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A comprehensive analysis of industrial compressed air systems performance: benchmark and decision support tools to improve the energy efficiency

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Ph.D. Candidate
Simone Salvatori

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Tutors
Prof. Vito Introna

....

Prof. Stefano Ubertini

....

Ph.D Coordinator
Prof. Danilo Monarca

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To my family.

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Abstract

Industrial energy consumption is responsible of about one third of global energy consumption. For this reason, increasing attention about energy efficiency and environmental problems leads scientific researchers to undertake several studies to improve energy efficiency both in industrial and other sectors. Compressed air is surely one of the most influencing system regarding energy consumption. On average, 10% of industrial energy consumption is due to compressed air system, consequently research has focused on technologies for reducing this consumption.

Exploiting the lack of complete procedures to prove compressed air system performance and reduce energy costs, a complex strategy is presented and discussed in this thesis. The developed methodology starts from the analysis of a large database coming from Italian industrial companies containing energy consumption of the most energy-intensive sectors and through the development of benchmark analysis and successive surveys (also applying a specific maturity model), proposes and implements some decision support tools to evaluate and improve compressed air system energy efficiency. Results show that all the developed methodologies can be applied on all industrial company highlighting possible improvements.

Introduction

Some estimates confirm that the industrial sector is responsible of up to 50% of the world energy consumption [1, 2]. Starting from this statement, it is easy to understand that is particularly important to keep energy consumption under control [3]. Energy efficiency is a critical aspect for any kind of organization both operating in industrial sector and in civil one. The reduction of energy consumption is globally considered very important both by national and international institutions. As an example, European Union members have subscribed the Directive 2012/27/EU [4] to strongly intervene on their energy consumption including industrial consumption.

Also in economic terms, energy consumption plays a fundamental role. It is one of the most important expense items for companies that have to carefully manage energy costs to the best of their potential because of the importance that they have gained in business budget. It is clear that energy management involves many respects of industrial companies including environmental management and the increasing of the company competitiveness [5]. Some studies have estimated that the industrial production costs can be reduced up to 20% optimizing energy management [6].

Since companies have to face all the risks deriving from competition of market and from fluctuations of the price of energy resources, the importance of energy efficiency is always increasing, especially in those energy-intensive. The reduction of energy costs allows companies to invest more economic resources in other aspects improving quality and competitiveness. For these reasons, more and more researches and technicians are working to optimize energy consumption of industrial processes and reduce the related costs. The belief that achieving energy efficiency entails large expenses of money is rather widespread in industrial sector [7]. Expected energy savings could be related to economic investments but, to improve the energy efficiency, is important to have awareness, ability and knowledge about energy management.

According to scientific literature, efficiency is defined as the possibility of doing more with less and this is precisely the starting point of the work. Energy efficiency principles can be applied to all industrial processes even if they do not bring added value. This is the main topic of the thesis. Within an industrial plant, there are numerous facilities that allow the production sectors to produce the final goods to sell. The management of facilities is, therefore, a very important activity. Clearly, most of the energy consumption is due to production processes, however the facilities consume a considerable amount of energy considering that the only compressed air systems (CASs) can consume $10 \div 25$ % of overall plant consumption [8]. These data point out how important is considering the possibility of improving the energy efficiency of the compressed air system, and how large the benefits of the entire company could be.

The compressed air is used in numerous industrial applications including the operation of machines and automatisms, material handling, liquid mixing, cleaning etc. The wide range of applications makes this facility practically irreplaceable thanks to its many positive aspects. Compressed air is easily produced, widely available and stored without problems. It can also be discharged into the environment and its use does not entail risks for operators and the plants. Obviously, the use of compressed air involves some negative aspects, above all related to energy consumption. The production of compressed air is intrinsically energy-intensive, therefore it must be treated very carefully trying to limit wastes. In scientific literature there are several documents regarding energy efficiency of industrial processes including [9, 10] but it is difficult to find well-organized procedures for managing and improving the performance of compressed air generation and transport systems.

The lack of procedures to increase energy performance of compressed air systems provided an opportunity to start the collaboration between the University of Tuscia and ENEA that is on the background of this thesis activity.

The research is specifically aimed at deepen all the aspects related to energy efficiency of compressed air production and use, characterization of the energy benchmark and development of a methodology, suitable for industrial companies, to improve the compressed air system energy efficiency. To achieve this objective, a complex analysis has been carried out and some procedure and tools have been developed.

The research managed by ENEA is a 3 years project titled “Efficienza energetica dei Sistemi Aria Compressa: metodologia di benchmarking delle prestazioni e strumento di supporto alle decisioni per l’efficientamento energetico” during which many results have been reached. The project has many objectives including:

- Individuation and characterization of energy consumption due to CAS for several Italian industrial sectors;
- Study and development of specific performance indicators for CAS energy consumption;
- Development and application of a method useful for industrial companies to assess CAS energy efficiency;
- Definition and development of benchmark methodologies and decision support tool;
- Definition of best practices and guidelines to develop a energy efficiency improvement strategy for CAS;
- Development of a series of Decision Support Tools to help companies in their choices regarding the improvement of energy efficiency for the production and management of industrial compressed air, based on technical-economic evaluations.
- Test of the developed methodologies on real case studies.

All the methodologies and the results achieved during the development of the project are extensively described in three year-end reports. The reports are available on line on the ENEA website ([11]).

In this thesis, all the activities related to the collaboration, for which the author has given his contribution, are collected. In the following, it will be specified in detail in which sections the contribution was substantial for the development and application phase of the methodology and those in which the contribution only concerned the consolidation and application of the methodology.

The first step of the work is the energy analysis of the compressed air systems performance on 9 Italian industrial sectors through statistical methods. Such activity allows to implement a benchmark analysis to assess the energy performance of each sector. To get more information about compressed air management procedures, a short questionnaire is administered to several companies belonging to different sectors. The results of the questionnaires have been used to analyse the situation and characterize the criticalities. To get more complete results, a more complex procedure is developed. Starting from the CASEEMM (a maturity model about compressed air systems) a set of guidelines is developed to guide the companies toward achieving energy efficiency. The procedure establishes to administer the maturity model and suggest some guidelines to overcome the highlighted criticalities. Lastly, to propose a summary evaluation of the potential performance improvement, a set of decision support tools in the form of standalone software are developed. It is important to underline that this thesis provides an original contribution compared to what is present in the literature. To the knowledge of the author, such complex and integrated procedures for the improvement of the energetic conditions of the CAS are not known.

The remainder of this thesis is divided in 5 chapters. The first chapter collects general information about compressed air system. The second chapter provides a description of the study and the development of a methodology suitable to provide a benchmark analysis for the most important energy-intensive Italian industrial sectors. In the third chapter the submission of a short questionnaire to Italian industries to get accurate information about compressed air system efficiency. The fourth chapter regards the development of a set of guidelines to improve energy efficiency. The fifth chapter describes the development and use of several decision support tools.

Chapter 1

Compressed air systems

1.1 Principal features of compressed air

Compressed air is one of the most important energy vector for industrial application. It is very largely used because of its advantages such as:

- Ease of transportation;
- Possibility of storage;
- Safety in use;
- High degree of purity.

Despite these positive aspects, compressed air use is one of the most important energy consuming processes within an industrial plant because of the physical transformation and the treatment that must be done on air before distributing. In particular, before its actual use, it has to be filtered, compressed and cooled, transported and stored.

The uses of compressed air for industrial applications are manifold and, even more important, transversal to the various production activities. Compressed air is applied in handling systems, for the operation of pneumatic transport and adjustments. It is very used in packaging applications, for forming plastic or glass containers (used in particular in the food and pharmaceutical sectors), aeration, cooling systems, for cleaning and also for agitation and mixing. Compressed air is also indispensable in explosive areas where the use of electricity is impossible (a situation often verified in the case of chemical and petrochemical companies).

Compressed air characteristics vary depending on the application. Most of the use require a pressure about $6 \div 7$ bar but, it can also be significantly higher or lower, moreover different pressures may be required within the same plant [12]. Furthermore, the degree of purity can be very variable depending on the application. For example, food and chemical sectors require more pure air than the other manufacturing sectors.

1.2 Configuration and components of a compressed air system

A common scheme of CAS can be typically divided in 3 sections:

- Intake and filtering;
- Compressor system;
- Distribution and use.

A general scheme of a CAS is reported in Figure 1.1. In the following, brief descriptions of components are given.

1.2.1 Air intake system

The intake section is the first part traversed by the air and is, as all the successive, very important because of its strong influence on the energy consumption of CAS. It is composed of: air intake, duct, and filtering system. Specifically, the requested power decreases reducing air temperature so, the air intake should be positioned exposed toward the north (to limit the solar irradiation) and $2 \div 3$ meters high to avoid the aspiration of dust from the ground. In this way it is possible to keep as low as possible the intake air temperature and minimize the power required to compress the air at the set pressure level.

After a (as short as possible) duct, near the compressor there is the filtering system. Air inlet filters protect the compressor from atmospheric airborne particles. Generally, other filters are installed downstream the compressor to protect the equipment. The filtering system type and quality vary depending on the application and the requirement of the CAS. Two examples of filters are reported in Figure 1.2. The filtering

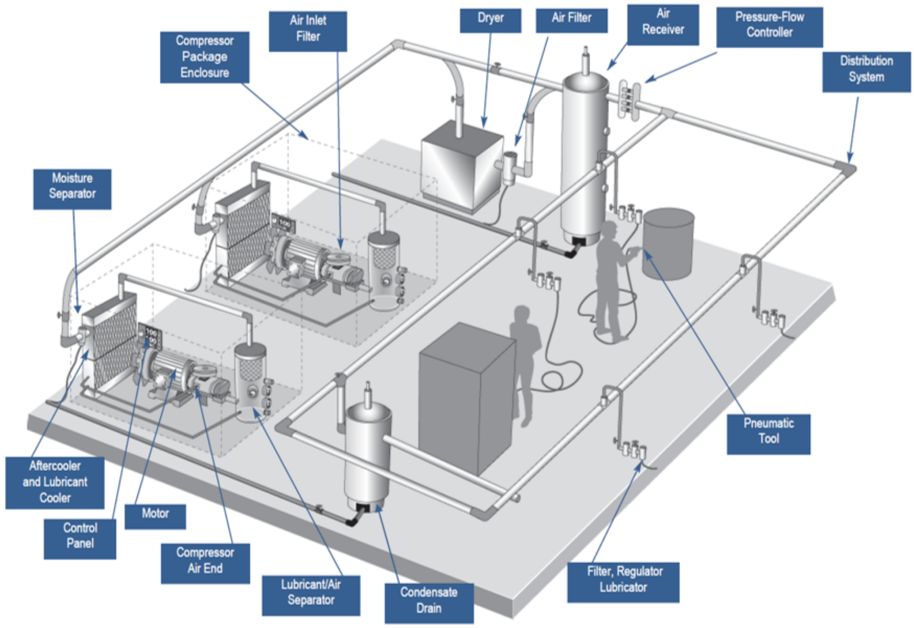

Figure 1.1: *Components of a typical industrial compressed air system [13].*

efficiency depends on the quality of intake air, on the filter type and on the management of the system.

In addition to filtering system, a vibration damping system could be installed. It is mainly used in presence of a reciprocating compressor. The operation of this machine causes pulsations in the air which generates large pressure drops and vibrations, risking resonance phenomena. For this purpose, damping lungs (silencers) are used on the compressor delivery to guarantee a uniform air flow. The vibration damping system also fulfills the task of reducing the noise of the compressors.

The entire air intake system has to be designed to minimize the pressure drop and keep the optimal velocity of air.

1.2.2 Compression systems

Air compressor can be classified according to their operation in positive-displacement compressors and dynamic compressors.

- Positive-displacement compressors compress the air by reducing the volume in which it is confined. They can be rotary screw

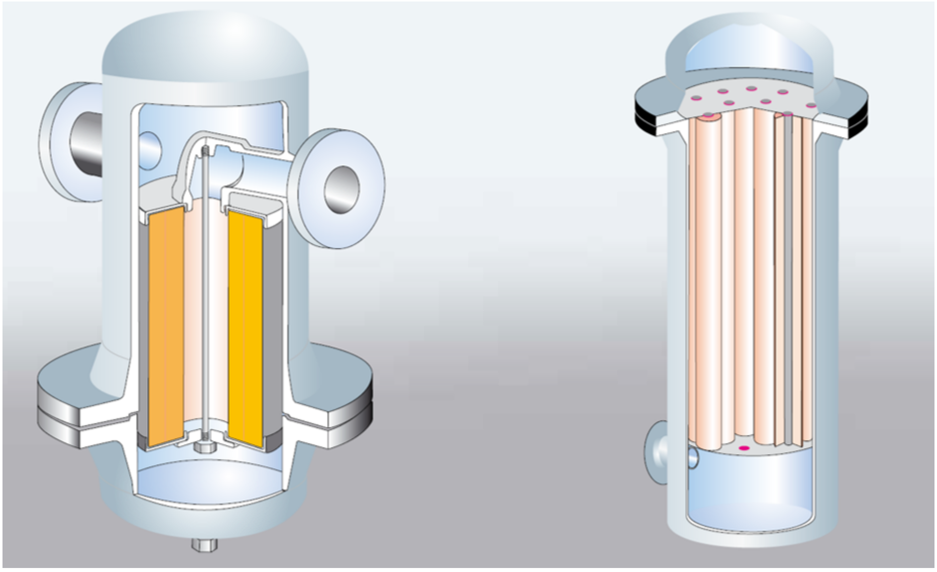

Figure 1.2: *Two typical filters for compressed air [14].*

compressors, rotary vane compressors, reciprocating compressors, diaphragm compressors, scroll compressors, etc. The simplest and most used type is the reciprocating compressor, consisting of a cylinder equipped with suction and delivery valves, in which a piston slides, controlled by a connecting rod-crank system. Another type of widely used displacement compressor is the screw compressor. It consists of two rotors, one with convex lobes and the other with concave lobes, which rotate in the opposite direction inside a stator. In this case, the rotation of the two lobes rotors reduces the volume available for air increasing the air pressure. The compression process is represented in Figure 1.3. These types of compressors are not equipped with valves and are not subjected to mechanical forces that could cause instability and therefore they can work at high rpm and manage to combine high flow rate and small external dimensions. They can also work without lubricant, providing oil-free air, providing an important requirement for many applications.

- Dynamic compressors compress the fluid transforming the kinetic energy impressed on the gas, they use the principle of momentum variation. They can be centrifugal compressors, axial compressors, mixed-flow compressors, etc.

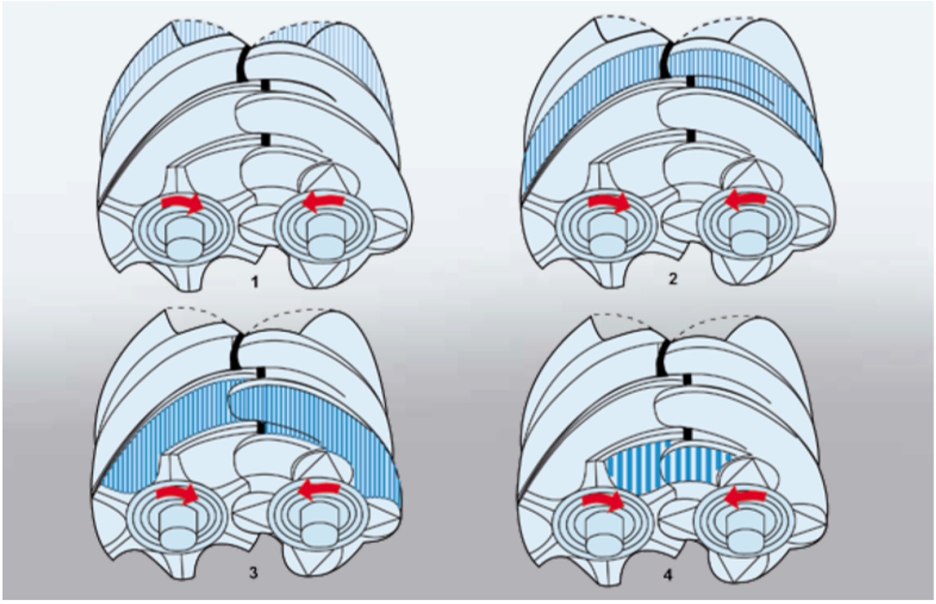

Figure 1.3: *Compression in a twin screw compressor. Phase 1: air fills the space between the rotors, Phase 2-4: gradually the enclosed space decreases and pressure increases [14].*

The air compressor has to be chosen depending on the application. Many parameters characterize the compressors including: pressure, flow rate, reliability, the presence of oil in compressed air, etc. In general, dynamic compressors elaborate larger flow rates compared with positive-displacement compressors but their pressure is lower.

The efficiency of the compressor largely depends on the possibility to remove heat during the compression phase to get isothermic compression.

Another aspect which strongly influences the energy efficiency is the type of modulation of the compressor. Typically air flow elaborated by compressors is modulated using three kind of approaches: on/off, load/unload and continuous modulation. The first is applied only on small compressors, the second is applied on large compressors with stable operation over time and the third is applied on very variable load on compressors with inverters.

1.2.3 Refrigeration and dryer system

The compressed air produced by compressor must be refrigerated to avoid both the transport of the lubricant, with the possible creation of explosive mixtures, and to prevent the formation of condensation, which leads to corrosion of the pipes and equipment and to various drawbacks in the production processes served. The refrigeration is operated thanks to the use of an heat exchanger.

The elimination of humidity contained in the air occurs through the use of dryers. In this way, it is possible to lower the dew point in order to minimize problems caused by moisture. Common dryers are: refrigeration dryers, absorption dryers and deliquescence dryers.Water separators can work with cyclone separating or separation through changes in direction and speed. In Figure 1.4 some examples of refrigerators are reported.

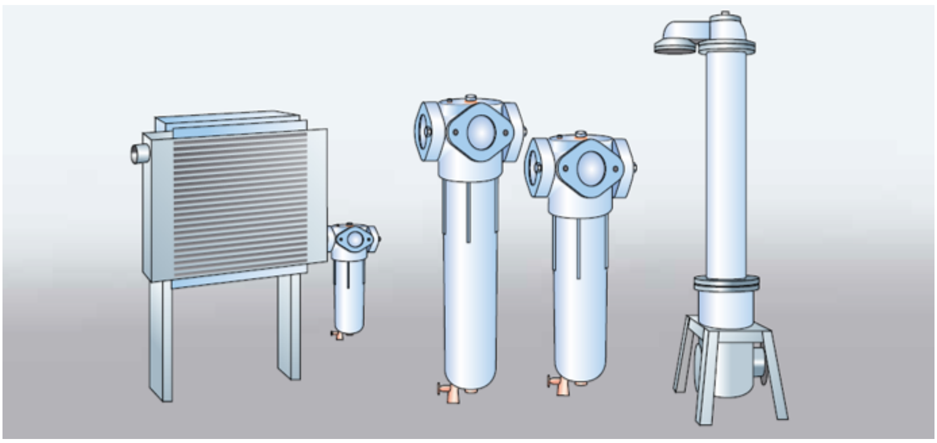

Figure 1.4: *Different after-coolers and water separators. [14].*

1.2.4 Tank and distribution network

After the drying phase, the compressed air is stored in one or more tank to:

- Keep constant the flow rate toward the users;
- Allow to stop the operation of compressor causing energy saving;
- Facilitate the elimination of the condensation by positioning the tank vertically and taking the air from the top.

So, the tank can be useful to uncouple the operation of the compressor from the consumption of compressed air by users.

To further reduce the water vapor still contained in the air, a dryer can be installed downstream of the tank, which can be based on adsorption, deliquescence or refrigeration. The first system allows to obtain very low dew temperatures (from -20°C to -50°C) but for moderate flow rates. The second system provides low performance but for larger flow rates. The last system allows to obtain dew temperature of 2 - 3°C for medium high flow rates.

