In general it is possible to identify five general KPIs for production processes (safety, efficiency, quality, production plan tracking and employees' issues) which are proposed to enable the comparison between short/medium term production strategy and production process management targets. **[ZHA12]**

An interesting model has been developed by A. Rakar, S. Zorzut, and V. Jovan. **[RAK04].** It identifies KPIs in a general manufacturing process.

It's an 8-stepiterative model for deriving KPIs of production processes as shown in **figure 3.1**. When defining production goals and objectives (first step), all key aspects of the organization should be considered and included. In the second step, it is recommended to use many indicators to reflect production goals and efficiency.

Additional and production-specific indicators should be considered when selecting indicators for implementation in step 3. The purpose of setting targets (Step 4) is to ensure the continuous improvement of production processes. New targets should be set once old targets have been reached. Step 5 (the most time consuming) includes the implementation of all necessary functions for representation of indicators.

Periodic communication and evaluation of results is a necessity (Step 6). In addition, it is necessary to establish a system to evaluate, interpret and act on results regularly (Step 7). Lastly, unnecessary indicators should be eliminated and the introduction of new indicators should be considered (Step 8) **[RAK04]**.

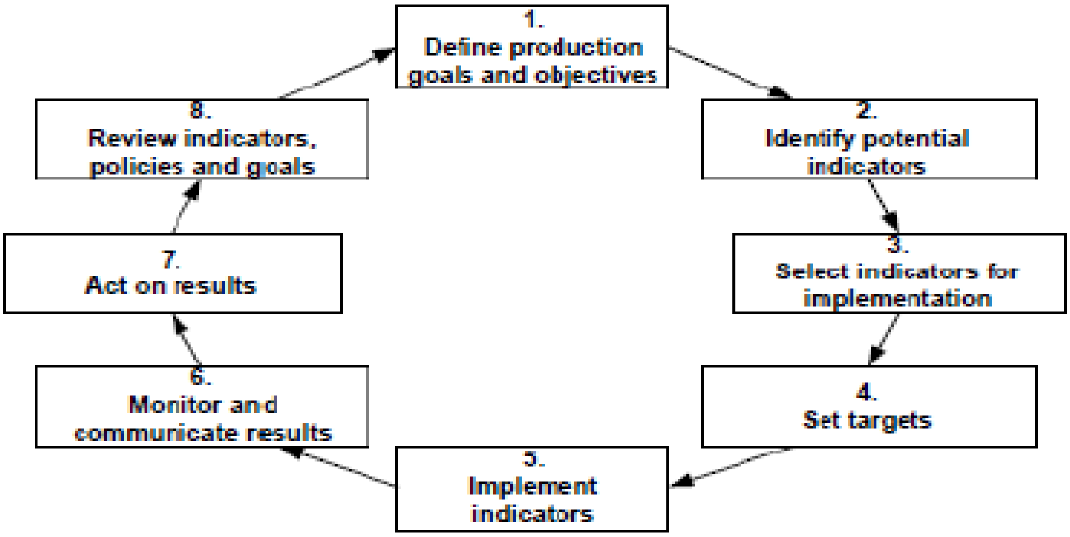


Figure 3.1 8 steps iterative model for design of production KPIs. **[ZHA12]**

Useful KPIs for maintenance

The work done by Maintenance needs to support the business aims and operating strategy. The ideal way to show that is to have maintenance performance clearly linked to the reasons your company is in business. In **Figure 3.2**, the pyramid of objectives, and **Figure 3.3**, the objectives cascade, you can see how KPIs are matched to business objectives and how maintenance and reliability activities cascade from the hierarchy of business purpose and aims1.

Developing useful maintenance KPIs starts by creating KPI pathways from top to bottom of the organization in order connect activities across the operation together with a corporate purpose. Note that the KPI pathways are not created top-down, but the corporate goals are achieved bottom-up. Operational success actually starts on the shop floor by doing those causes that bring success.

Once there is a clear link between business goals and the maintenance activities needed to achieve them everyone can see the benefits that maintenance brings to the business. With interlinked, cascading objectives connecting the business together from top to bottom you can use KPIs to measure and check if they are being achieved. **[LIFET]**

KPIs requirements and most common mistakes

A warning often heard about KPIs is to select those with outcomes that can be controlled by the group or persons responsible for meeting them. Trying to produce results that are not possible to be influenced there will be much frustration and running-in-circles. You need measures that are relevant to what Maintenance does each day and which Maintenance can mostly control.

MTBF is affected by original equipment manufacturing quality, by capital project design selection, by the quality and accuracy of initial installation, by the severity of operating duty, by the quality of operator practices, by the maintenance activities performed or not performed when due, by the quality of parts storage and by maintenance workmanship. A KPI that shows MTBF is not greatly under Maintenance control because of the extent of life cycle influences that Maintenance has no way of affecting. For a company to greatly improve the MTBF of its equipment the whole life-cycle needs to be addressed and not only its maintenance performance. If Maintenance is charged with improving MTBF it’s necessary to develop a company-wide training scheme to teach people at each phase of the life cycle what to do to improve reliability, and follow that with a business-wide project to change business processes to those that produce higher reliability.

Many companies only measure maintenance performance with historic indicators. A maintenance performance KPI that appears in a monthly report delivered mid-month is already six weeks out of date for the first week. Historic information is interesting, but feedback control means a lot of time passes before effects are observed and you can act in response. Useful and relevant maintenance performance indicators are those that drive the actions and behavior needed to meet the goals set at the lowest level in **figure 3.3**. If we can do the cause of high reliability well it automatically follows that we will get a good operating effect that feeds into the corporate goals.

It's also necessary to have KPIs set below the site measure level to confirm the right causes are being done to produce equipment reliability and operating risk reduction.

The types of maintenance KPIs to develop which are useful to the business are those that:

- Identify what are causing your equipment failures (measure the influence of life cycle factors);
- Direct what Maintenance is doing with its time and resources (measure effectiveness and efficiency of the Maintenance Group);
- Identify if Maintenance is removing the causes of failure (measure the reliability improvement and operating risk reduction results of the maintenance effort);
- Drive the business benefits delivered by Maintenance (measure the business value contribution of Maintenance); **[LIFET]**

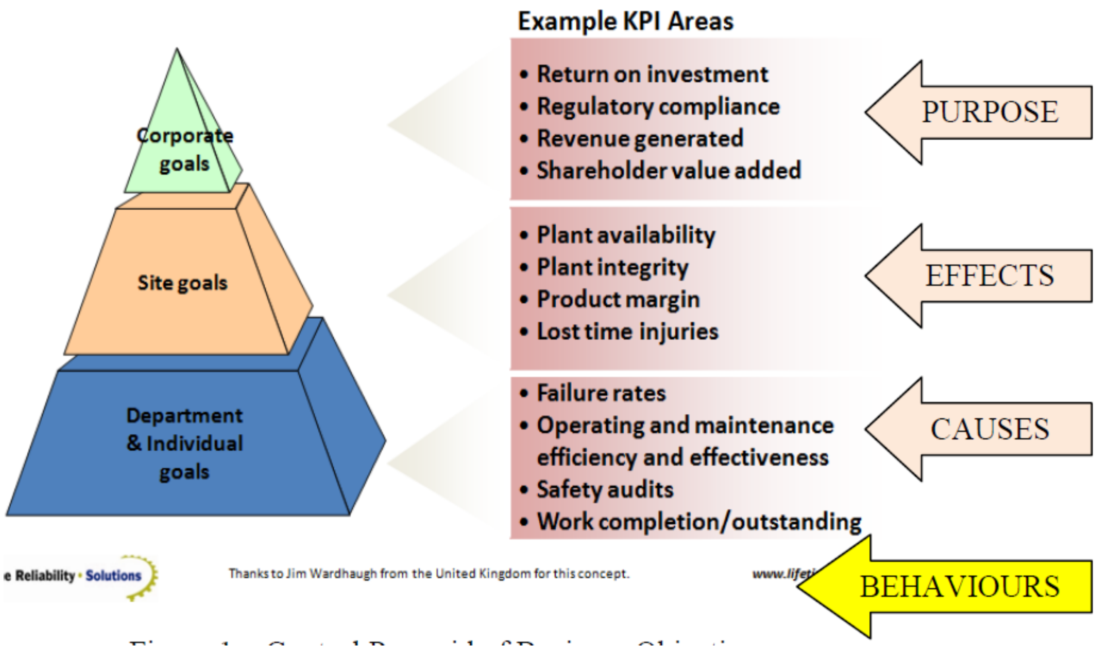


Figure 3.2 Control pyramid of business objectives **[LIFET]**

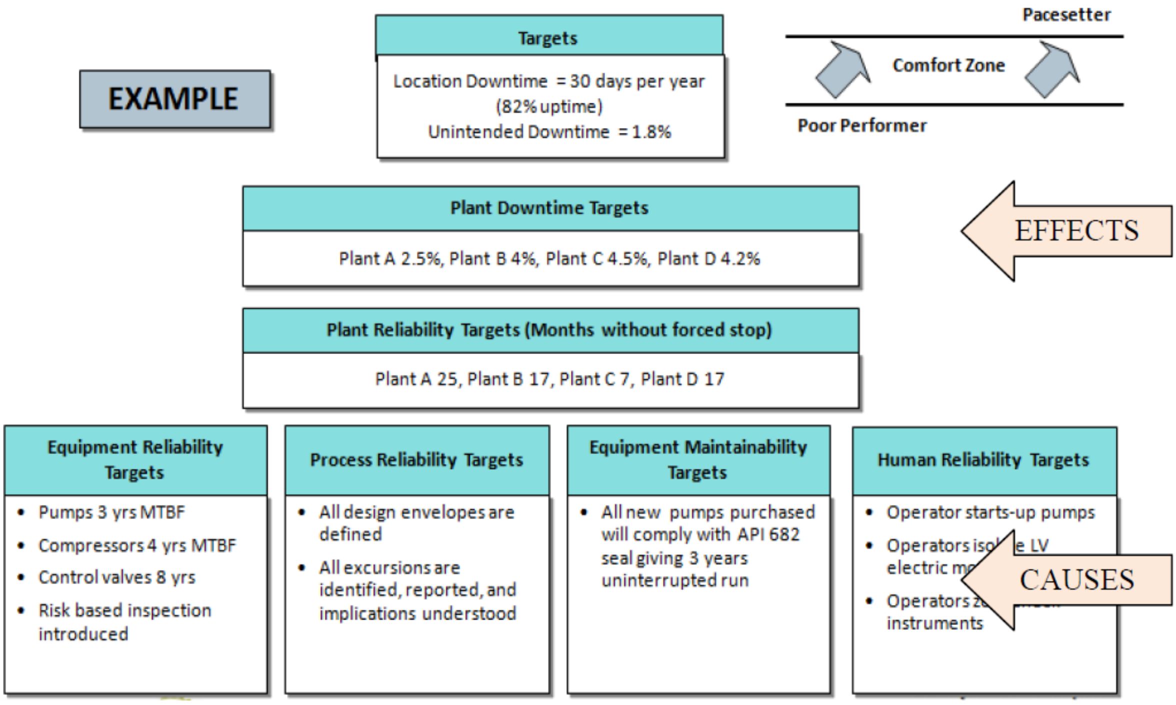


Figure 3.3 Cascaded objectives to achieve business purposes **[LIFET]**

Measure Where Equipment Problems Comes From

A useful maintenance KPI to collect and present is why failures are arising. Today‘s failures have root causes in the past and across several departments. Collecting the causes of repairs under separate life cycle categories lets you identify where to focus reliability improvement efforts.

The categories initially start with broad coverage such as manufacturing defects, production process causes, materials selection causes, equipment installation factors, human error causes, vendor-produced causes, procurement errors, storage failure, poor quality workmanship, etc. The aim is to find-out why people are doing repairs and what can be done to remove the causes of those repairs.

This KPI requires assessing each corrective and breakdown work order and allocating it to a suitable life cycle category. Typically a well experienced maintenance engineer or maintenance planner would investigate the failure and identify the categories that influenced the failures. A pie chart or bar chart of work orders per category each month would be a good way to show this KPI.

As time goes by and data accumulates you develop additional categories within the major categories to further target the actual factors contributing to the repairs and failures. This KPI justifies efforts to eliminate root causes of failure. **[LIFET]**

Measure What Maintenance is doing with Its Time and Resources

The sorts of KPIs in this category are those that identify where Maintenance allocates their time, people and money each month. Unfortunately Maintenance is often the "tail of the dog" it is an afterthought. If Maintenance has no focus on delivering business objectives Maintenance ends up doing anything and everything to keep the operation running. Over the centuries studies demonstrated that successful maintenance is not about fixing things; it is about not having to fix things. When done well Maintenance delivers reliability and lower risks that liberate fortunes of expenditure year-after-year.

The secret is not to focus on doing maintenance; rather focus on creating reliability and removing operating risk. Maintenance has the duty to stop problems starting and where there are problems they are responsible to remove them so that reliability and risk reduction are produced. It's only need to measure how much effort is being made in the company today to improve it and make it a better place tomorrow to predict its future. If KPI Maintenance on the factors listed below and they are not a significant use of its time and resources then it is easy to predict the future of operation, it will be the same as it is today and highly likely to get worse.

• Maintenance work orders spent on improving equipment
• Maintenance time and effort spent removing breakdown causes
• Maintenance time and effort spent improving maintenance procedures
• Maintenance time and effort spent improving maintainer skills/knowledge
• Maintenance time and effort spent reducing operating problems
• Time spent removing wasted effort and cost from maintenance processes
• Efforts spent improving stores management processes and stored parts reliability
• Maintenance work orders spent improving safety

Efficient maintenance is only partly about having the smallest maintenance crew. It is mostly about having the least equipment failures because the equipment is properly maintained. Efficient maintenance means doing high quality work right-first-time. In a reactive maintenance business maintainers average about two hours of tool time work a day per eight hour shift. In a highly planned and organized maintenance operation they average four hours tool time per eight hour shift. In a world-class, reliability-driven business the maintainers spend most of their time designing and doing production productivity improvements on equipment and removing maintenance costs. When people have more engineering knowledge, use precision skills, create standardized work management processes and build supportive quality management systems it's possible to run the business in very profitable ways. **[LIFET]**

Measure if Maintenance is targeting the Causes of Operating Problems

Equipment fails because a part's atomic structural integrity collapses from overstress or degradation. There are six major causes of mechanical equipment failure

- Lubricant contamination;
- Out-of-balance;

- Misalignment;
- Working component distortion;
- Incorrect fastening;
- Induced vibration.

For electrical equipment the six major causes are:

- Contamination;
- Induced vibration;
- Over temperature;
- Moisture;
- Distortion ;
- Power supply stability.

These are called “The Big 6” maintenance problems and they should be purged from the plant by Maintenance.

Proactive maintenance behavior prevents the “Big 6” from happening whereas reactive maintenance fixes them after they happen. You want Maintenance to go and find the “Big 6” problems in both mechanical and electrical equipment and get rid of them before they cause failure. This requirement is far beyond just using condition monitoring to observe equipment health. Condition monitoring accepts failure as a possible outcome, but the strategy of Big 6 prevention is all about never allowing the defects that produce those failures to arise.

KPIs that measure if Maintenance is focused on eliminating the Big 6 and how successful are their efforts are needed. The target is not to have operation living with risk of failures but instead it’s desirable to be proactively creating certain reliability. To make this happen it’s suggested to use maintenance KPIs in a different way “the scientific method”. **[LIFET]**

Scientific Maintenance

The scientific method says to first suggest the effect that will result from doing things in a particular way, then test your theory and if the experiment‘s result was not as postulated it means that the suggestion was wrong and it’s needed to look for a better approach. The way to apply the scientific method in Maintenance to improve reliability is to propose such things as, "**If we filtered our gearbox and hydraulic system oils to remove wear particles we should triple and even quadruple the MTBF**". Another postulate is, "**If we reduce atomic level stress in roller bearings by removing machine frame and bearing housing distortion we should get multiple increases in their MTBF**". A third, "**If we remove pipe stress from our flanges we will stop all flange leaks**".

With proposals like these it's possible to design experiments with specific causes to test, knowing exactly what was done to produce the results. The KPIs to use as measures are also clear. The wear particle removal experiment would have gearbox failures trended against numbers of gearboxes filtered each month. The expectation would be that as more gearboxes are regularly filtered the breakdown count falls significantly. The atomic stress reduction experiment is measured by electrical power consumption before and after rectification as well as bearing MTBF. An alternate measure would be to trend vibration of corrected bearings over the following months. A successful experiment would show that as the numbers of work orders raised and completed to rectify machine and bearing housing distortion (by using high precision methods) rises the bearing failure rate falls.

These are hypotheses that can be scientifically tested and measured in operation to see if they are true or not. Applying the assumed causes of higher reliability and then measure their effects with monthly KPIs. Now maintenance activities become proactive and each monthly report confirms the success (or not) of reliability improvement efforts. It's immediately possible to make useful and sensible adjustments to the experiment. If there are lower maintenance and operating costs in subsequent months than it's known exactly what caused them. **[LIFET]**

Measure What Business Benefits Maintenance is Achieving

Maintenance makes serious money for a company by delivering operating equipment reliability and operating equipment risk reduction. You see the effects of both good and bad maintenance in the cost of products. Bad maintenance policies and practices add operating cost whereas excellent maintenance policies and practices lower costs.