The distribution network serves to transport compressed air to every user. The distribution network can be made of steel, Nylon or Rilsan pipes.

The network can be designed according to two schemes: open ring and closed ring. In general, closed ring provides better performance but its installation is more expensive than the open ring because of the number of active branch and the larger number of used pipes.

The distribution network should be designed evaluating pressure drops and air velocity for all the principal backbones and the secondary sections and also taking into account:

- Maintaining $0.2 \div 0.5\%$ slope to avoid the accumulation of condensation;
- Posing junction sockets on the upper side of the pipe;
- Installing condensation separator filters.

1.3 Compressed air flow regulation

In an industrial plant, the compressed air flow need is variable over time and the CAS should provide the right flow rate every moments. several regulation methods are available. Most implemented are:

- Adjustment with throttle valve. The reciprocating, vane and screw compressors can be controlled using a suction throttle valve which can gradually close the suction pipe to compensate for the increase in pressure and thus reducing the flow rate. This type of keeps the pressure differential to a minimum, but requires high power also at low load. For this reason it is only used for compressors subjected to a high load.

- On/off regulation. This is one of the most widespread method. The compressor is activated or deactivated depending on the demand. This method is not applicable to power higher than 7 kW, since repeated stop and start can be very critical for the motor.

- Load/unload regulation. In this case, if the air demand is equal to 100% of the nominal capacity of the compressor, the compressor uses 100% of the power; if the request is null, the compressor starts idle but continues to consume between 25 and 30% of the power absorbed at full load. If after a set time, normally 15 $\div$ 20 minutes, the air request is still zero, the motor stops and restarts when a new request is made.

- Continuous regulation with inverter. This application involves the use of variable speed electric motors. Starting from a pressure signal, the electronic controller controls an inverter, which adequately varies the frequency of supply of the electric motor. If the pressure increases, in fact, more air is being produced than is being consumed and, therefore, the speed must decrease, to adapt production to consumption; in the same way, if the pressure tends to decrease, less air is being produced than is consumed and, therefore, the speed must increase. It can be mounted on reciprocating and screw compressors and in the presence of multiple compressors, speed control is necessary only on the final compressor, which will normally be “floating”.

The choice of the regulation method to be adopted depends, as mentioned, on the type of compressor and on how the demand varies over time. If the demand is variable with long intervals a load/unload control could be used. If demand is quickly variable the best choice is to install a continuous regulation with inverter.

1.4 Energy costs of CAS

The concept of energy management can be summarized as a systematic management and use of technologies to improve the energy performance maintaining constant the quality of products and services. It should be integrated, proactive and must include both the supply and efficient use of energy, as well as attention to renewable energy.

To improve energy performance it is important to act both on personnel and on technologies. It is important to focus on reducing waste in the use of energy, on the correct maintenance of the tools and on the revision of operating procedures in the direction of energy saving. By combining the use of new technologies and proper organizational management, aimed at efficiency, it is possible to evaluate all the opportunities for improving energy and environmental performance.

All the observation about energy efficiency can be extended to CAS management. Despite the importance in industrial plant operation, CAS energy consumption is often neglected. On average, CASs consume about 10% of overall industrial energy consumption, for this reason it is more important to take into account CAS energy management.

Moreover, the efficiency of the CAS is quite low: about 10% of electric energy provided is transformed into usable mechanical energy.

For all these reasons, many scientific works have been undertaken over the years to reduce energy consumption and also many practices have been proposed to improve energy performance.

In the following sections of the work, many aspects about CAS energy efficiency are faced up and some solution are proposed.

Chapter 2

Energy indicators and benchmark analysis

Introduction

The growing global energy consumption is at the base of the environmental problems that we all know, and causes noteworthy economic problems to national governments. The remarkable increase of world's energy consumption has encouraged scientists and industrial organizations to attribute even more importance to consumption reduction and energy management [6]. Considering that industrial sector is responsible for 54% of global energy consumption [15], a significant number of deeds have been undertaken by international governmental organizations to reduce energy consumption to their productive sectors. Industrial companies should consider the research for energy efficiency improvement as a pragmatic and attractive solution to reduce the production costs and increase their competitiveness in the market [16]. The increase in competitiveness, while conservating the profit margin, could be achieved by monitoring and controlling the performance, by highlighting weaknesses and using lessons learned [17].

The use of energy performance indicators and energy benchmarking is one of the most common and suitable approach to get information about energy performance and reduce energy consumption. Energy performance indicators and energy benchmarking have been applied and discussed in many scientific works [18] and their effectiveness is widely demonstrated.

The purpose of this section is to propose an energy benchmark analysis of industrial compressed air systems on Italian industries comparing their own performances with a benchmark previously unavailable.

2.1 Background

2.1.1 Energy efficiency measurement

The success of an industrial company derives from many aspects related to production, energy consumption and management [19, 20]. Energy efficiency and production improvements are two parts of a fundamental strategy to maximize revenue and minimize costs [21]. In terms of production and energy consumption, final performance can be monitored, as already said, through the use of the energy performance indicators (EPI) [22, 23]. Several EPIs are available for monitoring industrial energy performance and undertake energy benchmarking. In order to have a general overview, aggregated measures are suitable. Instead, detailed results require the definition of specific energy drivers for the facility [24]. Usually, in a specific application field, more useful EPIs are ratios describing the relationship between an activity and the required energy [25, 26].

Despite the paramount importance of compressed air generation in energy consumption, a common methodology to evaluate compressed air systems performance is still missing. Furthermore, only few documents and reviews regarding methodologies for energy benchmarking applied in compressed air production, consider operating conditions as well as nominal ones [27].

CASs are often very complex and composed of numerous components. Each of them could have very variable characteristics, which can make the overall performance and consequentially EPIs radically fluctuating. A typical compressed air system can be divided into 3 functions: compressed air generation (compressors, filters, dryers, etc.), transport (distribution network) and use (users). To get a high level of energy efficiency, all functions need to be well-designed and operate at their best. Therefore, the development of a complete framework of potential energy efficiency improvement actions for the whole system, comprehensive of all the factors influencing the effectiveness could be very complex. A possible solution could be to consider most influential factors of each function and to prioritize related activities. The following factors have been here considered essential on the basis of author's experience:

1. system pressure (set point and variation) and specific compressor energy consumption;
2. compressed air dispersion during transportation phase;
3. specific demand (air demand per unit of production);
4. environmental variables (air quality and humidity).

The number of factors that have to be monitored for a good characterization of the performance of compressed air generation is very large and each of them has a contribution in terms of percentage of overall energy saving [28]. Radgen and Blaunstein in [29], Saidur et al. in [30] and Compressed Air Challenge [31] provide lists of the most influencing factors for energy performance. According to author's experience, to implement a first level of control over the system, it could be sufficient to select the most important aspects and act on them. Therefore, selecting the most relevant factors allows to have a fast reaction and efficient interactions with companies.

Obviously, monitoring an industrial plant has become easier thanks to the wide use of distributed control systems and new measurement technologies that allow you to monitor energy consumption, production, hours of operation etc. The evolution of these systems is an essential part of the transition to Industry 4.0 [32].

Performance indicators, besides offering an indication of the industrial performance over time, are also used to compare the company performance with those belonging to the same productive sectors or even within the same organization (external and internal benchmarking).

The most used performance indicators can be grouped into four categories:

1. Thermodynamic indicators. These indicators provide measurements of the thermodynamic efficiency, for example in term of change of enthalpy (ΔH) for first law efficiency or change of entropy (ΔS) or exergy for second law efficiency.
2. Thermo-physical indicators. These are hybrid indicators describing how much energy is needed for producing each output.

3. Thermo-economic indicators. These indicators measure the change in secondary energy consumption led by the energy intensity differences between the computation year and the base year.

4. Economic indicators. These indicators consider that energy price should be adopted instead of thermodynamic units for the energy inputs.

A more extensive discussion about performance indicators was made in [27].

For every systems, depending on the available data type, it is useful to encourage a different approach to make a more effective analysis. Getting into details about CASs, energy consumption data are surely the most important index, but some relevant information can be obtained knowing both the equipment and the network type and their management.

In order to monitor the degree of potential efficiency improvement, for our application can be considered only thermo-physical indicators. These consider several factors including: leakage rates, system pressure (set point and variation), specific demand (CAS demand per unit of plant output), specific power consumption of compressors, environmental variables (air quality, water quantity [28]).

Mathematical and engineering methods often estimate energy consumption and main production from datasheets, physical relationships and working simulations. This kind of approach is favourable in regard to ease data collection but it is less reliable because of some important approximations. Energy consumption is indeed the result of many technical aspects [1] but also people behaviour and their awareness towards energy saving influence it [33]. These aspects, although very significant, are not taken into account. Because of these approximations, a novel method employing measured data and a questionnaire has been developed to led a benchmark analysis [34] and achieve more detailed information about working conditions (production schedule, maintenance schedule, etc.) [35] and system characteristics (size, elements which is composed of, etc.). Methods using measured data need large investments and a lot of time to collect requested data [36] nevertheless allow to use reliable data. Moreover, the questionnaire has positive and negative aspects: it can help companies to carry out the awareness of importance of energy efficiency improvement [37] but its compilation could require a lot of time.

2.1.2 Benchmark

Benchmarking is a valid process that allows companies to evaluate energy performance of an organization comparing with the others [18]. It means that, to assess energy performance, it is necessary to compare its substantial function with those of others. Benchmarking is regarded as an effective methodology to assess energy performance and improve energy efficiency [38]. According to [39], energy benchmarking allows a complete industrial plant (or sector) energy performance evaluation against a reference one representing the best practices. A benchmark analysis can help an industrial company to assess its own performance with that of other companies belonging to the same sector. Also, it could be used to evaluate energy efficiency of a specific facility in different plants. According to [40], performance benchmarking is a necessary step for a competitive industry. One of the main characteristics of the benchmark analysis is also the opportunity to identify and compare inefficiencies in energy use in different periods and conditions [39]. Benchmark results are also a valid starting point for the implementation of a targeted intervention aimed at improving energy performance [41].

Building a significant benchmark requires a certain number of data in order to calculate the indices necessary for the comparison. Thus, companies are obliged to install measuring systems and should collect the largest possible number of data sample to define a benchmarking model. Furthermore, there is not a unique method to develop a benchmark analysis; the choice of method depends on available data and obtained results [42].

Benchmarking could be achieved at different levels of complexity from basic single-factor measures up to complex econometric techniques and mathematical programming approaches [43]. In some cases, energy benchmarking has been performed on a whole industrial sector, analysing energy consumption related to CO_2 production [44], e.g. based on data from enterprises belonging to mineral comminution industry or cement industry [45, 46]. Moreover, there are some examples in which only a particular type of installation has been considered (e.g. wastewater treatment systems [47], ventilation systems for offices [48], thermal power plants [49], transport means [50, 51] and energy consumption of commercial buildings [52]).

2.2 Method

In this phase, a thorough benchmark analysis would be accomplished. Available data about industrial energy consumption come from a collection of Italian energy audits encouraged by European Union in [4]. About 15000 final reports of energy audit have been collected in 2015 by ENEA and analyzed to compose the available database [27]. The available database includes information about the annual consumption of the whole industrial plant, energy consumption related to main production and to compressed air service, annual industrial production volumes and production of compressed air.

To develop a benchmark, several analyses are performed on database. The first phase concerns a preliminary analysis that has allowed to select 9 significant industrial sectors in Italian context. The industrial sectors of food products, paper, metal products, plastics products, chemical products, pharmaceutical products, manufacture of basic metals, motor vehicles, textiles, have been selected because of their energy consumption and high number of samples available [27]. To develop this section, the definition of the CAS energy indices comes from the ENEA activity, instead data analysis and benchmarking are an original contribution.

2.2.1 Preliminary analysis

Before developing the energy benchmark analysis, it is necessary to provide a thorough description of data used. The preliminary analysis is useful to define the sample of usable data among the 15000 audit and permits to continue with successive analyses. Also, it allows to describe the importance of CASs energy consumption in Italian industry. In this phase, each sector is characterized in terms of energy consumption for compressed air use and its importance on the overall consumption.

It is important to note that available database come from energy audits. In some cases the indicated values for energy consumption both for the entire plant and only for CAS are not referred to direct measurements but they are the results of estimates provided by auditors. Specifically, estimated data could come from calculations on the basis of non-continuous measurements, spot measurements, running time of main productions and electric bills. Although available data could not come from continuous measurement, estimates are provided by experts and their significance is proved. Moreover, despite the unavoidable uncertainty, the methodology could be a good basis for further analyses based on more accurate data.

The first step in providing a valid benchmark based on actual production data consists in the definition of a set of Energy Performance Indicators (EPIs) specific for Compressed Air Systems. EPIs for CAS are based on the technical-scientific literature and industrial practice. They are defined in terms of energy demand, end use, technology, process and device. All of them could be used to compare various cases thanks to their universality. Starting from these considerations, four performance indicators have been used for the energy performance comparison as proposed in [27]. These indicators are related to both physical and energetic aspects. In general, physical-based indicators relate energy consumption to a physical quantity (e.g. tons of steel, passenger-kilometres, floor area in square meters, etc.) [53]. In CAS application, performance indicators generally refer to various aspects of industrial production, in particular specific energy consumption can depend on several energy drivers, such as the number of produced units and the operating hours.

The indicators identified as the most suitable are the following:

1. kWh_eCAS/ kWh_eTOT. It is the ratio between the amount of energy consumed for the compressed air production and the total electrical consumption.

2. kWh_eCAS/t. It is the ratio between the amount of energy consumed for the compressed air production and the principal production volume, generally expressed as tons of final.

3. kWh_eCAS/m^3. It is the ratio between the amount of energy consumed for the compressed air production and the volume of compressed air produced, providing an indication about the energy efficiency of CAS;

4. m^3/t. It is the ratio between the volume of produced compressed air and the production volume.

The first EPI (kWh_eCAS/ kWh_eTOT) allows evaluating the incidence of CAS on total electric energy consumption. It provides an indication on the influence of CAS on the electricity bill. It also allows the comparison between industrial plants belonging to the same production sectors because of their similarity regarding production type, production method etc. This indicator is often used to identify the sectors where energy consumption of CAS is more significant.

The comparison between the energy performance of companies belonging to different industrial sectors does not provide significant results. The compressed air consumption of different processes is not comparable in terms of amount of compressed air for unit of product. For this reason, the second KPI can be used to obtain information on the energy amount needed for a single productive unit or for a single type of production. Indeed, this is a very common benchmark indicator within a given sector (i.e. an industrial sector characterized by similar products). It can highlight performance gaps between two or more companies due to the implementation of different technological solutions.

The third indicator provides an indication about energy performance of compressed air transport and use. This is the most suitable indicator for a benchmark analysis involving a lot of enterprises belonging to very different sectors. It is not very sensitive to different application fields unless that the feature of compressed air requested (pressure, quality level, etc.) changes drastically from one case to the others.

The fourth indicator measures the energy performance of the compressed air users. It can indicate the presence of waste or improper use in production departments or losses in distribution systems.

The third indicator, $\mathrm{kWh}_e\mathrm{CAS/m}^3$, results the most suitable to develop our benchmark analysis. Its behaviour is substantially released from the type of production and plant taken into account. Indeed, such an indicator allows to compare data from different companies without considering the processes that use compressed air and the size of the company.

The results of the evaluation of chosen EPI on the whole database are statistically characterized through the analysis of average values, data distribution and Gaussian distribution. Initial analyses are undertaken using two basic statistical indicators, the mean and the median.

The further analyses are performed according to the following sequence:

1. analysis of the normality of data distribution through the Anderson-Darling test [54] performed through statistical software;

2. analysis of the standard deviation;

3. analysis of the population symmetry over the average value through the “skewness” index;

4. analysis of the extent of distribution through the index of “kurtosis”.

These analysis are important to establish if the samples within the database are normally distributed, if they can be correlated to each other and state if there are differences in data distributions among sectors. Also, analyses of variance (ANOVA) are implemented to evaluate if there are differences between the mean values of the samples of each industrial sector. ANOVA provides further information about the significance of the sample taken into account and it is useful to develop benchmark analyses.

All the introduced analyses refer both to the measured sample the estimated one. A sample is considered estimated when at least one of the component of the EPI is an estimate.

2.2.2 Benchmark

The benchmark should help organizations to determine how efficiently each plant is operating. It allows to highlight the worst and the best energy users, revealing which organizations would achieve the largest energy savings from implementing energy management measures.

Before introducing energy benchmark methods, it is important to remember that, to carry out a significant analysis, suitable EPIs should be selected and that provided results are strongly influenced by chosen indicator. After chosing the most relevant EPI, actual performance of a company can be compared with the performance of all existing samples [49].

The technical literature provides a wide range of methods to develop significant benchmarkings, as described below:

1. The *normalization* is the simplest and the most widely used approach in industrial sector thanks to its simplicity of implementation and interpretation. It consists in the evaluation of energy efficiency through the comparison of EPIs (often represented by simple ratios). These indicators are obtained normalizing the energy use based on a given level of output or activity. The energy consumption could be calculated referring to the volume of processed products or, in this case, to the volume of compressed air. Such data are often available to perform a simple comparison and also suitable

to create an EPI combining different indicators.
This kind of indicators have also some drawbacks represented by the excessive simplistic representation. The first is the assumption that small and large plants can be compared in their performance assuming a linear correlation between inputs and outputs. The second is the use of only one metric to compare the whole population not considering the different feature of industrial processes. For instance, pressure level and filtering methodology make inappropriate the use of too simplex indicators to represent the compressed air system performance. For these reasons, the use of this method is limited to evaluation of similar size organizations [47].

2. The *frontier analysis* uses a profile (a frontier) to define the average or the best performance for a determined set of inputs (i.e. operational and design data) [55]. To define the frontier, a linear regression model is developed using data on energy use or EPIs [56]. The linear regression model can be easily described through:

$$E = \alpha + \beta Y + \epsilon_i \tag{2.1}$$

where E represents the energy use, Y is the operational or design data, β is the slope coefficient, and ϵ_i is the error term that defines the relative inefficiency. The regression line represents the average efficiency level. A benchmark system is developed based on the distribution of residuals of the regression model. The residual is the difference between the actual and the predicted (represented by regression line) energy consumption. Thus, the residuals are treated as measures of inefficiency. Negative residual means that the plant uses less energy than similar plant with same characteristics. Regression-based benchmarking tool has been applied by Energy Star in [57]. This approach has some drawbacks. The first is the necessity of a large database to obtain reliable results. The second is the sensitivity of regression to functional form. The last is the possibility to monitor only one inefficiency using an unique indicator not considering the other inefficiencies.
The stochastic frontier analysis potentially leads to very accurate measures of relative efficiency because it assumes separately the distributions of the inefficiency and the errors. Error is considered

as a variable and its distribution estimation (to reach a sufficient robustness) requires a large database to be determined.

3. *Programming methods* are based on the frontier approach but apply optimization methods, based on the collected data, to define a useful contour for a subsequent comparison. This approach offers better frontier definition comparing with parametric models. In fact, the functional form of the frontier may be modified adding new data. In this way, the possibility to define a wrong model of the frontier is minimized. This approach has some disadvantages. The efficiency score tends to be sensitive to the choice of input and output variables; ineffective variable specification can lead to a wrong defining of the frontier and to wrong results. The variables should, as far as possible, reflect the main aspects of resource-use in the activity concerned. On the contrary, the KPI does not represent necessarily the organization performance.

2.3 Results

In this section, results of preliminary analysis and benchmarks are collected. The preliminary analysis is used to build and analyze the most suitable database and get preliminary information about selected industrial sectors.

2.3.1 Preliminary analysis

Within the over 15000 collected samples, a subset composed of 1735 industrial has been selected for benchmark analysis. The database collects data regarding 9 industrial Italian sectors that are: food products, paper, metal products, plastics products, chemical products, pharmaceutical products, manufacture of basic metals, motor vehicles, textiles. The remaining sectors are not used because of their scarce significativity and their lack of completeness.
From the selected database, data coming from those organizations that did not provided accomplished values are excluded. The remaining useful sample for the analysis is then made up of 475 samples, each from a different industrial plant. The percentages of data split by sectors are shown in Figure 2.1, which clearly shows that the most relevant sectors are food, metal, basic metal, plastic and chemical production.

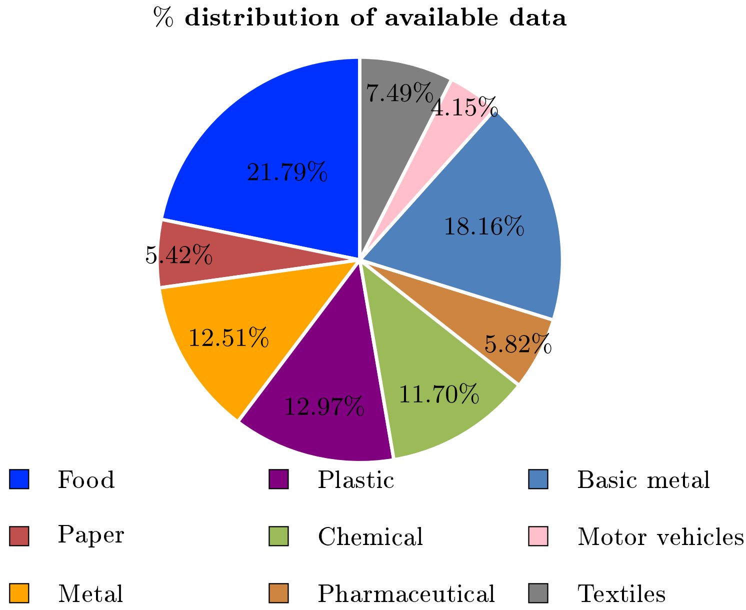

Figure 2.1: *Subdivision of available data among the 9 most relevant sectors: food, plastic basic metal, paper, chemical, motor vehicles, metal, pharmaceutical, textiles.*

Considering all 475 samples, the overall amount of energy consumed in one year is about 28 TWh. As detectable from Figure 2.2, metal and chemical production are, in absolute terms, the most important energy consumer sectors. In terms of percentage, it is possible to note that these two sectors consume together more than 55% of the overall energy.

As depicted in Figure 2.1, samples are not equally distributed among sectors, for this reason the average energy consumption of all sectors is calculated and represented through the barplot in Figure 2.3. The most energy-consuming industries belong to sectors that produce metal, paper and chemical products. For these industries the average energy consumption are respectively 48 GWh for metal production, 33 GWh for paper, and 26 GWh for chemical sector.

Different evaluations can be made considering the overall electric energy consumption and the electric consumption for CAS. The overall industrial electricity consumption for the reference sample is 28 TWh while the consumption for CAS is 2.56 TWh. This data confirms that CAS consumes about $9 \div 11\%$ of industrial electric energy. Figure 2.4

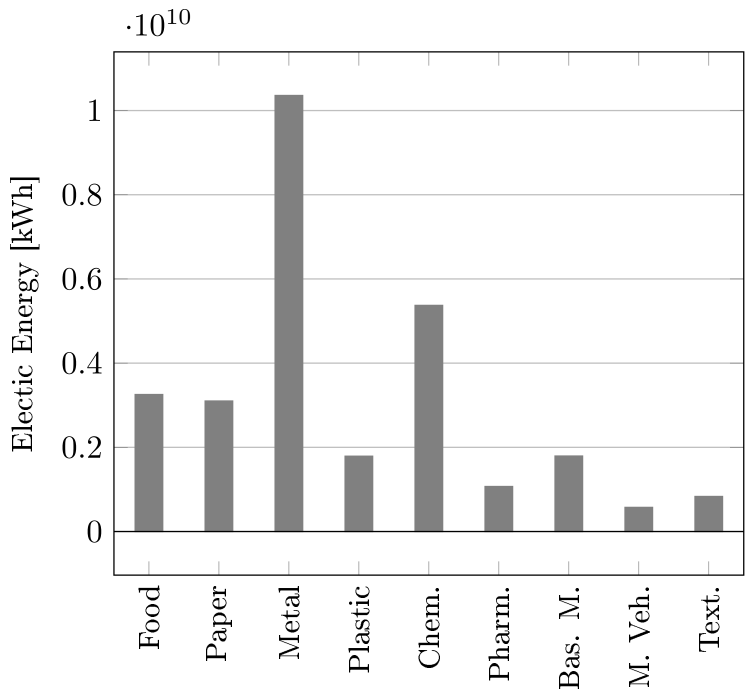

Figure 2.2: *Electric energy consumption of each considered industrial sectors.*

shows how the energy consumption, strictly related to CAS, is distributed for each industrial sectors. Getting into details, in chemical industrial plants, CAS energy consumption represents 25% of the overall and for metal production it can reach 12%. These values underline the importance of energy consumption monitoring considering an improvement of energy efficiency.

Examining in dept these data, as shown in Figure 2.5, most of the sample about industrial electric energy consumption (about 77%) derives from continuous measurements. The rest derives from estimates (spot measurements, estimation from bills, etc.) and from not available sources. This is a good scenario considering that performance measurement is universally acknowledged as the main activity to achieve energy performance improvement. For CAS, only 38% of data about electricity consumption due to this service derives from continuous measurement and then from a sure source, as shown in Figure 2.6. This low index is a limit to overtake in the future.

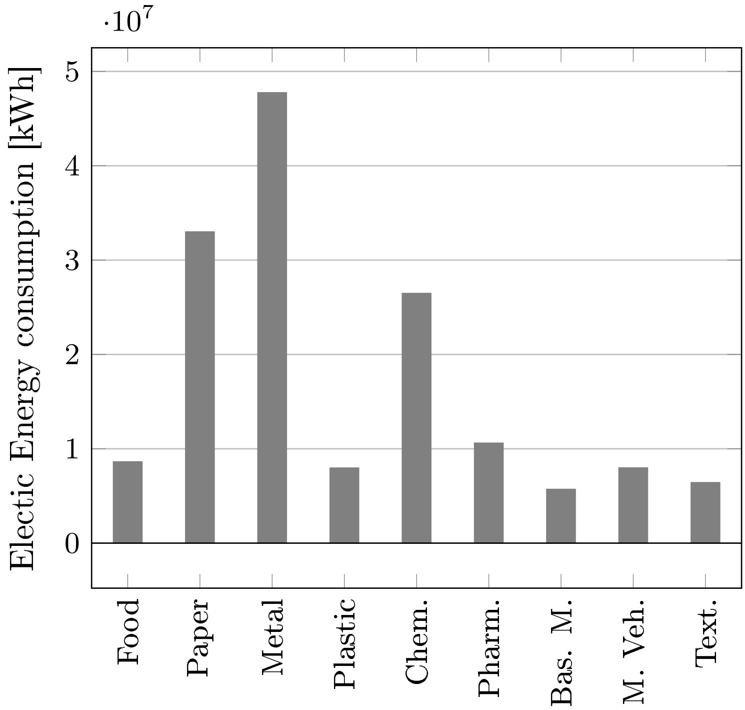

Figure 2.3: *Average electric energy consumption of each industrial organization of all considered industrial sectors.*

Scientific literature suggests several indicators to assess CAS energy performance as reported in 2.2.1.

The variables used for this data analysis are kWh_eCAS to measure electricity consumption and m^3 to measure compressed air. These variables have been aggregated into a single KPI: kWh_eCAS/m^3.

According to the European Community "The energy cost of compressed air is expressed in terms of specific energy consumption (SEC) in Wh/Nm^3. For a correctly dimensioned and well managed installation, operating at a nominal flow and at a pressure of 7 bars, the following can be taken as a reference (it takes different compressor technologies into account): 85< Wh/Nm3 SEC <130 Wh/Nm^3 (...) This ratio represents the quality of the design and the management of the compressed air installation. It is important to know and monitor it (...), because it can quickly deteriorate, leading to a large rise in the price of the air." [58].

In the present work, the scenario is substantially different. The suggested quantities can be referred only to well-designed systems

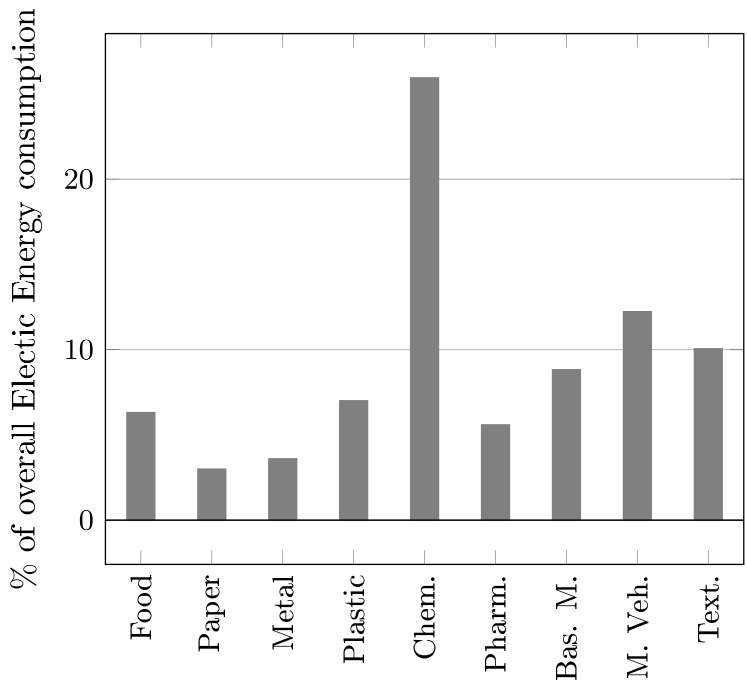

Figure 2.4: *Percentage of electric energy consumed by CAS in each considered industrial sector.*

operating in nominal conditions. These conditions are difficult to be comply with in everyday use, so only the volume of compressed air produced will be here considered. The data analysis has highlighted that most companies use the compressed air at a fixed pressure level between 6 and 6.5 bar. For this reason, the pressure has been considered equal for every sample.

The following sections will show the results of the statistical analyzes relating to each sector of interest. For each of the 9 sectors, statistical analysis are shown both on measured sample (when available) and on estimated one.

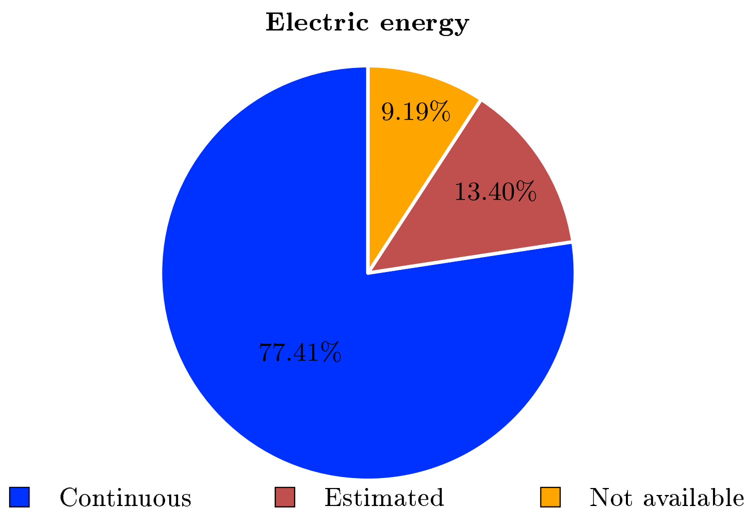

Figure 2.5: *Percentage of measured (continuous), estimated and coming from not available sources.*

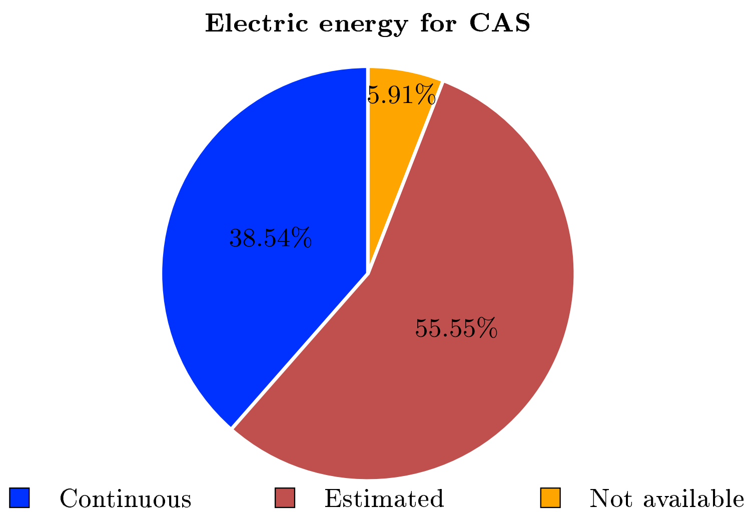

Figure 2.6: *Distribution of electric energy consumption data: measured (continuous), estimated and coming from not available sources.*

Food industry

The first sector under consideration includes the processing of products from agriculture, forestry and fishing. Companies belonging to this sector are employed in the transformation of raw materials into food and edible drinks for humans or animals. These companies process different products like meat, fish, fruit and vegetables, fats and oils, dairy products, grains, bakery and flour products and other food products. This sector also includes the processing of intermediate products that are not strictly related to food, such as leather from slaughterhouses. In general, production can be carried out on their own or on behalf of someone else. Some activities are considered as manufacturer (bakeries that sell their products) even if the products are sold at retailed in their own store.

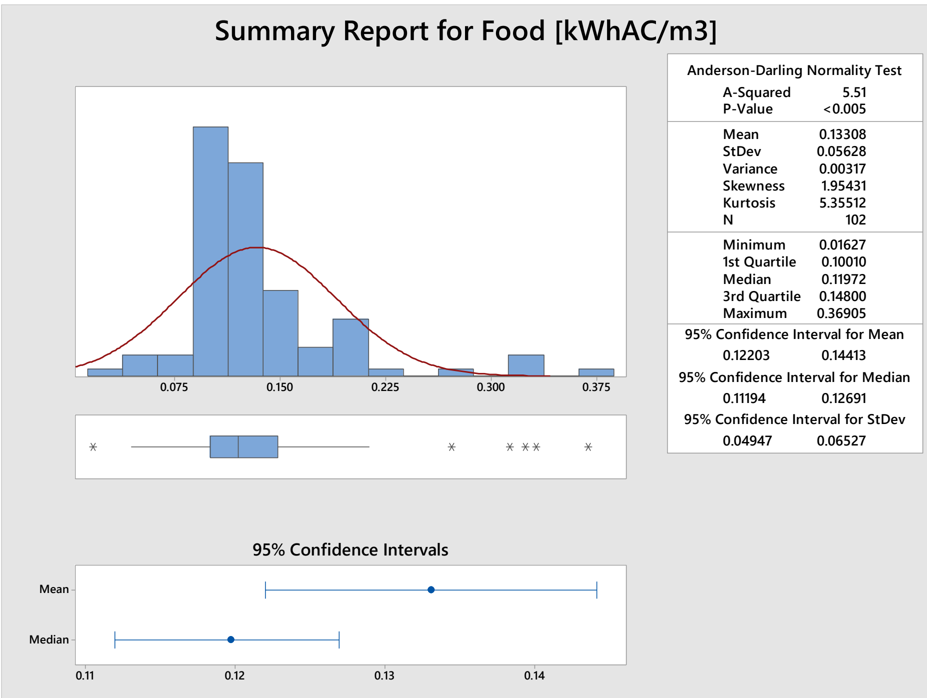

Figure 2.7: *Statistical analysis using the indicator kWh_eCAS/m^3 of the sample containing all data (both estimated and measured) about food organizations.*

This sector does not include the preparation of meals for immediate consumption as in restaurants. Also activities where the processing are minimal and do not lead to a real transformation, are classified in another sectors which includes wholesale and retail trade. The preparation of food for immediate consumption, the processing of food and beverage waste into secondary raw materials and the disposal of food and beverage waste are included in other sectors [59].

Statistical analyses on food sector are reported in Figures 2.7 and 2.8. Analyses and graphs are based on the indicator ($kWh_e CAS/m^3$) previously described and calculated on all the samples of the food sector (Figure 2.7). Considering both measured and estimated values, the results show that the statistical distributions, based on the Anderson-Darling normality test, are not symmetrical Gaussian distributions. Also kurtosis and skewness indices are higher than 0, confirming the absence of a Normal distribution.

Although the outliers are previously eliminated, from boxplot it is simple to find some out of control within the sample, these affect negatively the distribution above all the mean value. Considering mean and median values, the differences between the two values are obvious in overall analysis. Considering only continuously measured values, the difference is very reduced. Furthermore, as regards the data coming from continuous measurements (Figure 2.8) these do not represent a representative sample considering the scarcity of available data.

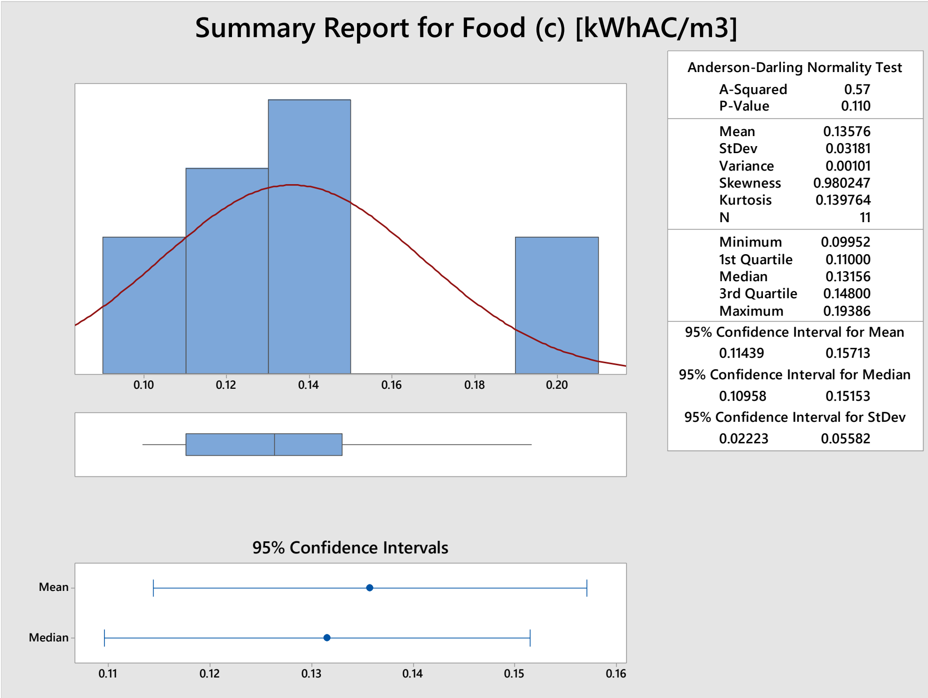

Figure 2.8: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing only continuously measured data about food industries.*

Paper

The activities belonging to the current sector are related to the manufacture and processing of paper and products resulting from its transformation. Three large categories of processes belong to this sector: the manufacture of pulp, the manufacture of paper, the processing of paper and cardboard products. The first activity involves the separation of the cellulose fibres from the other impurities of the wood or from the recycled paper. The second involves the processing of the cellulose fibres in sheets and the third is the production of paper and cardboard sheets adding different materials. The manufacture of printed paper articles (for example: wallpaper, gift wrap etc.) is included in this sector only if the printing activity is not the main purpose [59].