A useful site level maintenance KPI to measure is the proportion of operating costs attributable to Maintenance per unit of production. The Maintenance Group then has bottom level KPIs identifying where the cost contributions come from that make-up the maintenance proportion of the unit cost of production. This KPI directly links Maintenance to operating profit. You would be aiming to get a steady downward trend in maintenance cost per unit of production as evidence of continual improvement. The unit cost of production values may need to be identified by using Activity Based Costing, since financial accounting is often not detailed enough to differentiate the individual cost components of your products. **[LIFET]**

Use Visual Management Principles to Display KPIs for Action

Where possible show KPIs visually rather than in lists or tables. This encourages people to meet their obligations by employing psychology to drive good behaviors.

Many times this procedure has been tried and the result is that when the graphs were made public the people in charge of resources began to plan and schedule work to meet target dates. Within the first year the overdue inspections fell dramatically and breakdown rates plummeted. Changing behavior to the right practices is a powerful use of a KPI. **[LIFET]**

Reliability of gas turbines and failures types

Sarkara and colleagues analyzed the reliability of gas turbines in, Tripura (India). **[ASI12]**

Reliability of the generation system is divided into adequacy and security **[HOO]** System adequacy relates to the existence of sufficient generators within the system to satisfy the customer load demand or system operational constraints. System adequacy is associated with static conditions of the system and do not include system disturbances. System security on the other hand relates to the ability of the system to respond to disturbances arising within the system. Therefore, system security is associated with response of the system to whatever perturbation it is subjected to various factors. **[HOO]**

In the study of Tripuria energy plant, the reliability valuations is focused on the generation system adequacy and will not take into consideration system security. In a generation system study, the total system generation is examined to determine its adequacy to meet the total system load requirement. This activity is usually termed "generating system adequacy assessment". The transmission system is ignored in generating system adequacy assessment and is treated as a load point **[VAL07]**.

The main reason of the generating system adequacy assessment is to estimate the generating capacity required to meet the system demand and to have excess capacity to cater for planned and forced outages events.

A failure in a generating unit results in the unit being removed from service in order to be repaired or replaced, this event is known as outage. Such outages can compromise the ability of the system to supply the required load and affect system reliability. An outage may or may not cause an interruption of service depending on the margins of generation provided. Outages also occur when the unit undergoes maintenance or other scheduled work necessary to keep it operating in good condition. A forced outage is an outage that results from emergency conditions, requiring that component be taken out of service immediately. A scheduled or planned outage is an outage that results when a component is deliberately taken out of service, usually for purpose of preventive maintenance or repair.

The station consists of: gas turbine with total capacity of 82 MW (actual generation capacity =74 MW one unit of 8 M.W. is kept as standby).It has 7 generating units.

The study herein covers all the turbines.

The studies present reliability data from 2005to 2010, the plant was extremely unreliable so the failures which occurred can be considered as the most common failures in gas turbines. The failures occurred were:

- Failures related to high temperature in combustors;
- Excessive vibration on the bearings;
- Failures due to high temperature in the exhaust collector caused by combustor failure;
- calibration problems of pressure gauges located at the exhaust collector;
- Fuel filters premature cleaning due to premature clogging caused by poor natural gas quality;
- Problems related to the lubrication oil system (oil feeding pressure).

These failures can be reduced if the maintenance procedure tasks involve periodical inspection and replacement of parts, that were subjected to very high temperature and located in the hot gas paths (combustion chamber and turbine). However, sensors were installed in the oil pump to allow the use of a monitoring system, to check oil pump vibration and oil temperature and flow. But a bi-monthly oil analysis should be implemented in order to check for the presence of metallic particles in the fluid that could be an indication of possible bearings parts wear. The failure rate is a reasonable measure for durability of generating devices and indication for economical effectiveness of repairs **[ASI12].**

Availability can be improved significantly by reviewing maintenance practices. Planned maintenance is still essential but more and more, predictive maintenance is becoming the driver for planned outages. It has been reported that plant with availability of 50 to 60% gave 85% and above after it has been refurbished and maintained **[HOO].**

3.5 Evaluation of effectiveness of energy management

It's possible to use some indicators in order to evaluate the quality of energy management, basically it means to value the quality and the performances of the energy management strategies which have been adopted from the company.

The most common indicators are the following:

General efficiency criterion E_E:

$$E_E = \frac{W_{gen} - \Delta W + W_{buy}}{C_{pur} + C_{heat} + C_{exp} + C_{oc} - (I_{ser} + I_{sell})}$$

Where:

E_E= General efficiency criterion

W_{gen}= Sum of own energy and heat production (produced in own power plants) [kWh];

ΔW= Energy losses during the phases of generation and transport [kWh];

W_{buy}= Energy bought/delivered from outside (bought from the energy market) [kWh];

C_{pur}= Cost of electrical energy purchasing and post-sale services [Rubles];

C_{exp}= Cost of exploitation/utilization and management of energy equipment [Rubles];

C_{heat}= Cost heat purchasing [Rubles];

C_{oc}= Other expenses which are connected to problems of outside energy provision [Rubles];

I_{ser}= Incomes from sale from energy services [Rubles];

I_{sell}= Incomes from sale of energy generated from own power plants [Rubles]; **[GIT06]**

This indicators shows how much the company is independent from the market, the more the company produces energy in its own plants the higher this indicator will be

Coefficient of electrical & heat supply independence K_{ind}:

$$K_{ind} = \frac{W_{gen}}{W_{gen} + W_{buy}}$$

Where:

K_{ind}= Coefficient of electrical & heat supply independence [kWh];

W_{gen}=Volume of electrical energy and heat generated [kWh];

W_{buy}= Volume of electrical energy and heat bought from the market [kWh];

As shown from the formula this indicator shows the percentage of energy produced from own plants, the higher it is the lower it's the dependence of the company from the market.

Coefficient of impact of secondary production K_{sec}

$$K_{sec} = \frac{W_{sec}}{W_{gen} + W_{buy}}$$

K_{sec}= Coefficient of impact of secondary production;

W_{sec}=Volume of electrical or het power when it is the second production of the company [kWh];

W_{gen}=Volume of electrical energy and heat generated [kWh];

W_{buy}= Volume of electrical energy and heat bought from the market [kWh];

This indicator shows the percentage of secondary production in the total produced and bought energy, the higher it is the higher the importance of secondary production is.

Coefficient of energy flexibility K_{flex}

$$K_{flex,i} = \frac{\sum_{j=1}^{n} R_{ij}}{R_i}$$

Where:

K_{flex}= Coefficient of energy flexibility;

R_{ij}= Volume of resource of “i” type which can be replaced with a resource of “j” type [kWh];

R_i= Total volume of resource of “i” type [kWh];

Coefficient of development of energy business

$$K_{dev} = \frac{I_{ser} + I_{sell}}{C_{sup}}$$

Where:

I_{ser}= Incomes from sale from energy services [Rubles];

I_{sell}= Incomes from sale of energy generated from own power plants [Rubles];

C_{sup}=Total costs to supply energy to costumers (Total cost of production)[Rubles];

This indicator basically shows how much the incomes cover the expenses.

If this indicator is more than one this means that the company earns more than what it spends; the higher this indicator is, the higher the company business is developed.

4. LCC application in the gas turbines of "Kolomoenskoe" energy plant

4.1 Company and plant description

The data are related to the energy plant "Kolomenskoe", which take the name from the homonym district of Moscow. The plant is property of "NaftaSib Energia" which is a Russian private energy company.

They began to build "Kolomenskoe" plant in 2007 and they finished it in 2009, the whole construction time was 22 months; they started to produce energy in the middle of 2010.

The plant is gas alimented and it consists in a CHP simple cycle.

The plant supplies energy to a residential area of Moscow, customers are mainly private citizens and public institutions such as schools, public offices and some hospitals.

The power installed is 136 MW for electrical energy and 171 Gcal/h for heat, the energy is produced by 3 gas turbines SGT-800 of 47,5MW all of the same size (47,5MW of electrical power and 57 Gcal/h).

The investment costs for the whole plant were about 60 billion rubles, the investment cost per kW was about 41.000 rubles and the expected payback time is 8 years.