Figure 2.9 shows the results of statistical analysis performed on available database using the indicator described above ($\mathrm{kWh_eCAS/m^3}$). The sample is not very large, especially values derived from continuous measurement are not numerous. For this reason, the measured sample is not significant and the statistic analysis is performed only on overall sample not considering the differences between the estimated and measured data.

Considering the statistical distribution, the Anderson-Darling normality test states that the distribution is not normal and not symmetrical even if the index is quite low. The skewness index is low but the kurtosis has a negative value. These are other indications of the general deviation of data distribution. From boxplot it is easy to note that the difference between the second quartile and the first is much smaller than the difference between the third and the second, for this reason the median is quite different from the mean value.

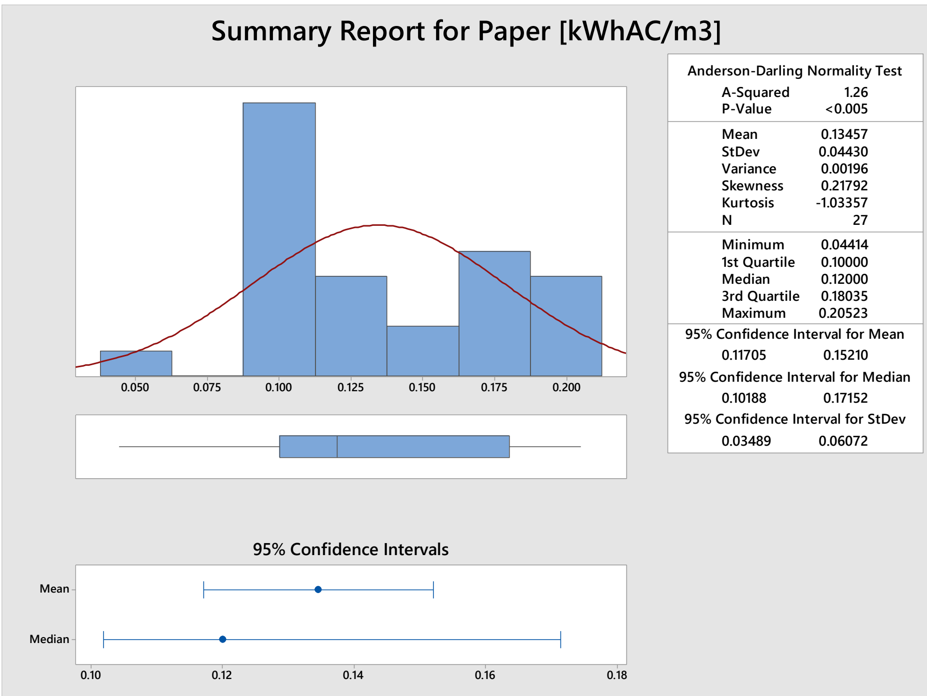

Figure 2.9: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing all data (both estimated and measured) about paper production sector.*

Metal products

This sector includes the manufacture of metal products (such as parts, containers, structures), generally with a fixed static function. The manufacture of weapons and ammunition is included in this division [59].

Figures 2.10 and 2.11 show the statistical analyzes and graphs performed on the overall sample and on the sub-sample deriving from measurements. For this sector, the statistical distributions of the values, based on the Anderson-Darling normality test, are strongly not normal and not symmetrical. The high values of the kurtosis and skewness indices highlight the dispersion of the sample. As can easily be identified in Figure 2.10, within the sample several values are considerable as outliers. They negatively influence the mean which is very different from the median.

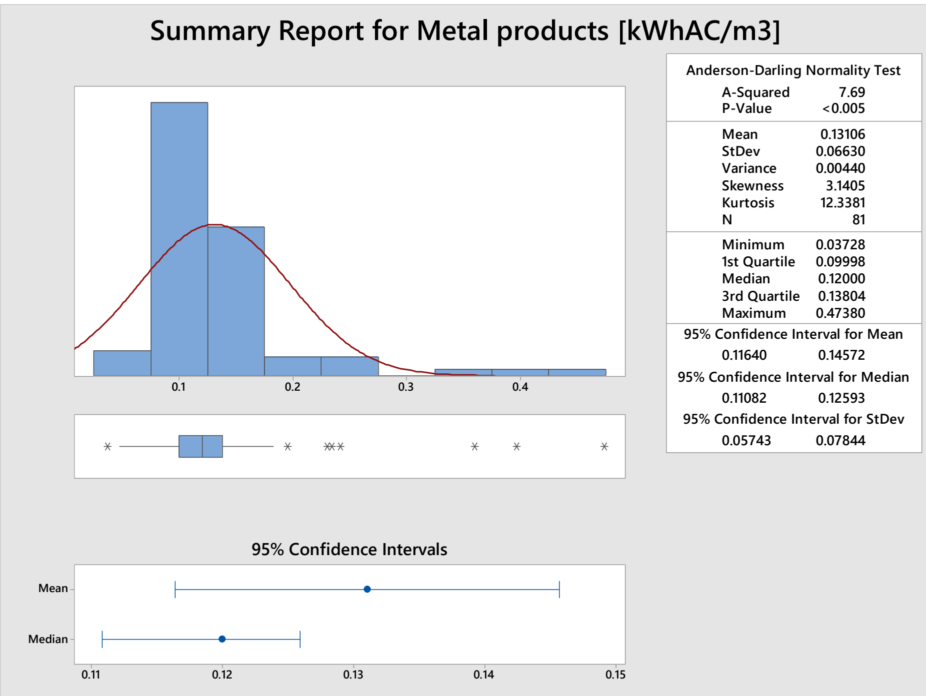

Figure 2.10: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing all data (both estimated and measured) about metal production sector.*

The boxplot highlights the presence of outliers and shows the comparability between the difference between the first, the second and third quartile. The analysis of continuously measured sample shows that

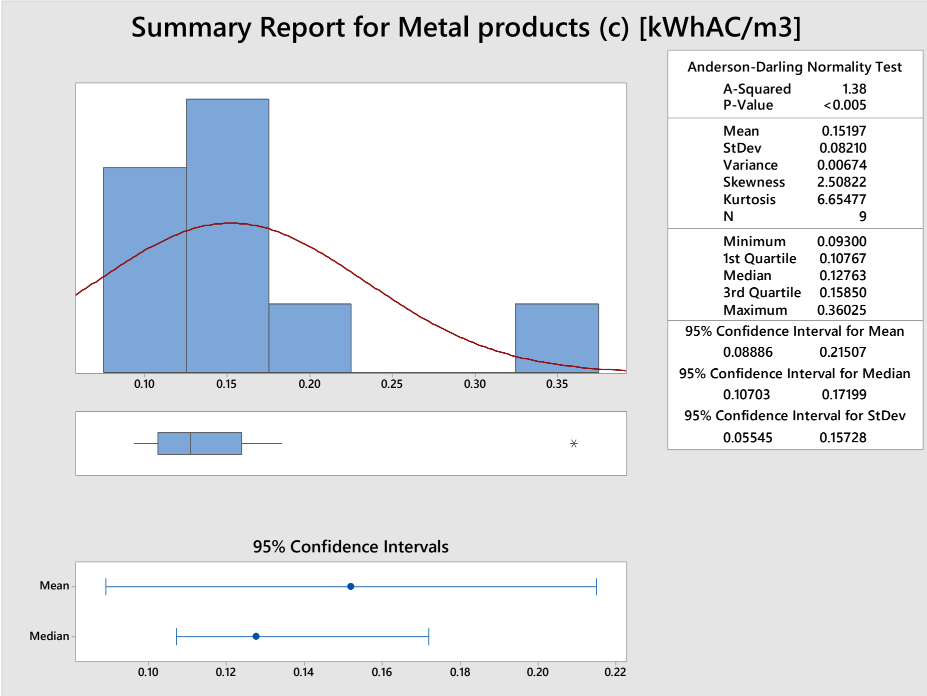

Figure 2.11: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing only measured data about metal production.*

the normality once again is not respected but mean and median are more similar.

Plastic products

The companies of this sector transform new or used plastic resins (for example recycled) into intermediate or final products, using processes such as compression, extrusion, injection, blowing and melting. The production process allows to obtain a wide variety of products [59].

The sample of measured data collects few values, for this reason the analyses do not consider the differences between overall and measured data. From the histogram in Figure 2.12, we notice a certain dispersion despite the out-of-control data have been previously eliminated. The distribution is not normal and this is highlighted by the Anderson-Darling test. The values of kurtosis and skewness also highlight this characteristic. The boxplot indicates the presence of only one outlier. The difference between the quartiles are low and also the mean and the median values are also very similar.

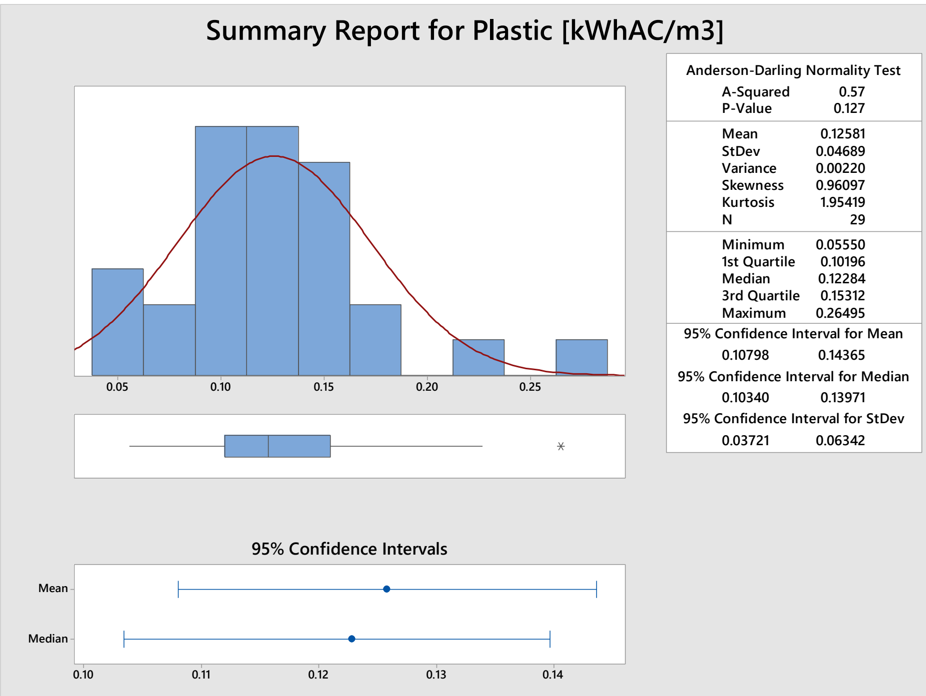

Figure 2.12: *Statistical analysis using the indicator kWh_eCAS/m^3 of the sample containing all data (both estimated and measured) about plastic production sector.*

Chemical products

The companies belonging to this sector work raw organic and inorganic materials through chemical processes and produce specific products. The production of basic chemical elements, which constitute the primary industrial group, is discerned from the production of intermediate and final products obtained through further processing of the basic chemical elements [59].

The results of the statistical analyses are collected in Figures 2.13 and 2.14. From the histograms, it is easy to note that the data available have a strong dispersion and a not normal distribution. The Anderson-Darling test confirms this characteristic and the index of skewness indicates that data are unbalanced with respect to the average value on the side of smaller values.

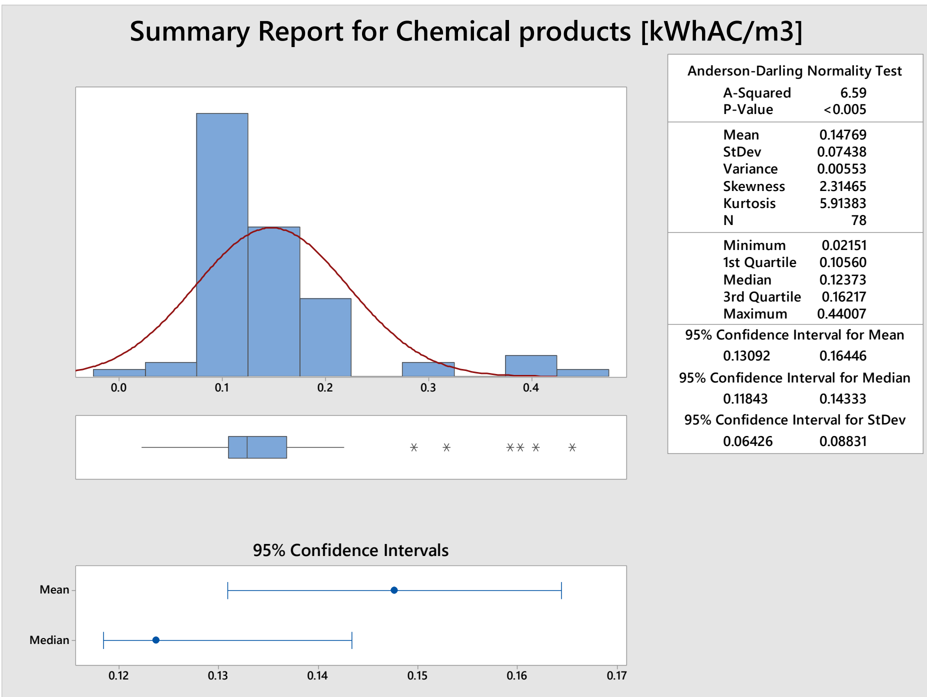

Figure 2.13: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing all data (both estimated and measured) about chemical production sector.*

The boxplot highlights the presence of several outliers that influence negatively the distribution and also the difference between mean value and the median. Considering only the database of measured data, the distribution shows a great dispersion even if the normality index improves respect to overall database. Visually, the distribution has null columns due to the lack of collected data and also 3 outliers showed in boxplot. The presence of these values modifies the distribution making the difference between the quartiles very large.

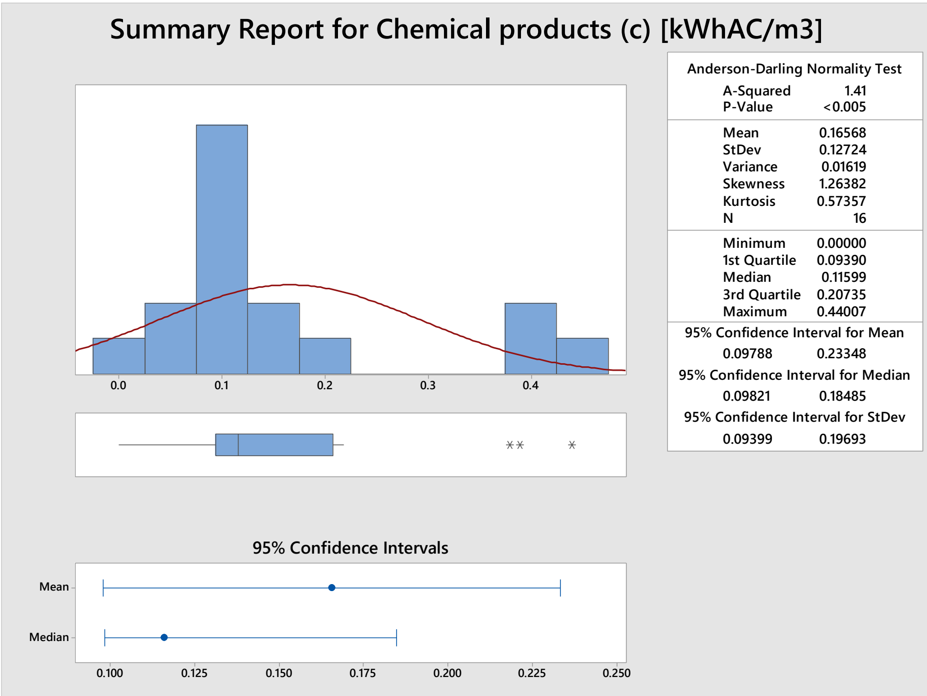

Figure 2.14: *Statistical analysis using the indicator kWh_eCAS/m^3 of the sample containing only measured data about chemical production.*

Pharmaceutical products

This sector includes the manufacture of basic pharmaceutical products and preparations. The manufacture of chemical and botanical products for medicinal uses is also included [59].

Figures 2.15 and 2.16 show the statistical analyses and graphs performed for the indicator described above and calculated on the totality of the sector data or on the part of the values deriving from measurements. The distribution of the sample data does not take the classic bell shape due to a Gaussian distribution as can be seen from Figure 2.15. The histogram shows that the samples are numerous both in lower and upper limits. Moreover, the central value is not the most numerous. The Anderson-Darling test values indicates a relatively low dispersion, the values of kurtosis and skewness are low, so data are fairly balanced.

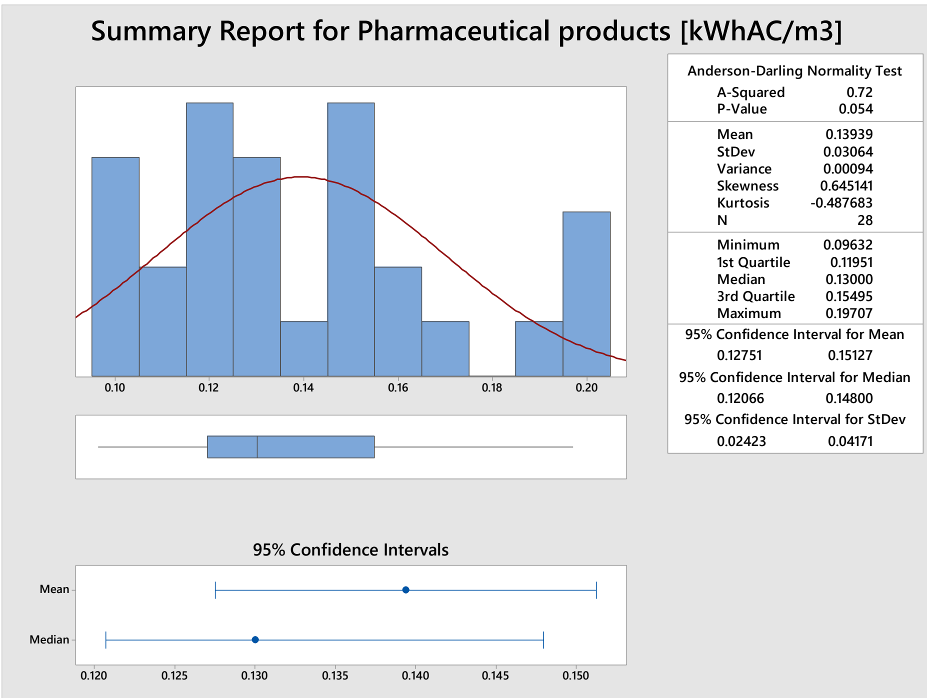

Figure 2.15: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing all data (both estimated and measured) about pharmaceutical production sector.*

The boxplot does not highlight any outliers but there is a large imbalance between the first, the second and the third quartiles.

Considering only the measured data it is not possible to make further statements considering the scarcity of data available (Figure 2.16).