4.2 Functional analysis of gas turbine SGT-800

As explained in chapter 3.1, the analysis is done in some steps:

- First of all it is necessary to identify all the components of the equipment which are relevant for the study, in **figures 4.1 4.2 and 4.3** the most important components of gas turbines are shown

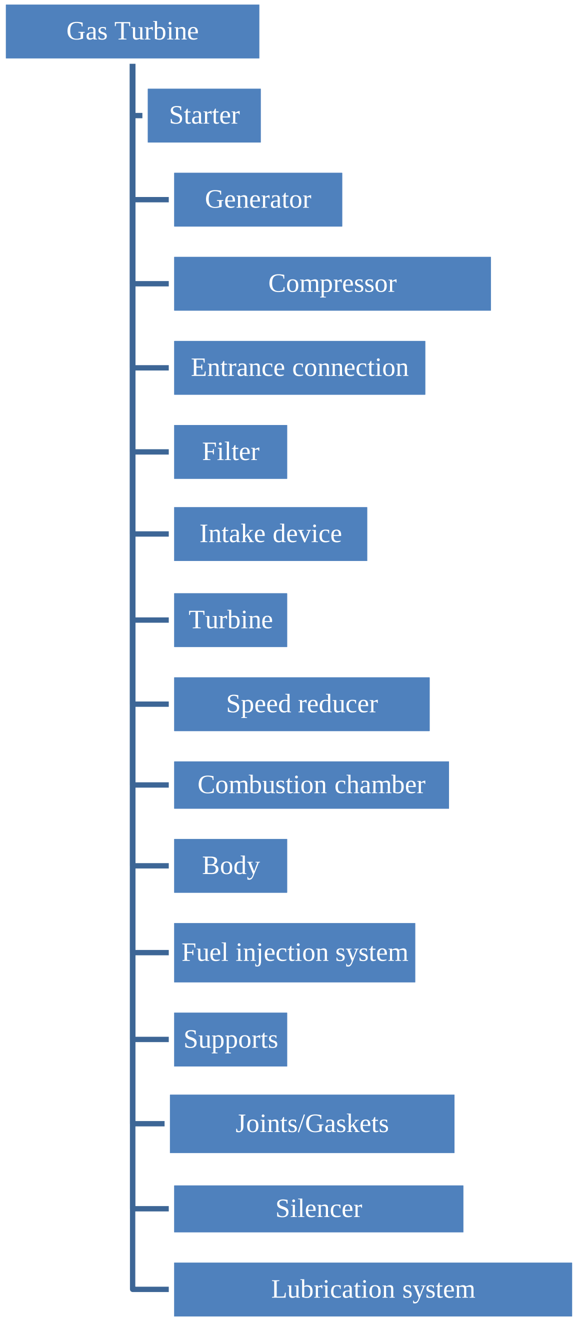


Figure 4.1 Construction scheme of gas turbines **[VLA12].**

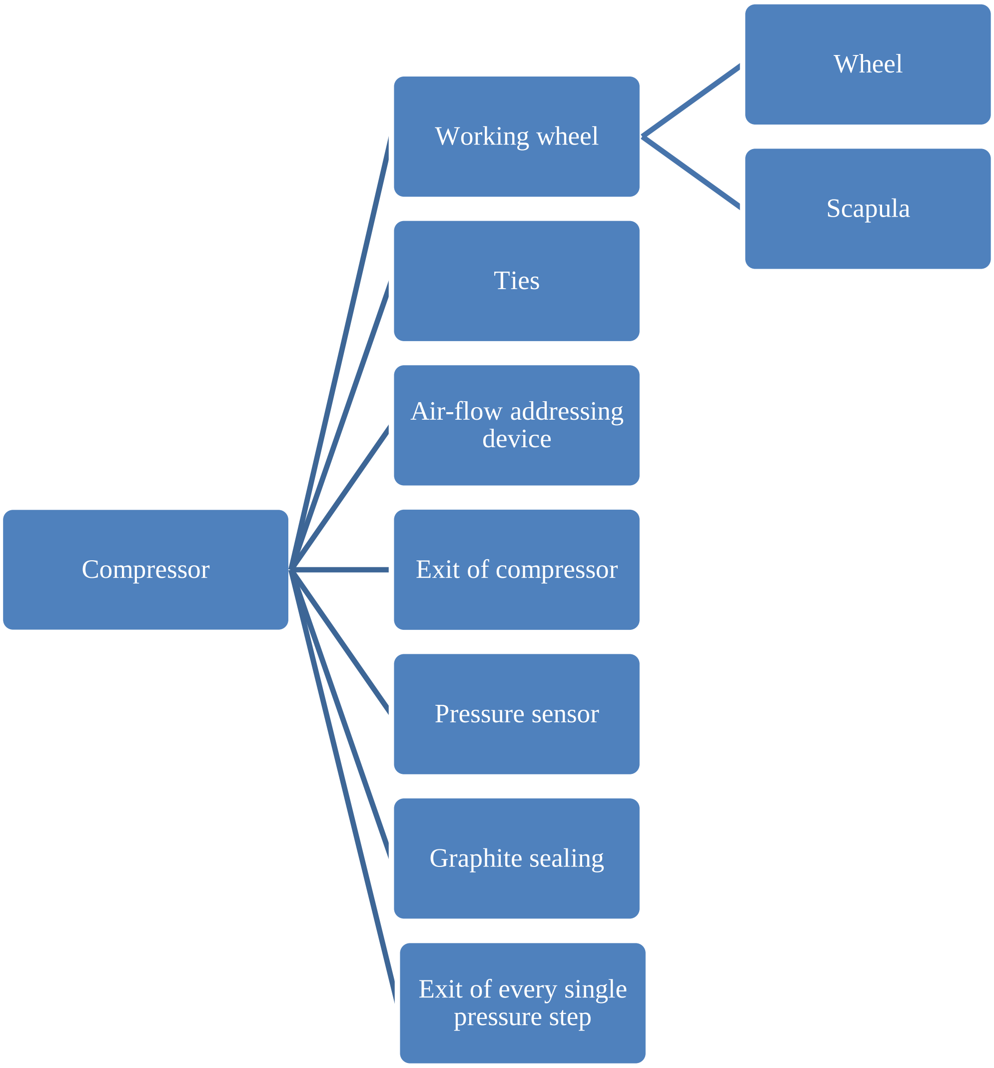


Figure 4.2 Construction scheme of compressor **[VLA12]**

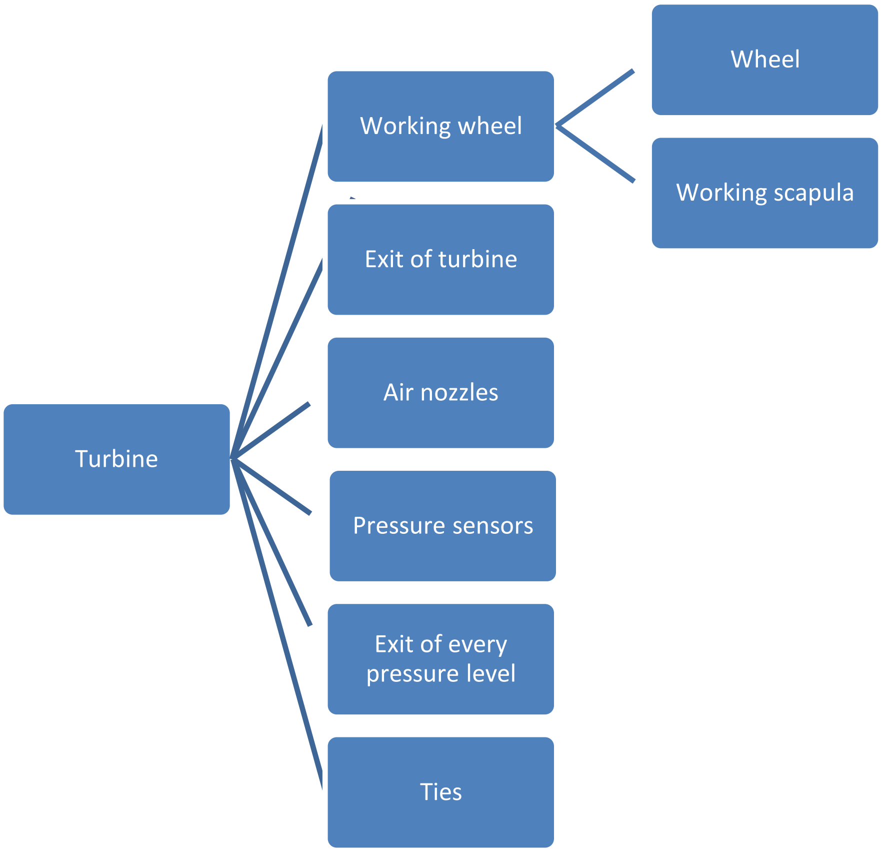


Figure 4.3 Construction scheme of turbine **[VLA12]**

- At this point it is necessary to identify all the basic functions of the turbine. Starting from the most aggregated and finishing with the most detailed ones, **figure 4.4**;