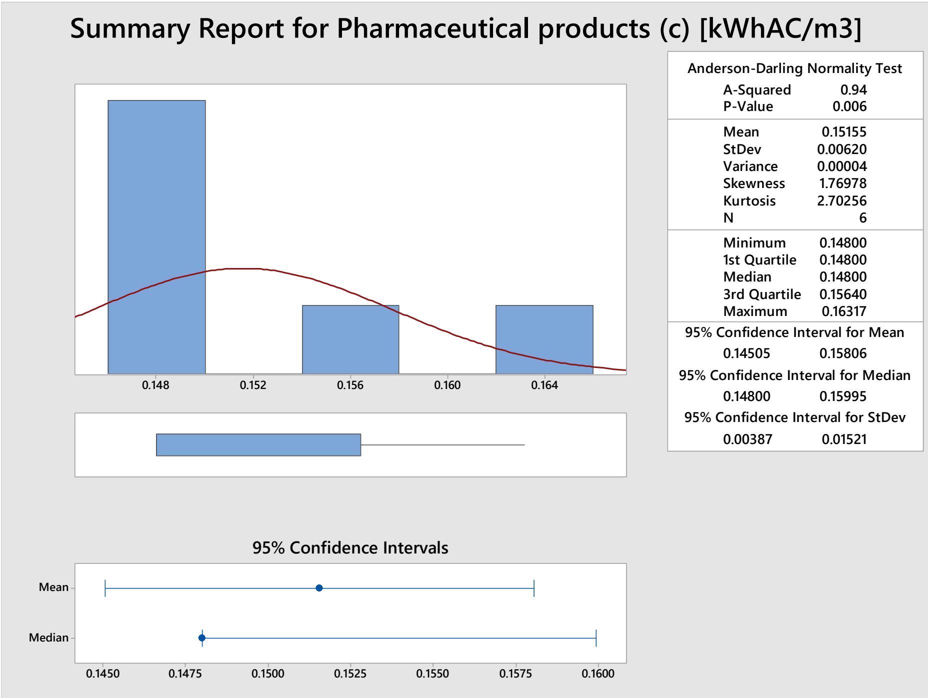

Figure 2.16: *Statistical analysis using the indicator kWh_eCASm^3 of the sample containing only measured data about pharmaceutical production.*

Basic metal

The organizations that are part of this industrial sector put their efforts in fusion and refining activities of ferrous and non-ferrous metals from minerals, metal ingots or metal scrap, with electrometallurgical techniques and other metallurgical techniques. The processing of addition of chemical elements in the pure metals to obtain alloys of metals is also an activity of this sector. The products obtained by melting and refining, generally in the form of ingots, are transformed by rolling, drawing and extrusion into sheets, strips, bars, rods or wire rods and in cast form, to make foundry pieces and other metal products [59].

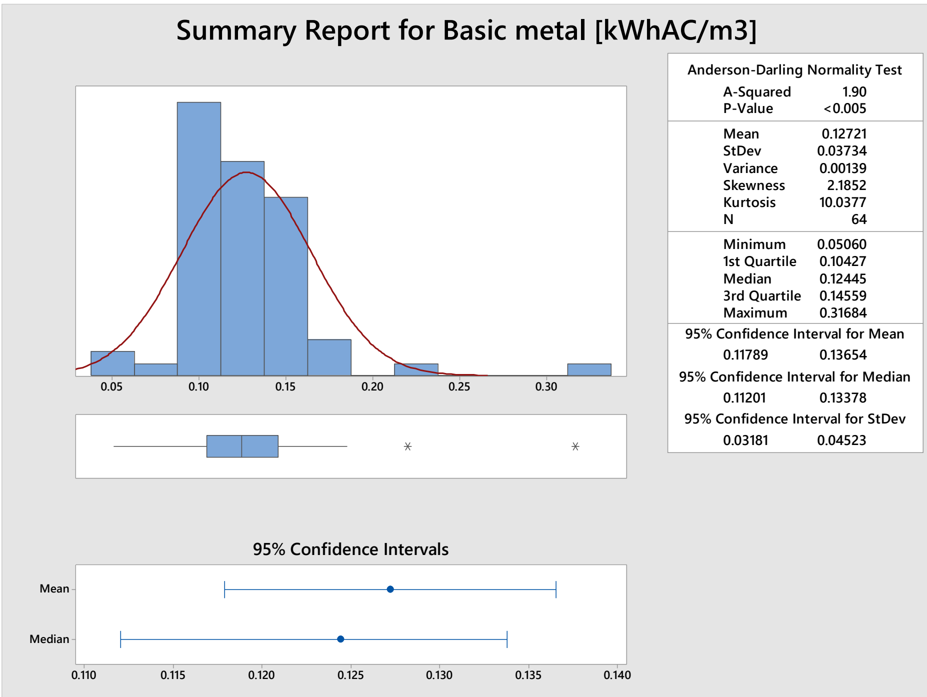

Figure 2.17: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing all data (both estimated and measured) about basic metal sector.*

Figures 2.17 and 2.18 show the statistical analyses and graphs made for the indicator described above and calculated on the totality of the sector data or on the part of the values deriving from measurements. For this sector, the statistical distributions of the values, based on the Anderson-Darling normality test, are not normal and not symmetrical, especially as regards the set of measured data. The out of control indices were previously eliminated as they were visibly wrong and radically modified the histograms, making them less representative of the sample. The boxplot indicates the presence of few outliers and the good correspondence between mean and median. This is also confirmed by the low difference between the first, the second and the third quartiles. Furthermore, regards the data coming from measurements, it must be said that these do not represent a representative sample considering the scarcity of available data.

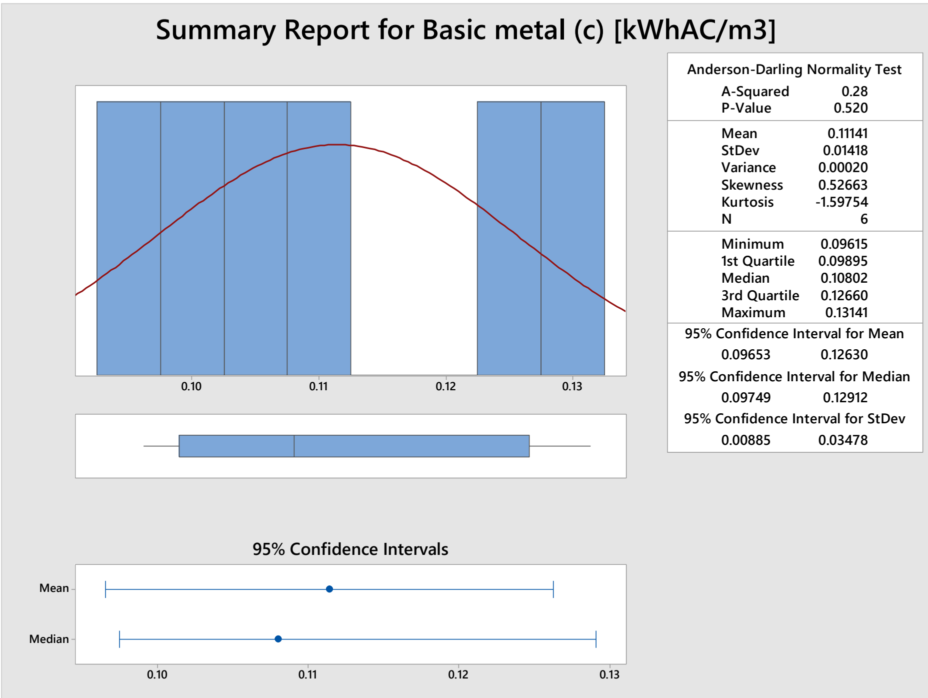

Figure 2.18: *Statistical analysis using the indicator kWh_eCAS/m^3 of the sample containing only measured data about basic metal production.*

Motor vehicles

This sector includes the manufacture of motor vehicles for the transport of passengers or goods. The manufacture of parts and accessories, as well as the manufacture of trailers and semi-trailers is included [59].

Figures 2.19 and 2.20 show the statistical analyzes and graphs performed for the indicator described above and calculated on the totality of the sector data or on the part of the values deriving from measurements. For this sector, statistical analysis shows that samples are not normally distributed and also symmetrical distribution is not respected both for all and for the measured data. Anderson-Darling normality test confirms these results. The boxplot highlights that there is a low difference between mean and median. Furthermore, regards the data coming from measurements, it must be said that these do not represent a representative sample considering the scarcity of available data.

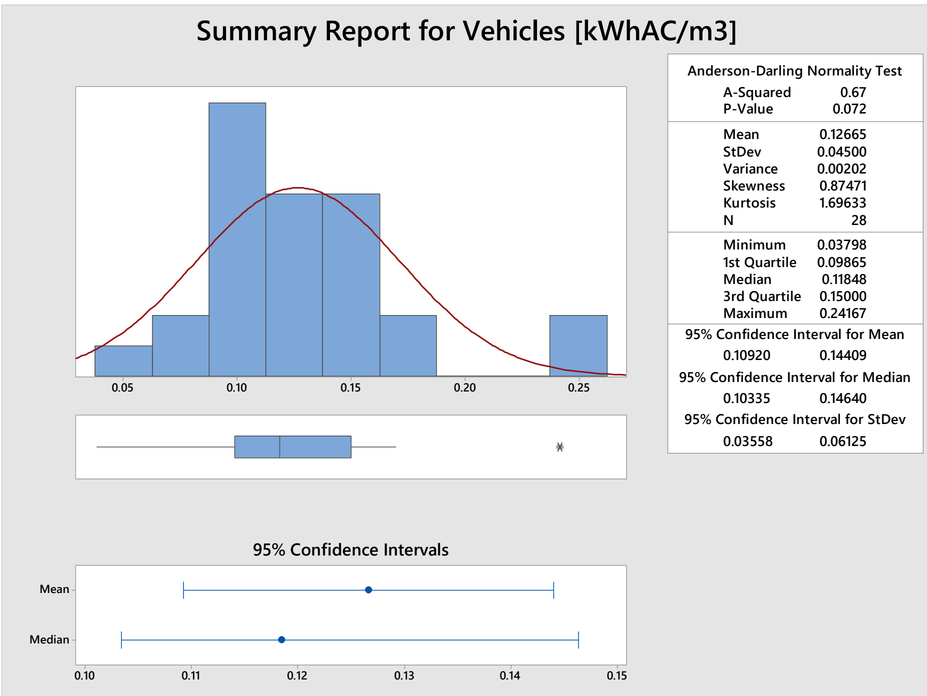

Figure 2.19: *Statistical analysis using the indicator kWh_eCAS/m^3 of the sample containing all data (both estimated and measured) about motor vehicles sector.*

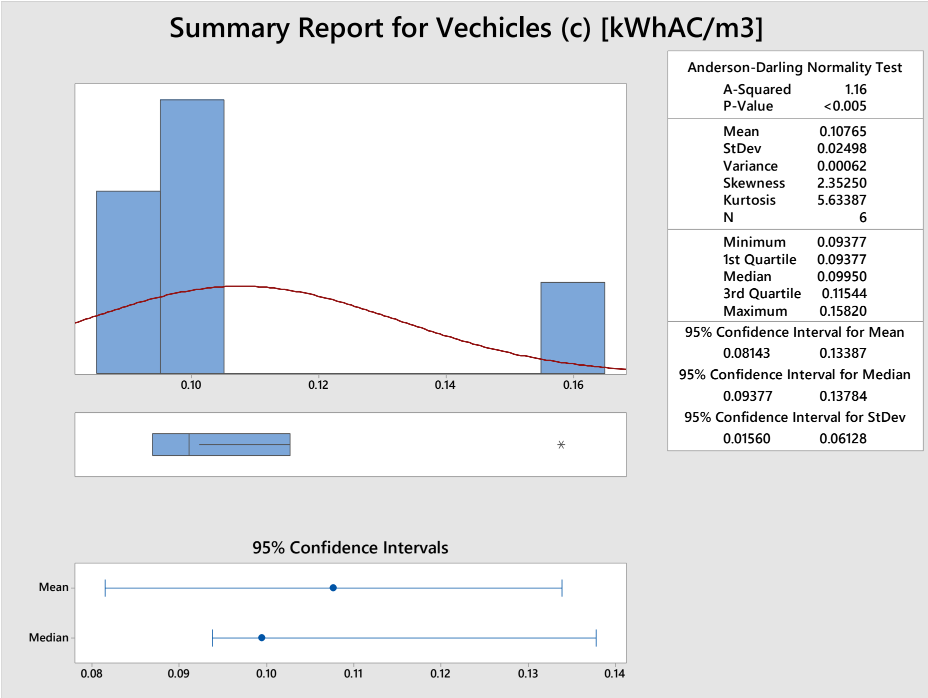

Figure 2.20: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing only measured data about basic motor vehicles production.*

Textiles

This sector includes the preparation and spinning of textile fibers including the weaving of textile materials, the finishing of textiles and clothing, the manufacture of fabric articles, other than clothing (for example: household linen, blankets, bedside rugs, ropes etc). The cultivation of plants that produce natural fibers is part of another sector, as it is the manufacture of clothing and artificial and synthetic fibers, which can be classified as a chemical process [59].

Figures 2.21 and 2.22 show the statistical analyzes and graphs made for the indicator described above and calculated on the totality of the sector data or on the part of the values deriving from measurements. The outliers were previously eliminated as they were visibly out of control and radically modified the histograms making them less representative of the sample. However, the latter are limited in number and therefore lend themselves to an in-depth study in a second phase of the project, in order to obtain more precise and reliable benchmark values. For the sector in exam, the statistical distributions of the values, based on the Anderson-Darling normality test, are not normal and not symmetrical. The boxplot highlights that there is a low difference between mean and median influenced also by the absence of outliers.

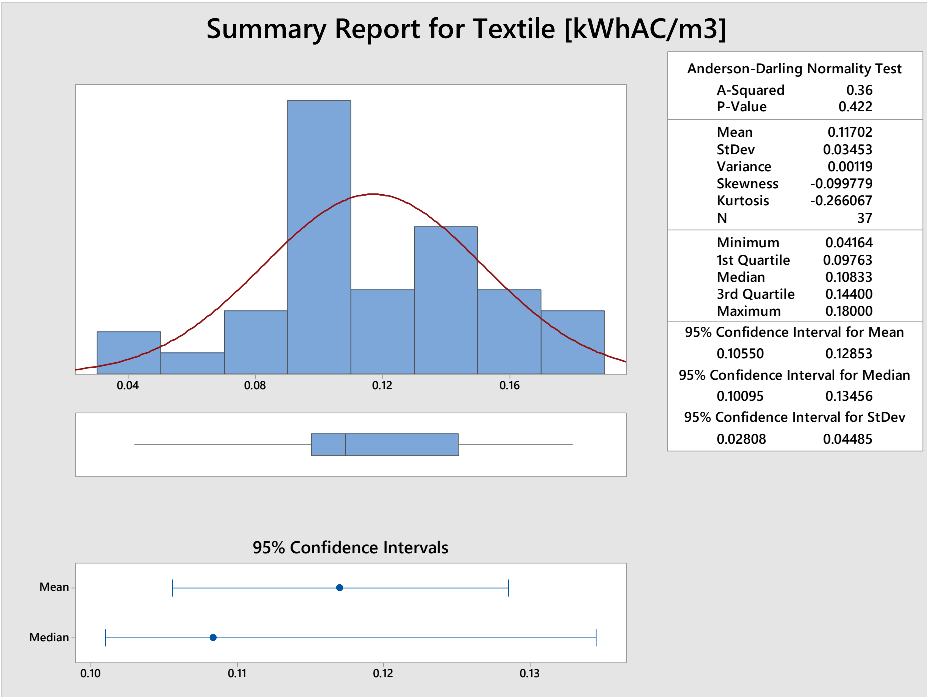

Figure 2.21: *Statistical analysis using the indicator $kWh_e CAS/m^3$ of the sample containing all data (both estimated and measured) about textiles sector.*

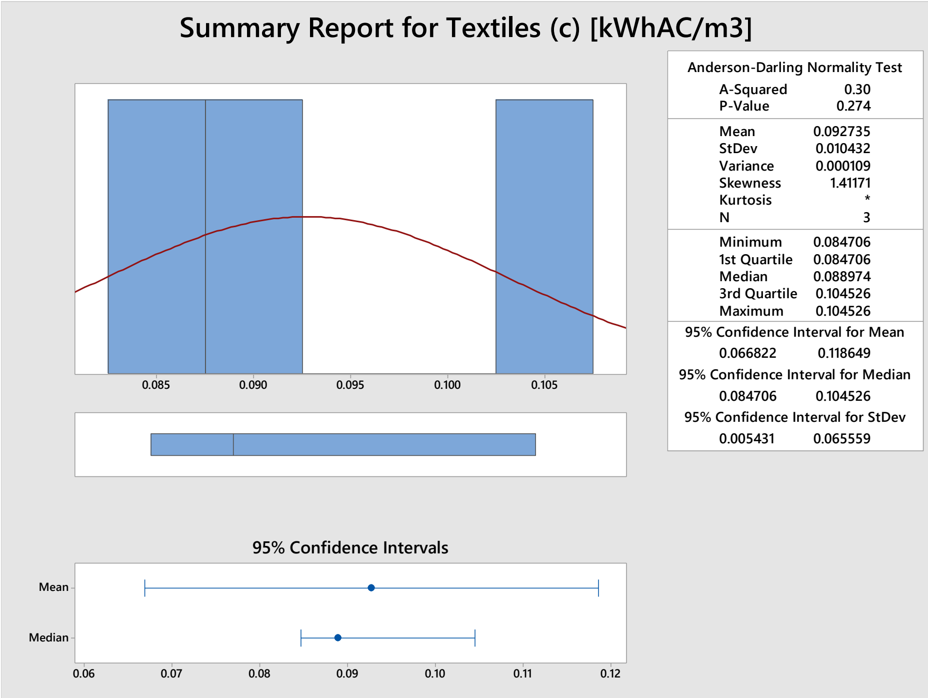

Figure 2.22: *Statistical analysis using the indicator kWh_eCAS/m^3 of the sample containing only measured data about basic textiles production.*

2.3.2 Analysis of variance (ANOVA)

The ANOVA one-way has been performed on the available database. The analysis, based on used EPI defined as $\mathrm{kWh_eCAS/m^3}$, shows that there are small differences between the mean values of all the examined sectors. This result could be influenced by too small samples, for example for textiles, pharmaceutical and motor vehicles. Data distribution in Figure 2.23 shows the presence of some outliers mainly in basic metal, chemical, food and metal product sectors. According to the statistical analysis based on the sample, there is at least a 90% chance of detecting a difference of 0.0549, and at most of a 60% chance to detect a difference of 0.0240. Full results are collected in Table 2.1.

A sample t-test performed on all the sectors returns some important results about mean values. In almost all sectors, mean values of the distribution are not significantly different from the other sectors. The only exceptions are the comparison between the textile and the food sector, and between chemical and pharmaceutical production. The results are shown

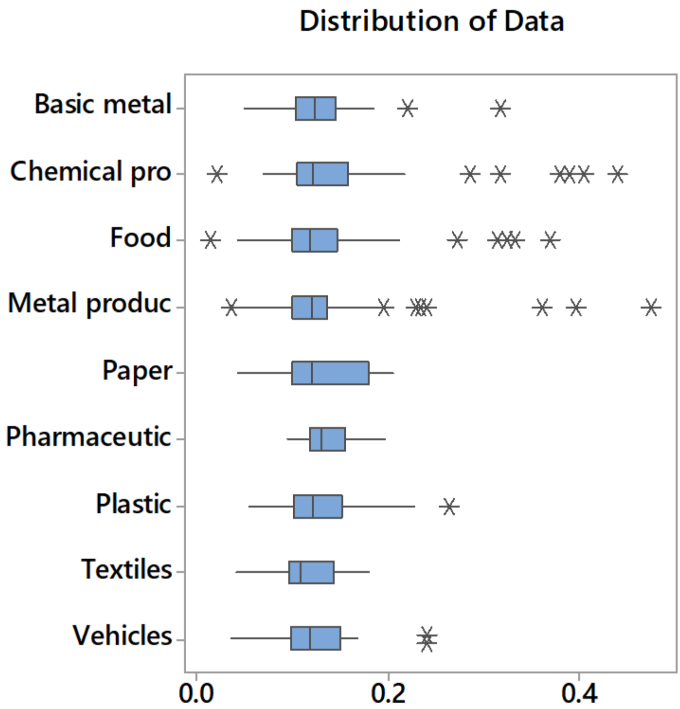

Figure 2.23: *Graphical representation of quartiles of the considered industrial sectors. The asterisks represent the outliers indicated by the programme used for data analysis.*

in Table 2.2. This layout can be explained if operative conditions are considered. Companies, or single production plants, can adopt various solutions and the compressed air features could be different both among sectors and within the same one. To get more accurate evaluation, it could be necessary undertaking specific analyses on each sector. Nevertheless, it could be very difficult or impossible considering the scarcity of available information. For this purpose, some further actions can be considered for future development. For example, it can be advantageous to get in touch with enterprises and associations to collect more data (as will be explained later in the work).