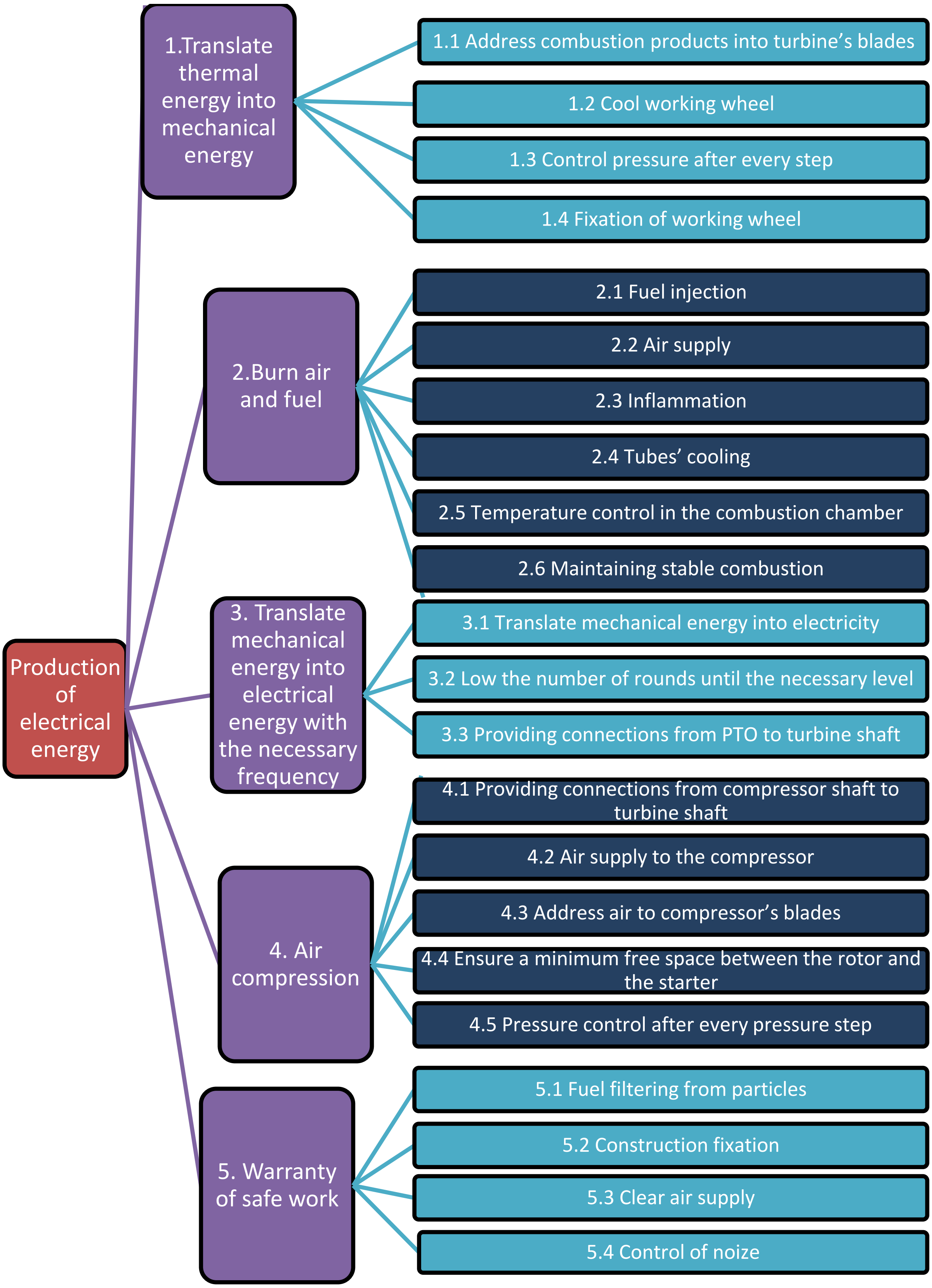


Figure 4.4 Functional structure of gas turbine **[VLA12]**

- Associate to every function the physical element which provide that function, **figure 4.5**.

	2nd level functions	3rd Level functions	Elements of construction structure
	1. Translate thermal energy into mechanical energy	1.1. Address combustion products into turbine's blades	Compressor exit and exit of every pressure level of the turbine
		1.2. Cool working wheel	Air pipe from compressor to turbine, shape and inner structure of working wheel
		1.3. Control pressure after every step	Pressure sensors after every pressure step
		1.4. Fixation of working wheel	Ties of turbine
	2. Burn air and fuel (Exothermic reaction to create heat)	2.1. Fuel injection	Injector, fuel pump
		2.2. Air supply	Air addressing device
		2.3. Inflammation	Spark plugs
		2.4. Tubes' cooling	Air tubes
		2.5. Temperature control in the combustion chamber	Temperature sensors
		2.6. Maintaining stable combustion	Flue
	3. Translate mechanical energy into electrical energy with the necessary frequency	3.1. Translate mechanical energy into electricity	Generator
		3.2. Low the number of rounds until the necessary level	Speed reducer
		3.3. Providing connections from PTO to turbine shaft	Joint/Gasket
	4. Air compression	4.1. Providing connections from compressor shaft to turbine shaft	Compressor ties and wheel
		4.2. Air supply to the compressor	Inlet nozzle
		4.3. Address air to compressor's blades	Entrance to compressor and entrance of every pressure step
		4.4. Ensure a minimum free space between the rotor and the starter	Compressor's graphite sealing
		4.5. Pressure control after every pressure step	Pressure sensors after every step
	5. Warranty of safe work	5.1. Fuel filtering from particles	Fuel filter
		5.2. Construction fixation	Supports
		5.3. Clear air supply	Air filter
		5.4. Control of noize	Silencer

Table 4.1 Association of all the functions to a single physical element **[VLA12]**

- Identify all the possible failures;
- Define a scale of occurrence probability and criticality level of failures, **table 3.1 and 3.2**;

Level of failure probability	Description
A	Frequent failure: it occurs more than 20% of the plant working time

B	Probable failure: it occurs between 10% and 20% of the plant working time
C	Possible failure: it occurs between 1% and 10% of the plant working time
D	Rare failure: it occurs between 0,1% and 1% of the plant working time
E	Unlikely failure: it occurs less than 0,1% of the plant working time

Table 3.1 Levels of failure probability **[VLA12]**

Criticality level	Description
I	Catastrophic failure: it can cause equipment death or destruction.
II	Critical failure: It can cause serious damages to the equipment.
III	Medium failure: It can cause medium sized damages to the equipment
IV	Border line failure: It can cause minor priority injuries or damages to the equipment
V	Slight failure: does not cause injury, not inflicting damage and does not affect execution of the mission, but leading to the need for unscheduled maintenance or minor repairs the final product

Table 3.2 Criticality level of failures **[VLA12]**

- For all of them identify the criticality of their impact and the probability of occurrence, **table 4.2.**

Failure type	Occurrence probability	Criticality level
Filter clogging	B	III
Contamination of compressor's blades	C	III
Abrasion of graphite sealing	E	V
Pipe burning	A	I
Failure of fuel pump	D	IV
Abrasion of the bearing pads	E	V
Silencer burning	D	IV
Failure of reductor	C	IV
Failure of generator	C	IV

Contamination of cooling pipes	B	II
High-temperature corrosion	C	II

Table 4.2 Example of some elements characteristics **[VLA12]**

- Having all these information it is possible to create a matrix combining occurrence probability and criticality level of failures, as shown in **table 4.5**, in order to choose the best maintenance strategies for all the groups

	Criticality level				
Level of failure probability	**V**	**IV**	**III**	**II**	**I**
A					Pipe burning
B			Filter clogging	Contamination of cooling pipes	
C		Failure of reducer, Failure of generator	Contamination of compressor's blades	High-temperature corrosion	
D		Air filter, Failure of fuel pump, Silencer burning			Lubrication system
E	Abrasion of graphite sealing, Abrasion of the bearing pads, Temperature sensors			Joint/Gaskets	

Table 4.5 Matrix failure level- criticality level **[VLA12]**

4.3 Calculus of LCC

4.3.1 Data

In this chapter are shown all data received by the company and the estimated ones.