Table 2.1: *Test power. Collection of chances to detect mean values differences.*

Difference	Power
0.02042	$22.6 \div 60.0\%$
0.039933	$60.0 \div 98.5\%$
0.043975	$70.0 \div 99.7\%$
0.048623	$80.0 \div 100\%$
0.054924	$90.0 \div 100\%$

Table 2.2: *Collection of t-tests for the mean of two sectors*

Sector		Food products	Paper	Metal products	Plastic products	Chemical products	Pharma. products	Basic metal	Motor vehicles
Textiles	Equal	Yes	No	No	No	Yes	Yes	No	No
	P-Value	0.046	0.093	0.134	0.402	0.004	0.008	0.169	0.351
Motor vehicles	Equal	No	No	No	No	No	No	No	
	P-Value	0.053	0.513	0.696	0.946	0.096	0.222	0.954	
Basic metal	Equal	No	No	No	No	No	No		
	P-Value	0.421	0.453	0.66	0.888	0.043	0.107		
Pharma. products	Equal	No	No	No	No	No			
	P-Value	0.435	0.642	0.376	0.2	0.47			
Chem. products	Equal	No	No	No	No				
	P-Value	0.175	0.31	0.161	0.087				
Plastic products	Equal	No	No	No					
	P-Value	0.485	0.475	0.647					
Metal products	Equal	No	No						
	P-Value	0.827	0.756						
Paper	Equal	No							
	P-Value	0.884							

2.3.3 Benchmark

After the first statistical analysis which highlights all the peculiarities of the sample, the benchmark analysis is performed. For each sector, both correlation and linear regression analysis are carried out.

Food industry

For food sector, the correlation analysis shows a good correlation between energy consumption and compressed air production. The correlation index reaches high values for all 3 cases analyzed: total, measured and estimated data; results are collected in Table 2.3. In this case, the correlation index shows better results for estimated data comparing with measured ones, this could be due to the larger availability of estimated values comparing with the continuous measured ones.

The linear regression analysis shows some particular aspects. From scatter plot (Figure 2.24), it is possible to note that for low production the energy consumption is quite aligned around the regression line (black). Several values, above all deriving from estimates, are very far from the benchmark both in positive than in negative. The values coming from measurements, which are the most reliable, are almost all above the trend line, this denotes some difficulties in the analysis that must be further investigated. Considering the significance of reached values (Table 2.3), the linear regression analysis shows that P-values for intercept for both overall and measured sample are over the 0.05 limit. This aspects could depend on the low significance of estimated values. Instead, the incline is significant for both samples.

Table 2.3: *Correlation values and linear regression P-Value for data of food industry.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Food products	0.97	0.992	0.882	0.582	9.60E-68	0.439	1.28E-15

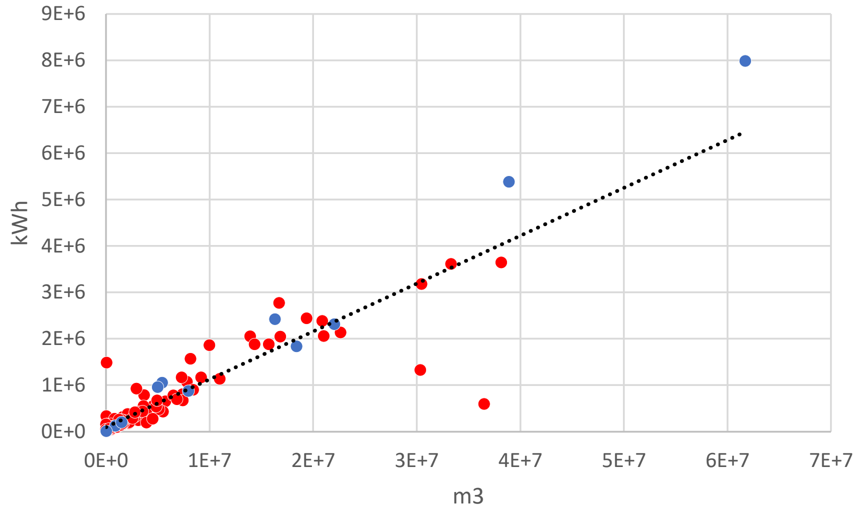

Figure 2.24: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in m^3. In red the values for estimated data, in blue the values of the measured data, in black the trend line; food industry.*

Paper

For paper sector, the correlation analysis highlights a strong correlation between energy consumption and compressed air production. The correlation index (Table 2.4) reaches very high values (over 0.95) for all 2 cases analyzed: total and estimated. There is a very little difference between the correlation index related to all values and the one related to estimated values due to the presence of only 2 measured values. In fact, for the estimates it reaches 0.963 instead for measures is 0.961.
The linear regression analysis highlights some differences between overall and measured sample. Observing the scatter plot (Figure 2.25) there is a strong dispersion around the linear regression line. The values due to measurements, which are the most reliable, are very limited in number (two) and therefore the data relating to their regression statistics are not reliable and it is not possible to provide further information. The scatter plot shows also a trend even if the values are arranged with considerable dispersion, especially for high production. Overall sample has both intercept and incline P-values significant (Table 2.4), the continuous

measured values are not calculated.

Table 2.4: *Correlation values and linear regression P-Value for data of paper sector.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Paper	0.963	- -	0.961	0.002	1.07E-15	- -	- -

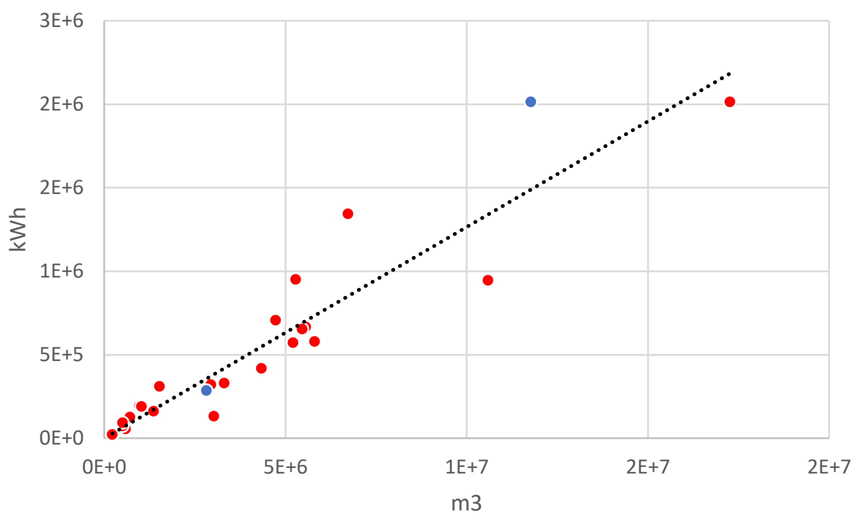

Figure 2.25: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in* m^3*. In red the values for estimated data, in blue the values of the measured data, in black the trend line; paper industry.*

Metal products

The metal products sector analysis shows a strong correlation between energy consumption and compressed air production. Correlation indices are homogeneous for the 3 analyzed cases (Table 2.5). There are no differences between overall and continuous measured values.
Scatter plot shows an outlined trend aligned with the regression line (Figure 2.26). The dispersion is very limited both for measured samples that for estimated ones. Linear regression parameters analysis (Table 2.5) shows that all inclines are significant, while the intercepts are not.

Table 2.5: *Correlation values and linear regression P-Value for data of metal products sector.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Metal products	0.983	0.983	0.986	0.025	4.69E-61	0.132	1.03E-06

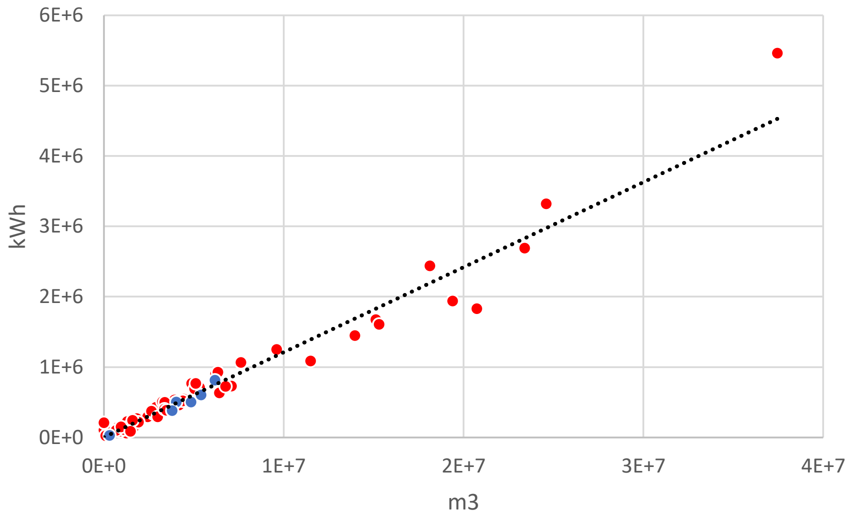

Figure 2.26: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in m^3. In red the values for estimated data, in blue the values of the measured data, in black the trend line; metal products.*

Plastic products

The correlation analysis on plastic production sector shows a strong correlation between energy consumption and compressed air production. The correlation analysis in Table 2.6 shows high values (>0.95) in all the cases analysed. For measured data the correlation is not significant because of the lack of samples.

The scatter plot indicates a large dispersion of data. Moreover the measured sample is very scarce and the estimated values are not aligned to the regression line (Figure 2.27). The linear regression shows that intercept of the overall data loses its significance, the P-value is over 0.05.

Table 2.6: Correlation values and linear regression P-Value for data of plastic products sector.

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Plastic products	0.969	- -	0.955	0.899	2.64E-45	- -	- -

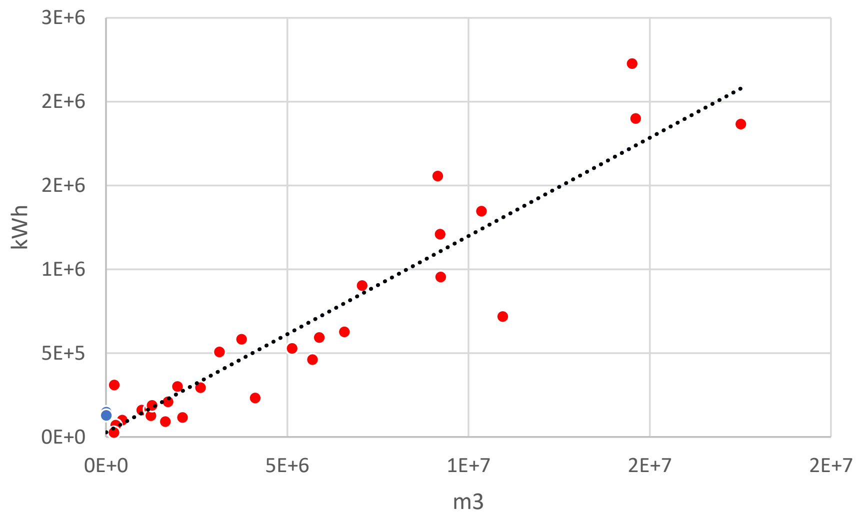

Figure 2.27: Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in m^3. In red the values for estimated data, in blue the values of the measured data, in black the trend line; plastic products.

Chemical products

The correlation analysis for chemical products sector indicates a strong correlation between compressed air production and energy consumption. The correlation index is very high, it reaches 0.99 for overall sample and it is significant also for measured values because of the availability of samples (Table 2.7).
The linear regression analysis shows some particular aspects. From scatter plot (Figure 2.28), it is possible to note that energy consumption is

quite aligned around the regression line (black). Several values, above all deriving from estimates, exceed in energy consumption, while those measured are very close to the regression line. This stability is also confirmed considering the three largest production (blue points on the right). The regression analysis shows that intercept and incline are both significant only for overall sample. For continuous measured sample, P-value decreases and the intercept is not significant.

Table 2.7: *Correlation values and linear regression P-Value for data of chemical products sector.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Chemical products	0.996	0.997	0.978	0.017	4.47E-84	0.119	1.36E-16

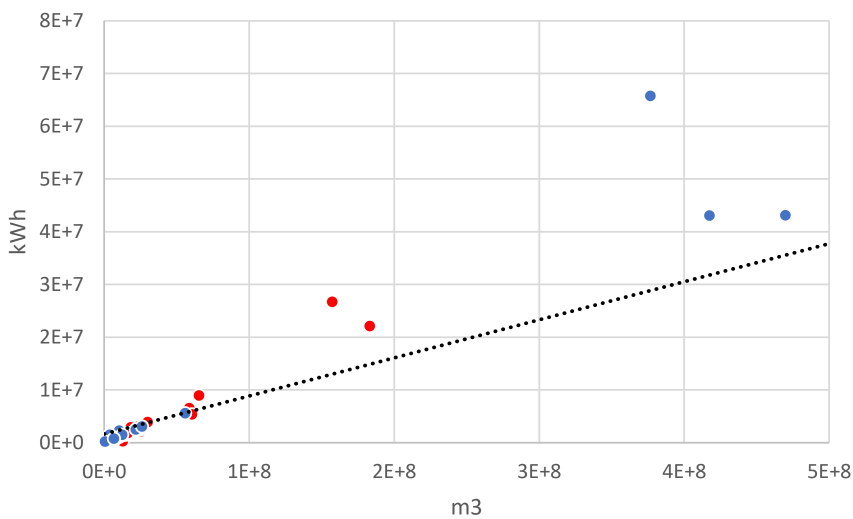

Figure 2.28: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in m*^{3}*. In red the values for estimated data, in blue the values of the measured data, in black the trend line; chemical products.*

Pharmaceutical products

For the pharmaceutical sector, the correlation analysis shows a good correspondence between energy consumption and compressed air production. The correlation index reaches high values especially for estimated values; the results are collected in Table 2.8.
The linear regression analysis shows some particular aspects. From scatter plot (Figure 2.29), it is possible to notice that for low production the energy consumption, above all deriving from estimates, is lower than the regression line (black), while for high production the samples are quite close to the regression line. The values coming from measurements, which are the most reliable, are almost all above the trend line, and this denotes some difficulties in the analysis that must be further investigated. Considering the significance of reached values (Table 2.8), the linear regression analysis shows that P-values for intercepts and also for incline of measured sample are over the 0.05 limit. This aspect could depend on the low significance of estimated values.

Table 2.8: *Correlation values and linear regression P-Value for data of pharmaceutical products sector.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Pharmaceutical products	0.865	0.821	0.991	0.811	7.15E-10	0.935	0.179

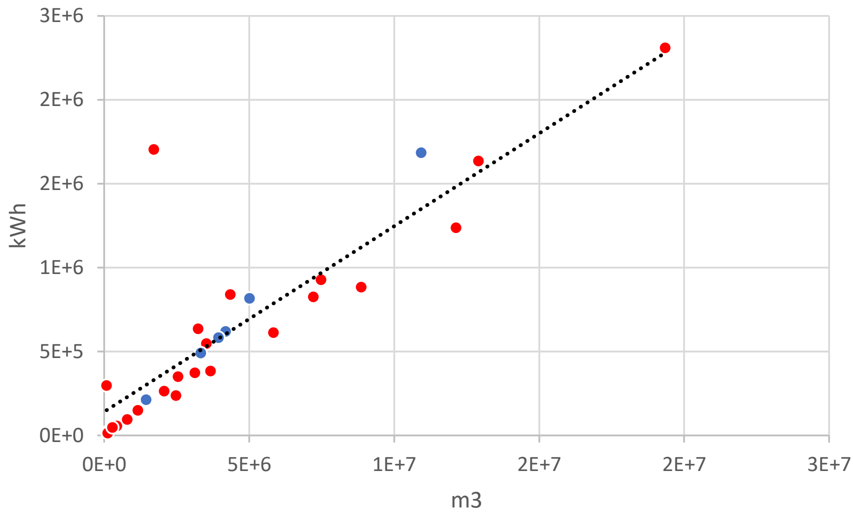

Figure 2.29: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in* m^3*. In red the values for estimated data, in blue the values of the measured data, in black the trend line; pharmaceutical products.*

Basic metal

The correlation analysis of basic metal products indicates a strong correlation between energy consumption and compressed air production. The correlation index reaches 0.97 for all the samples and there are not differences between estimate and measured values.
The scatter plot shows a good dispersion of the values (both measured and estimates) close to the regression line (Figure 2.30).
Analysing the parameters of the linear regression, the results are homogeneous but the Table 2.9 indicates that only inclines (both measured and estimates samples) are significant.

Table 2.9: *Correlation values and linear regression P-Value for data of basic metal sector.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Basic metal	0.974	0.978	0.974	0.248	2.67E-44	0.726	5.07E-06

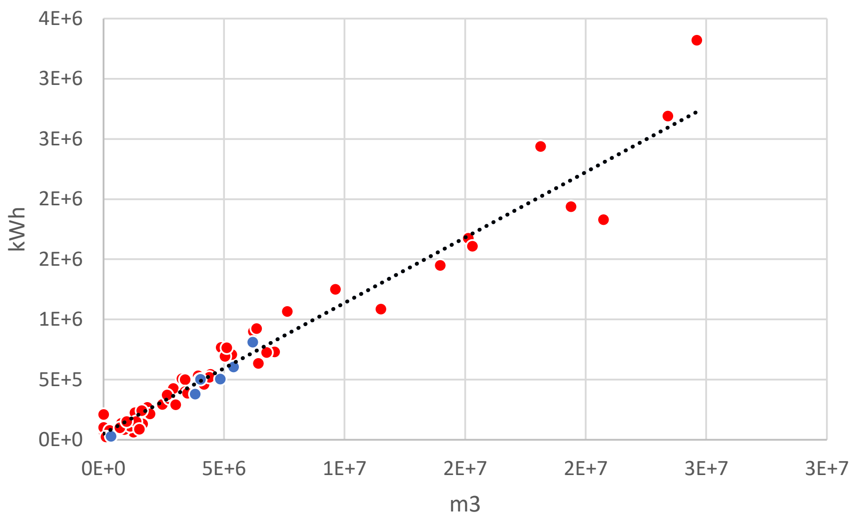

Figure 2.30: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in m^3. In red the values for estimated data, in blue the values of the measured data, in black the trend line; basic metal.*

Motor vehicles

For the motor vehicles sector, the correlation analysis shows a good correlation between energy consumption and compressed air production. The correlation index reaches high values for all 3 cases analyzed: total, measured and estimated data; results are collected in Table 2.10. In this case, the correlation index shows better results for measured data (0.99) comparing with estimated ones, this could be due to the scarce availability of measured values. The linear regression analysis shows some particular aspects. From scatter plot (Figure 2.31), it is possible to note that the distribution is of the samples is homogeneous for all air production values. The energy consumption is quite aligned around the regression line (black). Several values indicating the lower production, above all deriving from estimates are very far from the benchmark both in positive than in negative. The values coming from measurements, which are the most reliable, are almost all under the trend line, this denotes some difficulties in the analysis that must be further investigated. Considering the significance of reached values (Table 2.10), the linear regression analysis shows that P-values for intercept for both measured sample are over the 0.05 limit. This aspects could depend on the low availability of estimated values. Instead, the incline is significant for both samples.