P_{EL}=Electrical Power installed= 136 MW

P_H= Heat Power installed= 171Gcal/h

Equipment specific consumption 9730 Kj/Kwh

Cycle efficiency 37%

MTBF (turbine) =3500h

Official life of gas turbine = 120.000h

Time between capital repair= not less than 40.000h

Time between planned capital inspection= not less than 10.000h

Guarantee= 2 years

Coeff. Availability = 96%

Coeff. Reliability=98%

Coeff. Reliability at the beginning of life >95%

Loss of power after capital repair 3%

Decrease of cycle efficiency before capital repair 2,5%

Turn on time (including synchronization)= 21,5 min (6,5 min for the synchronization)

Energy expenses= 129 kW

U_{LO}= Oil require (for lubrication)= 50 l/kWh

C_{PM}^{AVE}=Average cost of planned maintenance during the official life (120.000h)= 23 SWK/MWh (Swedish crowns)

EE_{AVE}=Average annual electrical energy production= 890,62mln kWh

Percentage of electrical energy used by the company= 6,36%

Average annual heat production= 1155,14 MCal

Percentage of heat used by the company=1,56%

Hours equivalent of electrical energy= 7020,8

Hours equivalent of heat= 6933,3

U_{NG}^{AVE}= Average natural gas consumption per year= 261,05mln Nm^3/year

Number of people working in the plant 98

C_{UR}^{AVE}= Average cost of a single unexpected failure during the exploitation time = 858 000 rubles

BEGINNING OF LIFE (2008)

$C_{INST-sens}$= Cost of installation of all sensors = 4.850.000 rubles

$C_{INST-parts}$ Cost of installation of all the turbine parts = 52.000.000 rubles

$p_{1-contr}$= First control of automation and safety system = 2.443.036,87 rubles

$p_{clothes}$= Safety and special clothes for personnel = 600.000 rubles it's assumed that they are only clothes which are used for the people who work directly with turbines;

p_{TUR}= Price of gas turbines = 1.560.000.000 rubles (for all the 3 turbines);

C_{An}= Analysis of lubrication system = 61.950 rubles

YEAR 2009

$C_{CAL-fire}$Calibration cost of fire control and exhausting systems = 180.272,34 rubles

$C_{CAL-instr}$= Verification/Calibration cost of measurement instruments = 202.629 rubles

CONSUMPTIVE DATA FOR THE YEAR 2010

Ee_{2010}= Electrical energy produced= 445.000.000 kWh

Heat produced= 700.000 Gcal

$C_{PERF-LS}$=Cost of lubrication system performance checking = 12.744 [Rubles];

C_{Rec}= Reconstruction of TK1-19 = 3.612.522,67 [Rubles];

C_{VI}= Cost of valve installation = 305.940,34 [Rubles];

C_{AF}= Cost of acquisition and installation of air filters = 1.266.447,06 [Rubles];

C_{CAL-GA}= Verification/Calibration cost of gas analyzers = 50.000 [Rubles];

$C_{Loc\&Con}$= Development cost of the system for localization and control of failures = 350.000[Rubles];

C_{UR}^{0} = Repair cost on the gas turbines in the year 2010 = 3.650.972 [Rubles];

CONSUMPTIVE DATA FOR THE YEAR 2011

Ee_{2011}= Electrical energy produced= 534mln kWh

Heat produced= 793.000 Gcal

PERIODICALLY

$C_{Monit-Fund}$=Cost of fundamental settlement monitoring (2 times per year) = 57.794,04 [Rubles];

$C_{Monit-Def}$Cost of deformation monitoring (1 time every 3 months = 4 times per year) = 171.568,74 [Rubles];

C_{PERS}= Personnel costs=10.000.000 [$\frac{Rubles}{Month}$];

Contract with SIEMENS for 6 years of conditions inspections and repair of A, B, C and D type = 235.850.000 SWK. (It is assumed that the company renews this contract every 6 years).

In table 4.1 and 4.2 are shown the capital repair schedule (which has 4 levels), so after how many hours it is necessary to make a certain level of capital repair, and how much does it take to make it.

Level	**A**	**B**	**A**	**C**	**A**	**B**	**A**	**D**	**A**	**B**	**A**	**C**
Hours	10000	20000	30000	40000	50000	60000	70000	80000	90000	100000	110000	120000

Table 4.6 Capital repairs schedule

Level	**A**	**B**	**C**	**D**
Time	3 days	15 days	21 days	21 days

Table 4.7 Necessary time to make capital repairs

C_{DIS}= Average cost of waste disposal= 173.000 [$\frac{Rubles}{Year}$];

ESTIMATED

p_{NG}=Price of natural gas for industries in Moscow region = 3,058$\frac{Rubles}{m^3}$ **[FED13]**

p_{EE}Average price of electrical energy for final customers = 3,58 $\frac{Rubles}{kWh}$ **[FED13]**

p_hAverage heat price= 1570 $\frac{Rubles}{Gcal}$ **[FED13]**

p_{LO}= Price of lubrication oil = 14 $\frac{Rubles}{l}$ **[TRA13]**

$MTTR = \frac{MTBF}{Coeff.Ava} - MTBF$ = 146 h

Discount ratio= Risk free ratio + market risk ratio

Market risk ratio= 5,7% It's the market risk ratio which ENI uses for Russia **[ENI13]**

Market free ratio:

It correspond to the interest ratio of state bonds for that period, in Russia the state bonds for the referred periods have the following interest ratio:

1 year = 5,940%

2 years = 6,000%

3 years = 6,050%

5 years = 6,400%

10 years = 6,930%

15 years = 7,450%

25 years = 7,720% **[INV]**

For all the years after the 25th it is used the interest ratio of the 25th year as the planning horizon is too far to be reliable, for all the other years included in these 25 years it is assumed that the discount ratio grows in a directly proportional way.

In figure it's shown how the discount ratio during the years:

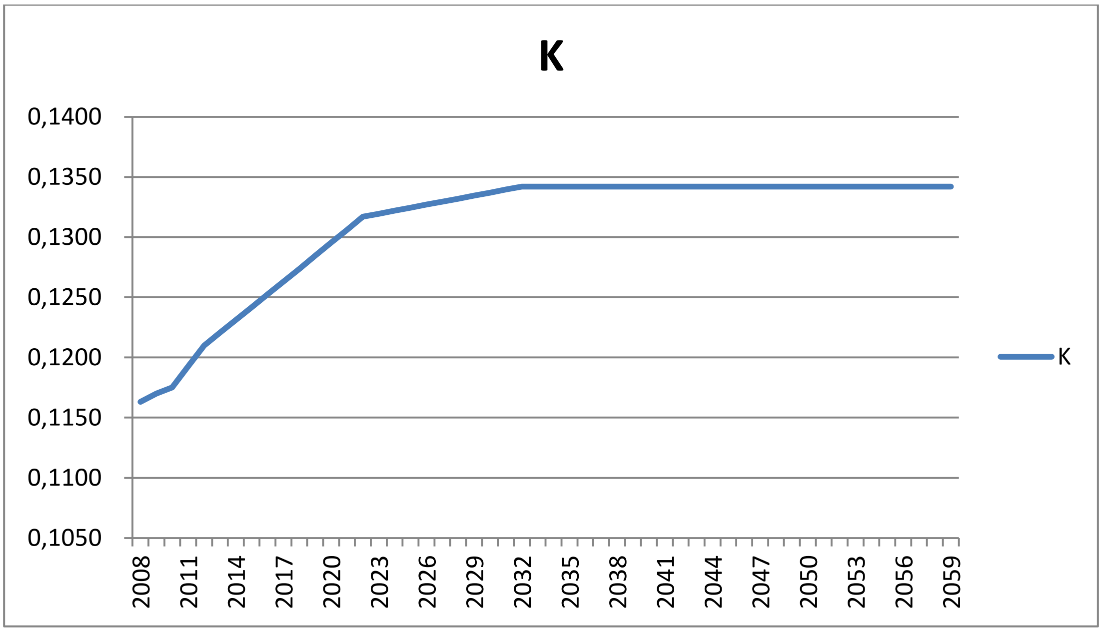


Figure 4.5 Discount ratio during the years

4.3.2 Calculus development

In this chapter it's showed the calculus of the LCC for the 3 gas turbines referred to the year 2008.

The production started in the middle of the year 2010 and also during the year 2011 the turbines didn't work for all the time but for about half of it (the reasons are not specified).