Table 2.10: *Correlation values and linear regression P-Value for data of motor vehicles sector.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Motor vehicles	0.949	0.999	0.955	0.049	1.69E-14	0.288	0.027

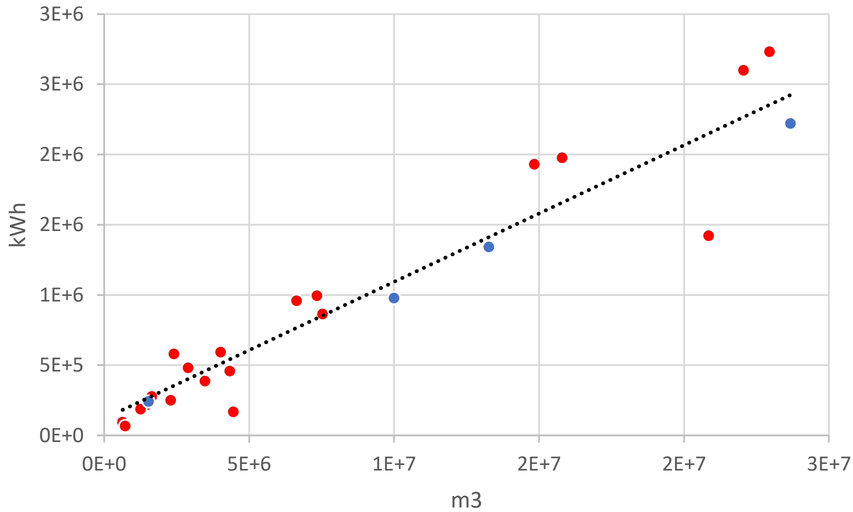

Figure 2.31: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in m^3. In red the values for estimated data, in blue the values of the measured data, in black the trend line; motor vehicles.*

Textiles

For the textile sector, the correlation analysis shows a good correlation between energy consumption and compressed air production. The correlation index reaches high values for all 3 cases analyzed: total, measured and estimated data; results are collected in Table 2.11. In this case, the correlation index shows results close to 1. This could be due to the scarce availability of values for this sector comparing with the others. The linear regression analysis shows some particular aspects. From scatter plot (Figure 2.32), it is possible to note that for low production the energy consumption is quite aligned around the regression line (black). Several values, above all deriving from estimates, are over the benchmark. The values coming from measurements, which are the most reliable, are almost all under the trend line, and this indicates low production; for this reason the regression is strongly influenced by estimates.
Considering the significance of reached values (Table 2.11), the linear regression analysis shows low significance for almost all the parameters. This denotes some difficulties in the analysis that must be deepened

further considering also the scarce data available.

Table 2.11: *Correlation values and linear regression P-Value for data of textile sector.*

	Correlation (R)			Linear Regression			
				Overall		Measured	
Sector	Overall	Meas.	Estim.	Intercept (P-Value)	Incline (P-Value)	Intercept (P-Value)	Incline (P-Value)
Textiles	0.997	1	0.999	0.142	1.30E-42	0.947	0.118

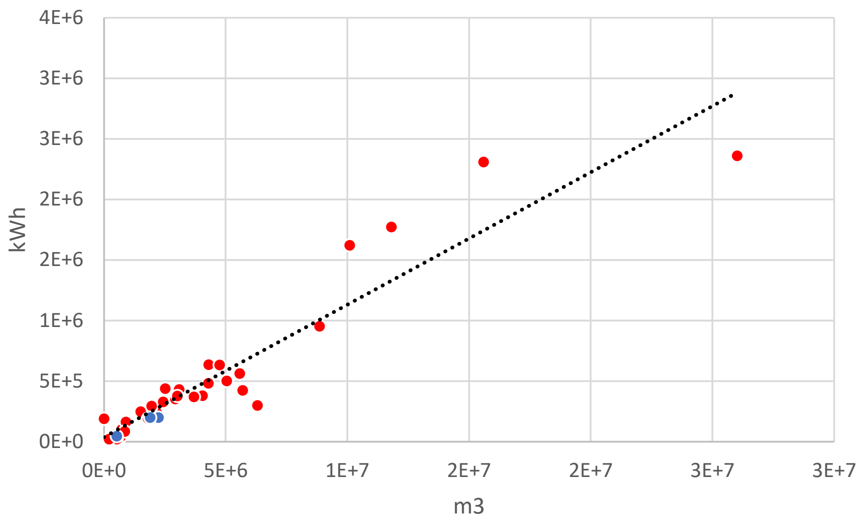

Figure 2.32: *Scatter chart of energy consumption values for compressed air expressed in kWh depending on the amount of compressed air produced expressed in m*^{3}*. In red the values for estimated data, in blue the values of the measured data, in black the trend line; textiles.*

2.4 Discussion

The results of correlation analysis show that for all companies the correlation between energy consumption for compressed air systems (kWh_eCAS) and compressed air production (m^3) is good, but not homogeneous among the sample. In details, correlation indices are lower when estimated data are used, also it is worth to note that the sample of measured data is smaller than that of estimated values. Therefore, the companies that provided estimated data may have made some hypotheses from the literature that could invalidate the analysis.

Linear regressions are performed considering compressed air production (m^3) as the independent variable and energy consumption for compressed air systems (kWh_e CAS) as the dependent variable. The linear regression with the available data allows to analyse the P-Value and the significance. We observe that if all available data are considered, the P-Value is below 0.05 for all linear regression inclines. If only measured data are considered, for some sectors such as paper, pharmaceutical, vehicles and textiles, the regression loses its significance. Such a result could be due to two reasons. The first is related to the differences between the analysed enterprises, as a relation between electric consumption and compressed air production is possible if inputs and outputs could be scaled linearly. The second reason relies on the quantity of measured values, that could not be enough to lead to right conclusions. This heterogeneity is also due to the different methods employed by the companies to estimate their energy consumption and compressed air production. Difficulties in results evaluation could be also considerable and are provided by the paucity of information on the operating pressure of compressors, as well as by the type of installed compressors and plant characteristics. Furthermore, among all enterprises for which data were available, about 38.6% have measured their energy consumption due to compressed air in a continuous way, about 56.6% have calculated the consumption through bills and the rest did not specify the measurement method; moreover, the calculation method applied to estimate the energy consumption from the bills is not known and if the data come from continuous measurements, not all enterprises adopt the same tools and the same procedure to collect data.

In the following, only the results related to metal and chemical productions are considered. Such a choice is motivated by the importance of these sectors in the overall energy consumption and for large data availability.

Figure 2.28 shows all collected data for chemical products and the corrispondent linear regression. Red points represent estimated values while blue points stand for measured values. The largest part of the data come from companies whose annual production of compressed air is below 10^9 m^3. Those data, referring to an annual production of compressed air above 3×10^9 m^3, are significant as they derive from continuous measurements.

We also observe that, 5 industrial plants, whose annual compressed air production is higher than 10^8 m^3, have a very high electric energy consumption compared to the benchmark represented by the regression line. From this analysis, some considerations could be done in order to help enterprises to improve their CAS energy performance.

All the plants whose consumption data come from estimates and are beyond the benchmark, first of all, might implement efficient measurement systems to evaluate the significance of their collected data. Two remaining plants which have high significance (and also high production) considering that their data come from continuous measurement, could adopt some important action to reduce their energy consumption related to compressed air production.

Regarding metal production, the situation is quite different. Figure 2.26 shows all collected data of metal products, denoting with red points the estimated values and with blue points measured values, and the corresponding linear regression. Data distribution is more homogeneous, almost all the available data are close to the regression line. Also in this industrial sector, all the production plant whose KPI is over the reference line should implement actions to reduce their energy consumption due to compressed air generation. The largest part of the data indicates enterprises whose compressed air production is less than 3×10^7 m^3 per year. Values over this limit are represented by estimated values whose significance is quite low.

2.4.1 Possible developments

Considering the difficulties and problems shown in the development phase of the benchmark analysis, mainly due to the differences between systems and available parameters, it is possible to improve the analysis by taking into consideration some aspects.

- The first problem encountered in the analysis is the absence of measured data in most of the surveys. This problem can be solved by offering companies the implementation of a system for measuring energy consumption and compressed air production. Possible schemes of measuring systems are proposed in the Figure 3.5.

- The second problem is the difference in operating pressure of the different systems. As is known, producing air at higher pressure leads to higher energy consumption. The presence of consumption readings at different pressure levels leads to the need to develop some performance indices that take into account the pressure level as well as the flow rate and energy consumption. These benchmark indices could be developed through two or more variable models or after a data clustering procedure. Clustering could be based on the operating pressure level, type of installed compressors, adopted plant solution, etc.

- The differences in the use of the compressed air according to the sector to which the company belongs have shown that the performance level of the sectors themselves is highly differentiated. This can lead to rigorous action by companies belonging to a sector or by trade associations that could push companies to adopt unified performance measurement strategies in order to better monitor the results.

For all these reasons, it could be possible to develop several strategies to deepen the knowledge of differencies between the sectors and compare the performance.

2.5 Conclusion

In this section, a benchmarking model for industrial CAS has been presented. Starting from a large dataset deriving from an energy audit campaign, a methodology to improve energy efficiency of CAS has been proposed. The methodology includes statistical analysis of available database. Despite the differences between the regression analyses, ANOVA shows that no significant difference is registered among mean values of different sectors. This aspect is particularly important because it enables to develop a wider inter-sectoral benchmark. Benchmark analyses show the most relevant problems of the dataset, i.e. a limited availability of measured values.

The analysis has allowed the definition of new benchmarks for CAS energy management in 9 different industrial sectors. Such benchmarks, not available before, could be applied by industries to measure their energy performance over time, thus informing and motivating energy saving, facilitating energy accounting, assessing energy management opportunities, and quantifying and verifying performance improvement.

Chapter 3

Development and administering of a short questionnaire

Introduction

Collected data about CAS are frequently not completely usable for an exhaustive benchmark analysis in terms of energy consumption and amount of produced compressed air. In such cases, a further data collection should be accomplished in order to have a better evaluation of system performance. Starting a new, more detailed data collection campaign about compressed air and measurement systems management (comparing with the already completed) could be a very long and expensive procedure. For this reason, we submitted a questionnaire to a sample of companies in order to get more relevant information about important aspects of CAS energy characterization. In fact, gathering additional information on how CAS related data are measured and used within the company can give a rather reliable idea of the data quality itself. The administration of a questionnaire has positive and negative aspects for the company. The positive aspects concern the possibility to assess the awareness of importance of energy efficiency improvement [36] while the negative one is the require of time to compile the questionnaire.

In this section, it is described the development and the administration of a short questionnaire useful to get more detailed information about working conditions (production, schedule, maintenance schedule, etc.).

In this part, the author's contribution is important for the development of the questionnaire, for the selection of the companies and for the analysis of the results. With regards to collecting the results of the companies, the only activity was support.

3.1 Background

The nature of the study leads to investigate the energy performance of multiple sites and achieve more information to get more significant results. Obtaining further information from a large sample could be difficult, for this reason the part relating to the development of a questionnaire was useful for bringing companies closer and analyzing their situation. The need to obtain precise information on the energy management has led many researchers to develop and submit questionnaires.

In general the questionnaires can be submitted in many ways through telephone interviews, direct administration in person and also through online forms.

Within the technical and scientific literature, there are numerous cases in which the questionnaires were applied.

[60] shows that the increasing need of industrial energy leads to the development of several studies about energy efficiency whose implementation is limited by the existence of some barriers. Such limitations, about the implementation of energy efficiency, in Swedish foundry industry are investigated through the administration of a questionnaire. Results show that the large differences in energy efficiency management depends on organizational problems (mainly for group owned companies) and on information problems (for private industries).

In [61], the factors that influence the company decision makers to proceed with investments in energy conservation are analyzed. In this case, a questionnaire is administered to determine which companies decided to implement an energy efficiency plan based on classical economic evaluation (cash flow) and understand which method, alternative to the classical evaluation, is used by companies. Results of questionnaires are useful to explain in detail the reasons of the implementation of energy efficiency measures and what are the most common methodologies.

In [62], authors propose a questionnaire to get information about production and energy consumption. Some questions are about industrial characteristics such as the size of the plant, the number and the education level of employees. Other questions are about the forms of energy use, the energy costs, the portion of energy on total costs, the saving opportunities and the methodology to overcome the barriers to energy efficiency investments.

In other works like [63] and [64] questionnaires are used to collect general information about energy management.

3.2 Method

The complexity and heterogeneity of CAS management together with the difficulties to deduce clear information from statistical and benchmark analyses lead to the development of another strategy of intervention. Although case studies and on-site inspection would give more detailed information, questionnaires allow to spend less time to get information about a large sample of companies and cover more industrial firms.

3.2.1 Development of the questionnaire

To develop a questionnaire able to collect information about CAS management, the activity starts from the previous developed works. In [5], many important aspects are considered as key aspects for industrial energy management such as the level of implementation of best practices, the awareness of the importance of energy management and the methodological approach. Taking as reference the example in [5], some questions about CAS management are developed.

Before drafting the questionnaire, a careful analysis of the CAS is undertaken. In this way, it is possible to highlight the most important functions of the system, in terms of energy consumption. The complexity of a CAS could lead to analyse to much functions and to develop a very complex questionnaire. For this reason, only few important technical aspects are taken into account. In particular, some aspects such as the level of implementation of best practices, the typology of installed measurement system, and the good design of the CAS are here considered the most important.

The optimal design of a questionnaire is available in several scientific works e.g. [65] and [66]. In general, questions should avoid too complex and scientific terms, should be short and require only a piece of information. It is suggested to avoid unnecessary negatives in the sentences. Starting from these guidelines, to develop such a questionnaire three principles are followed:

- The questionnaire should touch upon only the most influential themes of the CAS management that affect energy performance.
- The questionnaire should be easy to be compiled from the responsible personnel.
- The questionnaire should be brief. A questionnaire containing too many questions and too many answers would not be filled with the necessary attention.

Starting from this principles, a questionnaire made up of 12 question is formulated. Such questions are related to technical aspects grouped in 3 main contents: general aspects of energy management and efficiency improvement for CAS, measurement systems and their management, working conditions of CAS. The questionnaire pays attention also to the effect of current and future policies; therefore, company attitudes towards energy efficiency programs development are also mentioned. For each question from 3 to 5 possible answers are defined. The answers are sorted on the basis of growing degree of awareness of energy efficiency importance. In this way, from the analysis of results it is easy to state the level of development of each applied technology and practice.

3.2.2 Administering of the questionnaire

Administering the questionnaire to a not significant sample of companies leads to possible waste of time and unreliable results. So, to administer the questionnaire, a sample of companies is chosen within the already analysed ones. The companies are chosen within the sub-sample of those whose percentage of energy consumption due to CAS over total consumption is higher. The threshold is set at 5%. The questionnaires are sent to the companies that should independently fill out the answers. Results from this survey are analysed together with those deriving from benchmark analysis. So, it is possible to relate a particular performance result (both low or high level) to critical or positive aspects about energy management and implemented practices for energy performance evaluation. The questionnaire is therefore a useful tool to identify energy management opportunities in specific industrial applications, also to derive general guidelines for improving efficiency in CAS. The results analysis is useful to characterize the most criticalities of industrial companies and above all to allow the suggestion of practices to improve energy efficiency.

3.3 Results

3.3.1 Developed questionnaire

In this section all the developed questions and answers are collected. In order to have meaningful results, questions regard many technical and managerial aspects about CASs.

Question 1: What about an energy efficiency program of the compressed air system serving the production processes within the company?

- It has never been planned.
- It has been planned but not undertaken.
- It has been only recently undertaken.
- It is a consolidated procedure and opportunities have been sought systematically.

Question 2: Systematic diagnoses of the compressed air system, to find out energy saving opportunities carried out including measurement campaigns and energy audits.

- They have never been done.
- They have been carried out in the past but inadequately or without significant improvement over the medium term.
- They have been carried out in the past bringing some improvements but only a small part of the opportunities identified were subsequently harvested.
- A diagnosis has been recently carried out and now the efficiency opportunities identified are applied on the basis of their priority.

- They have periodically been conducted to identify a saving opportunity plan eventually implemented.

Question 3: What about the scheduling maintenance of compressors?

- A maintenance plan does not exist.
- A plan for maintenance and compressor substitution exists (eg cleaning and lubrication, belt replacement or replacement with higher efficiency motors), but cleaning of inlet filters and cooling benches have been done when necessary.
- In addition to engine maintenance, the maintenance plan also includes periodic cleaning of inlet filters and cooling benches.
- Maintenance of motors and cleaning of inlet filters and cooling benches takes place at regular intervals and its effective execution and effectiveness is monitored.
- Motors maintenance and cleaning of inlet filters and cooling benches are performed depending on condition or on the basis of monitoring of certain variables (weak signals).

Question 4: What about the analysis of the cost and energy consumption data of the compressed air system?

- Cost / consumption data are not analysed.
- An analysis of the trend in cost / consumption time is periodically carried out and the current and historical data are compared.
- Consumption / production or specific consumption is periodically monitored and, in case of anomalies, specific analyses of consumption / production ratio or specific consumption (e.g. per unit of product, hour worked, etc.) can be conducted.

Question 5: What about the analysis of the compressed air leaks in the distribution network?

- An assessment of their size has never been carried out.
- It has been estimated on the basis of on-board ignition / shutdown tests of stationary compressors and is considering taking action to improve it.

- Surveys were carried out following which the most significant losses have been removed and at least the planned introduction of solenoid valves on the ducts to the user equipment has been planned.
- Minor losses were also eliminated or reduced.

Question 6: What about the pressure drops in distribution system?

- They have never been measured.
- The magnitude of pressure drops is known and some more immediate and cost-effective corrective actions have been planned (regular maintenance of filters, replacement of other welding connections, etc.).
- The magnitude of pressure drops is known and almost all the most immediate and low-cost correction work was done and some of the most important interventions planned (check the correct size of the pipes and replace them, purchase pressure gauges on condition Filters, correcting the shape of the net to avoid curves).
- All the most important interventions have been planned and some have been implemented;
- The network is optimized for minimizing pressure losses.

Question 7: What about measurement systems with which determine the amount of compressed air produced and/or used (definition of a measurement plan able to determine the variables to be measured, the measurement frequency and the measuring instruments)?

- They have never been considered.
- They have been considered and used sporadically (indicate the frequency of the measurements, the unit of measurement of the amount of compressed air measured and the measuring point).
- They have been considered and used regularly (indicate the frequency of the measurements, the unit of measurement of the amount of compressed air measured and the measuring point).

Question 8: What about the displacement of the intake air inlet?

- It has never been verified.
- It has been evaluated not correct (the air intake is often hot and humid) but no improvement work has been planned on this.
- It has been evaluated not correct (the air intake is often hot and humid) and improvements have been planned on this.
- It is correct.

Question 9: What about the evaluation of compressed air delivery pressure?

- The possibility of reducing it has never been evaluated.
- It is set to the maximum value required by the users, identified on the basis of a series of tests.
- It is adjusted according to the operating conditions of the plant (e.g. weekdays and public holidays) and requests for individual utilities.
- It has been evaluated the possibility of separately managing certain branches of the plant requiring different pressures (using different compressors or booster).

Question 10: What about the improper use of compressed air?

- They have never been identified.
- The operators were informed about the correct operating procedures and the need to turn off the equipment not in use but their operation in this sense is not verified.
- Specific procedures to switch on and off exist furthermore procedures to control the correct use of the equipment which use compressed air are widespread and their application is periodically verified.
- The previous procedures are observed and the uses for which it is convenient to replace the compressed air with another carrier (e.g. preferring a low pressure blower for applications such as air blades, air vents, etc.) are identified.