The investment costs are spread during the years 2008, 2009 and first half of 2010 and are given by the following formula:

$C_{INV}^{0} = P_{TUR} + C_{INST-sens} + C_{INST-parts} + p_{1-contr} + C_{An} + p_{clothes} =$ 1.619.954.986,87 rubles

$C_{INV}^{1} = C_{CAL-fire} + C_{CAL-instr} = 382.901{,}34$ rubles

$C_{INV}^{2} = C_{PERF-LS} + C_{Rec} + C_{VI} + C_{AF} + C_{CAL-GA} + C_{Loc\&Con} = 5.597.654{,}07$ rubles

Where:

C_{INV}^{i}= Investment cost of the year "i" [Rubles];

$C_{INST-sens}$= Cost of installation of all sensors [Rubles];

$C_{INST-parts}$ Cost of installation of all the turbine parts [Rubles];

$p_{1-contr}$= First control of automation and safety system [Rubles];

$p_{clothes}$= Safety and special clothes for personnel [Rubles];

p_{TUR}= Price of gas turbines [Rubles];

C_{An}= Analysis of lubrication system [Rubles];

$C_{CAL-fire}$Calibration cost of fire control and exhausting systems [Rubles];

$C_{CAL-instr}$= Verification/Calibration cost of measurement instruments [Rubles];

$\mathrm{C_{PERF-LS}}$=Cost of lubrication system performance checking [Rubles];

$\mathrm{C_{Rec}}$= Reconstruction of TK1-19 [Rubles];

$\mathrm{C_{VI}}$= Cost of valve installation [Rubles];

$\mathrm{C_{AF}}$= Cost of acquisition and installation of air filters [Rubles];

$\mathrm{C_{CAL-GA}}$= Verification/Calibration cost of gas analyzers [Rubles];

$\mathrm{C}_{\mathrm{Loc}\&Con}$= Development cost of the system for localization and control of failures [Rubles];

$\mathrm{C_{UR}^{0}}$ = Repair cost on the gas turbines in the year 2010 [Rubles];

0,1 and 2 are respectively the years 2008,2009 and 2010.

To calculate the annual cost of utilization for the generic year "i":

$$C_{UTI-i} = U_{LO}\, p_{LO}\, h_{eq-i} P_{EL} + C_{PERS} * 14 + U_{NG-i} * p_{NG-i}$$

Where:

C_{UTI-i}= Utilization cost of the year "i" [Rubles];

p_{LO}= Price of lubrication oil [$\frac{Rubles}{l}$];

U_{LO}= Oil require (for lubrication) [$\frac{l}{kWh}$];

h_{eq-i}= Hours equivalent of the year "i";

P_{EL}=Electrical Power installed [kW];

U_{NG}^{AVE}= Average natural gas consumption per year [$\frac{Nm^3}{year}$];

p_{NG}=Average price of natural gas for industries in Moscow region [$\frac{Rubles}{m^3}$];

It's assumed that the price of lubrication oil and is constant during the life and the machines always need the same quantity of lubrication oil per hour equivalent (as there are no other information available), the monthly personnel cost is multiplied per 14 as in Russia they have the 13th and the 14th salary (exactly as in Europe).

The use of natural gas for the year 2010 and 2011 is calculated as:

$$U_{NG-i} = \frac{h_{eq-i}}{h_{eq}^{Ave}} U_{NG}^{AVE}$$

Where:

U_{NG-i}= Natural gas consumption of the year "i" [Nm^3];

h_{eq-i}= Hours equivalent of the year "i" [h];

h_{eq}^{Ave}= average annual hours equivalent [h];

U_{NG}^{AVE}= Average natural gas consumption per year [$\frac{Nm^3}{year}$];

There are no data available from the year 2012 to the end of the turbines' life so it is used the average natural gas consumption.

It is assumed that the natural gas price is fixed, in Russia this is not a very strict condition as the natural gas price doesn't change as much as in Europe.

For capital maintenance the company signed a 6 years contract with Siemens for the amount of 235850000 Swedish Crowns (1.128.377.155rubles with the exchange ratio 1SWK= 4,78 rubles), as there are no other information which would allow to calculate the cost of planned and capital maintenance it's assumed that every 6 years the company renews this contract at the same price.

To calculate the cost of unexpected repair it's necessary to use the concept of MTBF, MTTR and coefficient of availability; as already shown in the data estimation it is possible to find the MTTR from the other 2 quantities which are given by the company:

$MTTR = \frac{MTBF}{Coeff.Ava} - MTBF$ = 146 h

For the first 120.000 hours it is possible to assume that unexpected failure happen exactly every MTBF which might be not correct for the single year but it is not far from reality considering the whole life.

MTBF is more than 3500 hours, it's possible to assume that there will averagely be 2 failures per year, in the first 2 years of activity (2010 and 2011) there will be only 1 failure per year as the turbines work half of the time.

C_{UR}^{0} = 3.650.972 rubles

$C_{UR}^{1} = 3 * C_{UR}^{AVE}$= 2.574.000 rubles

$C_{UR}^{i} = 2 * 3 * C_{UR}^{AVE}$= 5.148.000 rubles

Where:

C_{UR}^{i}= Total cost of unexpected repairs for the year "i" [Rubles];

C_{UR}^{AVE}= Average cost of a single unexpected failure during the exploitation time [Rubles];

To calculate the cost of planned maintenance:

$C_{PM}^{0} = C_{Monit-Fund} + 2 * C_{Monit-Def} + C_{PM}^{AVE} * ER * EE_{2010}$= 49.368.242,02 rubles

$C_{PM}^{1} = C_{Monit-Fund} + 2 * C_{Monit-Def} + C_{PM}^{AVE} * ER * EE_{2011}$= 59.161.704,12 rubles

$C_{PM}^{i} = 2 * C_{Monit-Fund} + 4 * C_{Monit-Def} + C_{PM}^{AVE} * ER * EE_{i}$ = 98.736.484,11 rubles (when i $\neq$ 0,1);

Where:

C_{PM}^{i}= Cost of planned maintenance of the year "i" [Rubles];

$C_{Monit-Fund}$=Cost of fundamental settlement monitoring (2 times per year) [Rubles];

$C_{Monit-Def}$=Cost of deformation monitoring (1 time every 3 months = 4 times per year) [Rubles];

C_{PM}^{AVE}=Average cost of planned maintenance during the official life [$\frac{SWK}{kWh}$];

ER= Exchange ratio Rubles/Swedish crowns;

Ee_{2010}= Electrical energy produced in 2010 [kWh];

Ee_{2011}= Electrical energy produced in 2011[kWh];

Ee_i= Electrical energy produced during the year “i” [kWh];

The costs of disposal are given, in the first 2 years of production it’s assumed that it is proportional to the hours equivalent

$$C_{DIS}^{0} = \frac{h_{eq-0}}{h_{eq}^{Ave}} C_{DIS} = \text{ 80.627,02 rubles}$$

$$C_{DIS}^{1} = \frac{h_{eq-1}}{h_{eq}^{Ave}} C_{DIS} = \text{ 96.752,42 rubles}$$

$C_{DIS}^{i} = C_{DIS} = 173.000,00$ rubles (when i ≠ 0,1);

Where:

C_{DIS}^{i}= Cost of disposal of the year “i” [Rubles];

C_{DIS}= Average cost of waste disposal [Rubles];

h_{eq-i}= Hours equivalent of the year “i” [h];

h_{eq}^{Ave}= average annual hours equivalent[h];

It’s not possible to calculate the opportunity cost of the planned maintenance cost as there is no information about the time needed to do it but it is possible to calculate opportunity costs of capital repairs and of unplanned repairs:

$$OC_{CR-i}^{j} = d_j * 24 * [(p_{EE} - CV)P_{EL} + (p_h - CV)P_H]$$

OC_{CR-i}^{A}= 15.881.222,24 rubles

OC_{CR-i}^{B}= 132.343.518,63 rubles

OC_{CR-i}^{C}= 164.105.963,10 rubles

OC_{CR-i}^{D}= 164.105.963,10 rubles

Where:

OC_{CR}^{j}= Opportunity costs of capital repairs of “j” type in the year “i”[Rubles];

p_{EE}= Average price of electrical energy for final customers [$\frac{Rubles}{kWh}$];

p_h= Average heat price [$\frac{Rubles}{kWh}$];

d_j= Number of days necessary to make a capital repair of j type [days];

P_{EL}=Electrical Power installed [kW];

P_H= Heat Power installed [kW];

CV= Variable costs of production [$\frac{Rubles}{kWh}$];

As no other information is available, it is assumed that it always takes the same time to make capital repairs.

The variable costs are calculated as following:

$$CV = p_{LO} * U_{LO} + p_{NG} \frac{U_{NG}^{AVE}}{EE_{AVE}} = 1{,}6 \frac{Rubles}{kWh}$$

Where:

CV= Variable costs of production [$\frac{Rubles}{kWh}$];

p_{LO}= Price of lubrication oil [$\frac{Rubles}{l}$];

U_{LO}= Oil require (for lubrication) [$\frac{l}{kWh}$];

p_{NG}=Average price of natural gas for industries in Moscow region [$\frac{Rubles}{m^3}$];

U_{NG}^{AVE}= Average natural gas consumption per year [$\frac{Nm^3}{year}$];

EE_{AVE}=Average annual electrical energy production [$\frac{kWh}{Year}$];

To calculate the opportunity cost of unplanned repairs:

$$OC_{UR}^{i} = 2 * MTTR\ [(p_{EE} - CV)P_{EL} + (p_h - CV)P_H] = 64.407.179{,}07 \text{ rubles}$$

(when i ≠ 0,1);

$$OC_{UR}^{0} = OC_{UR}^{1} = MTTR\ [(p_{EE} - CV)P_{EL} + (p_h - CV)P_H] = 32.203.589{,}53 \text{ rubles}$$

Where:

OC_{UR}^{i}= Opportunity cost of unplanned repairs of the year “i” [Rubles];

MTTR= Mean Time To Repair [Hours];

p_{EE}= Average price of electrical energy for final customers [$\frac{Rubles}{kWh}$];

p_h= Average heat price [$\frac{Rubles}{kWh}$];

d_j= Number of days necessary to make a capital repair of j type [days];

P_{EL} =Electrical Power installed [kW];

P_H= Heat Power installed [kW];

Then the lifecycle costing of the 3 gas turbines is calculated as following:

$$LCC = \sum_{i=0}^{52} \frac{C_{INV}^i + C_{UTI-i} + p_{SC}^i + C_{UR}^i + C_{PM}^i + C_{DIS}^i + OC_{UR}^i + \sum_{j=1}^4 OC_{CR-i}^j}{(1+K_i)^i}$$

$$= 10.389.934.078,59\ rubles$$

Where:

LCC= Lifecycle cost [Rubles];

C_{UTI-i}= Utilization cost of the year "i" [Rubles];

p_{SC}^i= Price of Siemens contract for the year "i" [Rubles];

C_{PM}^i= Cost of planned maintenance of the year "i" [Rubles];

C_{UR}^i= Total cost of unexpected repairs for the year "i" [Rubles];

C_{DIS}^i= Cost of disposal of the year "i" [Rubles];

OC_{CR}^j= Opportunity costs of capital repairs of "j" type in the year "i"[Rubles];

K_i= Discount ratio of the year "i";

Problems:

During this application some big approximations have been done:

- The exchange ratio SWK/Rubles has been considered constant for all the period, this is a strong approximation but there is no way to know how it will change in the future;
- The price of lubrication oil, natural gas, electrical energy and heat are considered constant, this is another strict approximation;
- There is no information about final cost of disposal so it has been neglected;

Results:

As shown in **figure 4.6**:

- The opportunity costs play an important role:

- LCC without opportunity costs= 10.389.934.078,59 rubles;
- LCC with opportunity costs= 9.820.374.041,38 rubles;
- About 5,8% of difference;

- Very big difference between cost of acquisition and LCC:
  - Total discounted investment costs= 1.624.784.413,97rubles;
  - The investment costs are the 15,64% of the total LCC;
- Cost of capital repairs is a very big part of the total costs.
- The biggest part of total costs is the cost of utilization;

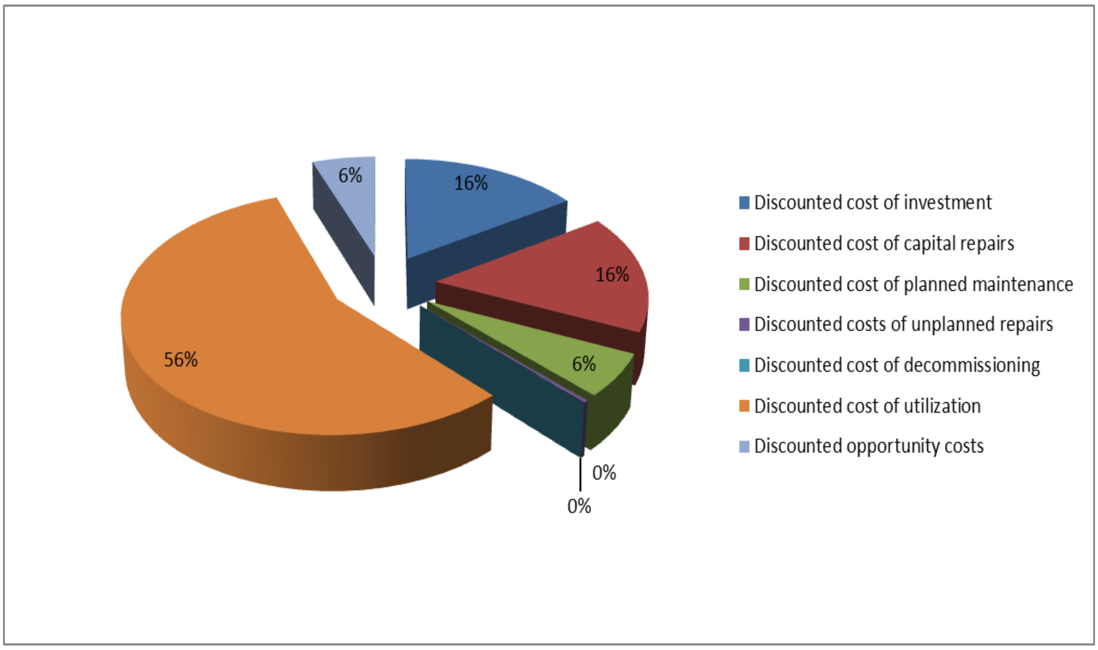


Figure 4.6 Impact of the different cost voices

5 Conclusion and future trends

As already said energy business plays an extremely important role in every day life, it's the basis of all the other businesses in the planet earth and it's indispensable for life of human beings. For this reason energy equipment must have a high reliability in order to be always able to supply energy, while in the other side, as all businesses, energy business needs to be profitable; thus it is necessary to have tools which allows to achieve both these 2 targets which are often in trade-off.

The analysis of PLM systems and PLM concepts showed that right now in the market there are PLM models which help companies with design and production of energy equipment but not with their exploitation.

Yet, models which allow to keep into account the phases of exploitation and end of life are FMECA models, which allows to manage maintenance policy and failures, and LCC which counts all the costs of the whole lifecycle. That's the reason why they have been chosen in this work as the right models to use in order to manage energy equipment during their exploitation and end of life.

The model chosen is correct and the introduction of opportunity costs really helps to make better choices.

The case study of "Kolomenskoe" energy plant showed some interesting results:

- Cost of acquisition have a strong impact but not as much as the utilization costs;
- Cost of utilization are more than the 50% of the total lifecycle costs;
- Opportunity costs are not high but still not negligible, it's important anyway to say that they are not high also because in this plant they installed new equipment and moreover the plant is located in Russia where the cost of electrical energy is lower than in Europe; the same study conducted in Europe would have shown different results;
- Capital repairs have a strong impact on the total costs, that's why it is interest of the company to minimize stops for repairs and maintenance, also there are some studies now which are showing that when turbines don't work in regime but have peak and stops, they suffer some erosion activities, especially related to vibration of blades and to asynchronous behavior;

It's well known that LCC are not precise systems, in energy equipment this problem is even bigger than in other sectors as they have a very long life and there are a lot of factor for which it is impossible to make a precise prevision for a so long period of time; some of these factors are:

- Price of electrical energy;
- Fuel price;
- Price of lubrication oil and other materials;
- Exchange ratios;
- Real failure ratios.

They are anyway very useful when it is necessary to make a choice between different maintenance policies or between different equipment.

Finally, as cost of utilization and cost of maintenance are so important and have a so big impact on total costs it is necessary to introduce new systems in the market which are able to manage them. Moreover it is a heuristic fact that data supplied by producers are usually very different from real data, so these systems should be able to keep into account this fact and eventually there should be feedback information between the 2 companies (producer and user of energy equipment) in order to improve energy equipment using real data.

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Acknowledgements

I would like to express my gratitude towards my advisor Alla Efimovna Brom at the Bauman Moscow State Technical University for supporting me through my project and sharing his professional and personal wisdom with me. Furthermore I would like to thank Sergio Terzi from the Politecnico di Milano for creating the opportunity for me to develop my Master's thesis in Russia. Furthermore, I am very thankful to Jean-François Labrecque-Piedboeuf, my roommate and friend, for sharing the everyday life experience in Moscow with me and making my time in Russia unforgettable. Finally I am very thankful to Vera Yurevna Martynova for helping me with Russian translations and for making me discover a lot about Russian culture and traditions which made my experience priceless.