- The procedures outlined above have been and have been verified, improper use of compressed air has been identified and replaced (e.g. preferring low pressure blower for applications such as air blades, air ducts, etc.) and exist specifications or design checklists to prevent new ones from being introduced.

Question 11: What about the compressors control system (on/off, inverter)?

- It has never been studied and evaluated.
- It has been taken into consideration as a subject of study but any improvement has never been evaluated in economic terms, postponing that evaluation at the time when one or more compressors will still need to be replaced.
- The insertion of the inverter control system on the master compressor was evaluated on the basis of nominal data.
- The insertion of the inverter control system on the master compressor was assessed on the basis of measured data.
- The system is optimized from the point of view of regulation and the efficiency of the modulation system is controlled over time.

Question 12: What about the analysis of compressed air demand profile?

- It has never been evaluated.
- Has been summarized on the basis of performance data and the optimization of accumulation has been considered (e.g. resizing existing tanks or placing new tanks near key users).
- Air demand has been measured and the optimization of accumulation and load shifting has been evaluated.
- Accumulation and load shifting optimization has been planned.
- The load profile is optimized and new loads have been studied taking into account the impact on the demand profile.

3.3.2 Administering of the questionnaire

As already written, the questionnaire has been submitted only to enterprises whose electric consumption related to compressed air system is higher than 5% of the total. The percentage of the enterprises that made up the sample are represented in Figure 3.1. The most numerous sample is represented by the chemical sector which is also the most energy-intensive. Using the results, it is possible to assess the quality of analysed data and suggest some corrective actions.

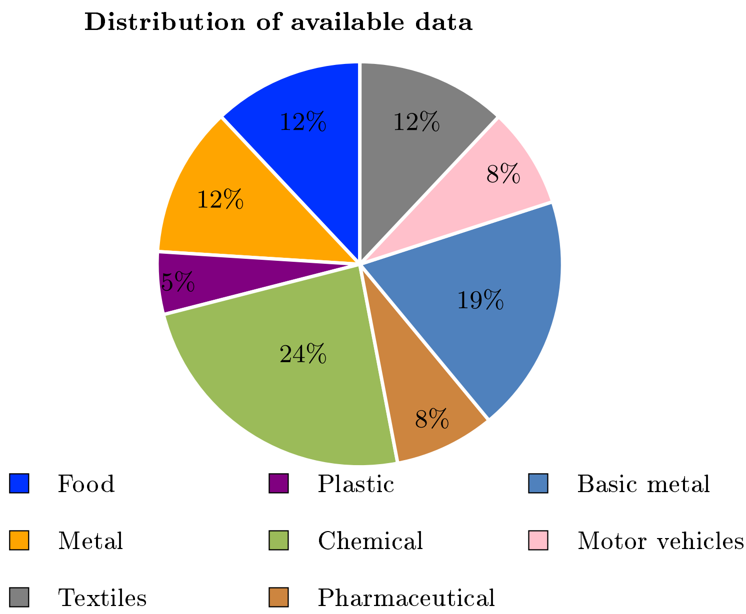

Figure 3.1: *Distribution of the sample of enterprises which compiled the questionnaire.*

- Answers to question 1, about the development of an energy efficiency program, show that most companies adopt a well defined energy efficiency program for their CAS. This aspect highlights the widespread interest of the companies management toward the energy consumption reduction. In particular, the question does not ask for more information about the installed measurement system, but it highlights the interest of management toward energy costs. The results are collected in Figure 3.3.

- The second question is about the identification of compressed air saving opportunities. The answers show that less than 20% of the companies surveyed do not carry out systematic measurement procedures or they do not get good results from implementing measurement systems. The results also show that more than 40% of the samples have recently implemented a procedure to identify energy efficiency opportunities (Figure 3.2).

- The results of question 3, about maintenance scheduling, show that 50% of the sample adopts a well defined procedure to maintain the most important equipment. (Figure 3.2)

- The question 4 is about the cost analysis of compressed air production. The results show that only 25% of the sample do not consider the problem. The remaining part analyses the energy costs and also uses EPIs to compare their performance. (Figure 3.4)

- Compressed air leaks are the most important efficiency losses. The results of question 5 in Figure 3.3 show that almost all the companies consider the problem of air leakage very important but only 50% of them have undertaken some action to reduce the losses.

- The pressure drop (indicated in question 6) is an important parameter to establish if the distribution system is well designed. The answers indicate that in most cases it is not know by management (Figure 3.2). When it is measured, only few immediate and cost-effective corrective actions have been planned.

- The answers of the seventh question show that the sample is almost equally divided in two parts (Figure 3.4). Most companies have not considered the definition of a measurement plan, instead more than 35% regularly use the measurement system.

- The displacement of the intake air inlet, subject matter of question 8, is an important aspect to reduce CAS energy consumption. Most companies consider correct the displacement, however more than 20% have never verified this aspect (detailed results in Figure 3.3).

- The question 9 regards the regulation of the pressure level. In most cases it is set to maximum value required by the users. Some companies have also undertaken some action to reduce the pressure set point (Figure 3.3).

- The tenth question is about the improper use of compressed air. The results in Figure 3.2 show that most of the samples (more than 50%) confirm that the companies have strong awareness of the importance of the correct use of compressed air but the procedure to minimise compressed air use and wastes are not well implemented.
- The results of question 11 highlight that more than 70% of the interviewed companies use an advanced control system. Most of the companies use variable speed compressor with inverter on the basis of measured data. The regulation results optimized and energy efficiency is improving (Figure 3.2).
- Question 12 is about the compressed air demand profile. The results in Figure 3.2 show that the answers are almost equally distributed. These results do not denote a clear picture of the situation.

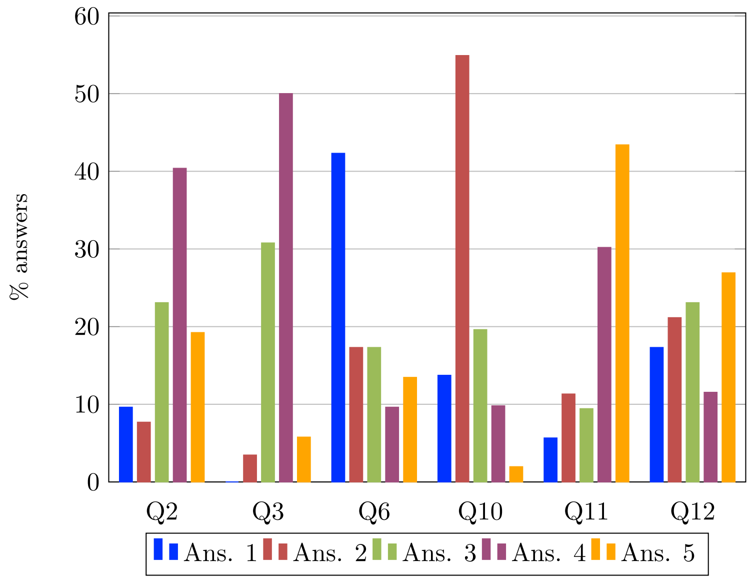

Figure 3.2: *Results for questions 2, 3, 6, 10, 11 and 12.*

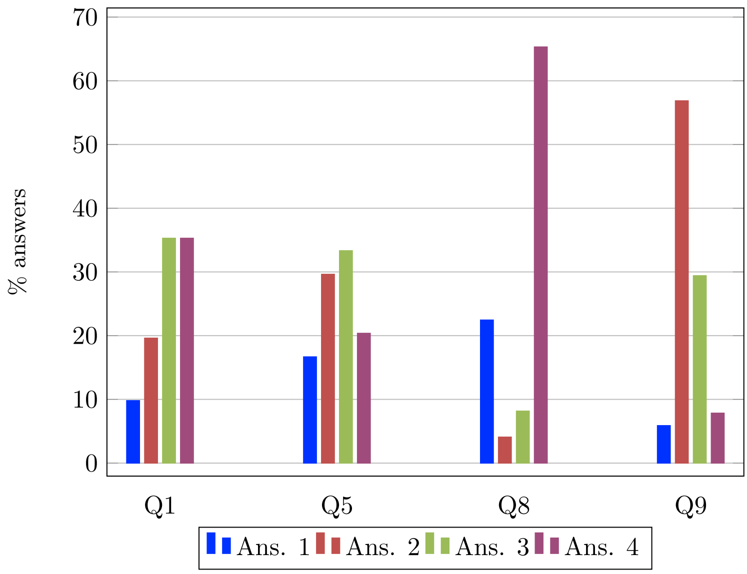

Figure 3.3: *Results for questions 1, 5, 8 and 9.*

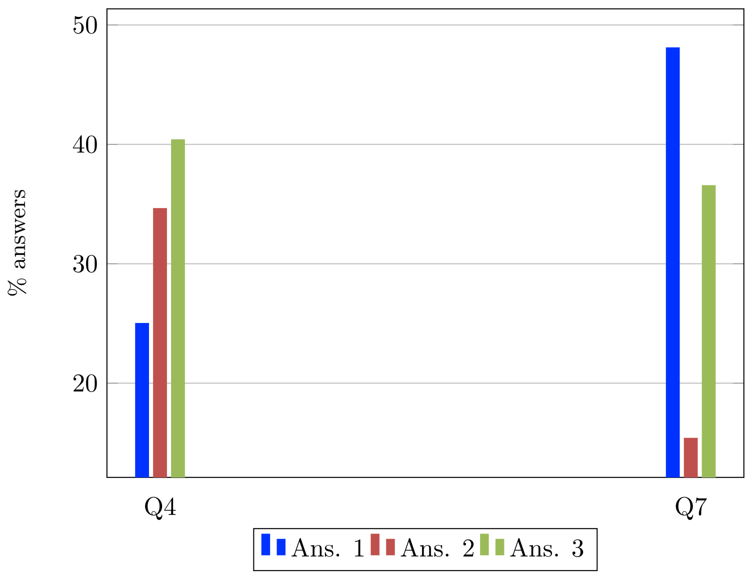

Figure 3.4: *Results for questions 4 and 7.*

3.4 Discussion

The analysis of the results of the questionnaire leads to 3 main findings:

- The compressed air production sector has large margins of improvement. In particular, both the level of maturity for the control of pressure drop and energy consumption (questions 4 and 6) are very low and the best practices are still not sufficiently diffused. Concerning improper use of compressed air and delivery pressure (question 9 and 10), the percentage of the answers shows that the largest part of the sample has an elementary control system.

- The maturity level of the enterprises is very heterogeneous. This aspect highlights great variability in energetic performance and confirms the need of a benchmark indicator. In particular, all the answers to questions about systematic diagnosis, demand profile and leaks control (respectively questions number 2, 5 and 12) are rather equally distributed. This confirms the need of a further intervention.

- The use of measurement systems is still not sufficiently widespread. The proof of this statement is given by the answers to question 7, which show that about 48% of the companies surveyed do not have a measurement system and about 15% of them have the equipment available but rarely use it.

Potential improvements

Starting from the results of the administration of questionnaires, statistical analyses and benchmarking, some suggestion for achieving more improvement of energy efficiency are drafted. More significant information about CAS would be useful to achieve better results and more improvements of energy management. Companies should have available:

1. Larger availability of data from measurements in order to get more reliable results. Companies should install a minimum measurement system to measure the amount of energy used by all compressors including cooling system's pumps and the total amount of compressed air produced. In Figure 3.5 two examples of measurement system are collected. "E" indicates electric power measurement devices and "A" indicates compressed air measurement systems. These schemes would allow a more accurate and reliable calculation of the KPIs.

2. Some further information about the quality of the produced compressed air and, in particular, its pressure level. In case the

systems have multiple pressure levels, it would be useful to develop a benchmark analysis that considers the effect of pressure and develop different benchmarks based on the pressure level. A further path could be the development of a more complex benchmark system capable of different pressure levels.

Enterprises could take advantage of gathering:

1. More information about compressor parks, for example compressor size, compressor type, modulation type (i.e. presence of inverters or of electronic control units for ignition and shutdown of individual compressors). Whenever possible, if there are more than one compressor, it would be useful to know the energy consumption of each compressor or, at least, an estimate of the annual operating hours of the single compressors. An indication of the variability of air demand over time could also be useful, despite being complex. Such an information would allow to compare the performance of the different systems.

2. More information about the compressed air system management as the maintenance scheduling, maintenance costs and energy consumption. Defining a maintenance schedule can represent a possibility to reduce CAS costs.

Using data from surveys, it is possible to estimate the potential for energy savings and in general assess the company's level of performance over time. The installation of an adequate system for measuring energy consumption, compressed air flow rate and other useful parameters to define energy performance would allow companies to provide suitable indicators to understand their improvement margins. Moreover, they could control their energy consumption with significant economic benefits, certainly sufficient to repay the investment very quickly [19]. The introduction of performance-oriented measurement devices is the first step to develop an energy performance management and information system based on an energy management system [5].

Each company can also develop a baseline for internal performance benchmarking, monitor them through the regression analysis on historic data and analyse them through the use of specific control charts like CUSUM, in order to find any malfunctions through a real-time monitoring system. This kind of procedure allows to have alarm signals about malfunctions and excessive consumptions ensuring significant savings [67].

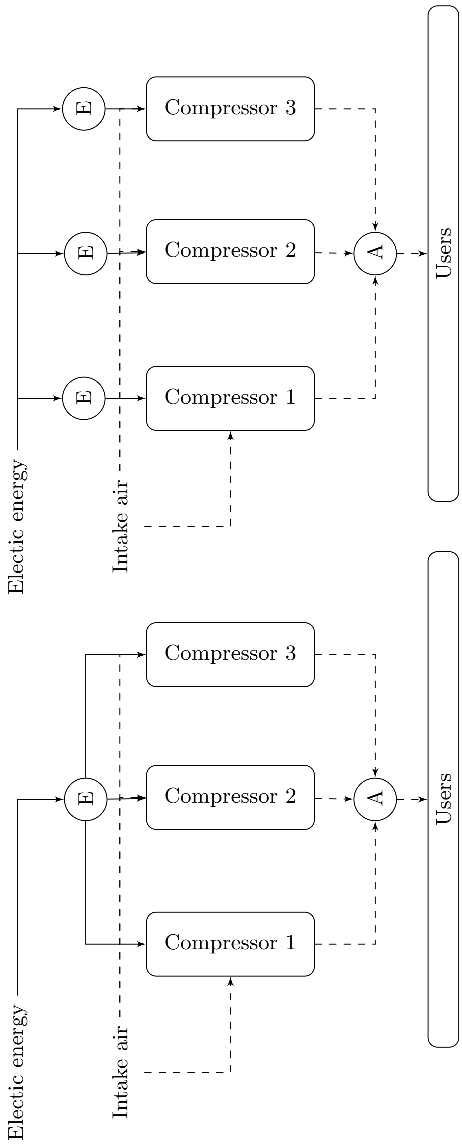

Figure 3.5: *Minimum measurement system (left hand side), optimal measurement system (right hand side).*

Chapter 4

Best practices and guidelines for CAS

Introduction

Dozens of documents regarding energy efficiency are available in scientific literature. Some of them, such as [9] and [10] collect many indications about energy efficiency improvements of industrial processes but it is difficult to find well-organized procedures for managing and improving the performance of compressed air generation and transport systems.

The activities summarized in this chapter are about the development of a procedure suitable for enterprises to improve the CAS energy efficiency based on the assessment of the maturity and the proposition of guidelines to reach the best practices level.

The best practices are very common in technical and scientific literature, they are well explained in many works and are proposed in numerous manuals. In order to draw up an appropriate set of guidelines to help companies achieving best practices, a careful bibliographic analysis is first carried out to identify a series of best practices related to compressed air systems. All developed guidelines can be suggested matching each of them with one or more questions of the maturity model and the best practices already available. In this way it is possible to define a complete procedure that aims at energy efficiency consisting of two steps. The first, through which a company can measure its own maturity regarding energy efficiency. The second, through which obtaining useful suggestions on the procedures to be adopted in order to raise the efficiency level to the point considered as objective.

The first and best known definition of Guidelines has been formulated by the "Institute of Medicine" in 1992. The field of application was very different from that taken into consideration in this work but the "systematically developed recommendations to assist physicians and patients in decisions on appropriate management of specific clinical conditions" can be surely transposed in industrial energy management. In a certain sense, the objective of the work is the same defined in 1992 definition, that is, to provide suggestions to companies on the subject of improving the efficiency of the production, transport and use of compressed air sector. A guideline must be considered as an aid to lead a procedure of development to an upper level comparing with the starting one.

The purpose of this chapter is to show how a set of guidelines based on the best practices have been developed and to propose the application of these to real case studies. For this reason, a sample of companies are collected, their performance are assessed and after results analysis guidelines are suggested. This section is entirely developed by the author.

4.1 Background

The guidelines are common tools to improve the performance of a defined system or subsystem. They are widely recognised as important tools for defining the objectives to be achieved in terms of performance and efficiency [68]. The guidelines represent a valid decisions support leaving the user freedom of action. Despite their generality, they should be addressed to a defined objective [69] and should not be represented as checklists of technical practices to be implemented but they should only outline the direction that the company must take.

The guidelines have achieved major success in recent years thanks to the ever increasing diffusion of the company's efficiency and growth policies; these represent a synthesis of the scientific information available and aim to bring the company to the level defined by best practices.

The most interesting feature of the guidelines is the tendency to promote the continuous and progressive improvement of the company (in this case in terms of energy efficiency). This feature is common to many approaches including that required in ISO standard.

Adopting a continuous improvement based approach, a company is encouraged to think about achieving a high level of performance, in any considered area, and also to continue in the research of ever-increasing level objectives. In this way, any business aspect can be improved and all components can contribute to the process.

Considering the importance that industrial competitiveness has assumed through the years, many industries try to redefine their objectives, reorganizing every single process in order to get more efficient productions to achieve competitiveness both in national and international market. In such a scenario, the most critical challenges faced by enterprises are related to the improvement of energy efficiency and reduce energy costs. To implement energy efficiency measures and improve industrial production, organizations increasingly base their interventions on some guidelines that guide them towards effective implementation.

A number of guidelines for industrial applications were proposed in previous studies. Some examples of these are reported below. In [70] authors provide guidelines for preparing a careful energy audit. They list a series of practices (energy bill analysis, cost-benefit analysis, etc.) and propose a series of suggestion to plan and conduct a well-structured energy audit and get the best possible results.

[71] proposes a series of guidelines for energy management based on Energy Star principles. Guidelines are addressed to paper industry for improving energy performance and reduce energy costs. Guidelines are based on a systematic approach involving four major factors: targeting, implementation, monitoring and adjustment.

In [72] seven guidelines are proposed for improving the performance of plastic footwear production. Through the use of the guidelines, the enterprise can get more control over processes and eliminate wastes. According to the authors, performance increase helps enterprises to improve their social image and their competitive position in the market. These improvements could be widespread in all the company achieving a decrease of operational costs, a reduction of waste of raw material, water and energy, etc.

[73] proposes a series of guidelines suitable in wine industry to implement an energy management system. Obviously all the guides are tailored for the South African context. The objectives of such a system of guidelines include costs reduction, continuous improvement based on plan-do-check-act cycle, improvement of energy performance and increase

in sustainability.

In other cases, guidelines have been addressed to national institution and government to increase the performance of the industrial sector. As an example, Roberts in [74] investigates the application of industrial ecology and develop a set of principles and planning guidelines to improve the sustainability of Australian industry. Following these guidelines and principles it is possible to facilitate the development of eco-industrial parks.

In closing, international organizations offer guidelines for specific objectives. For example, ASHRAE offers guidelines for cooling and heating systems of industrial plants, also ISO offers numerous guidelines in its standard.

In this work some guidelines are developed to help industrial enterprises in the process of improving energy efficiency with regard to CAS.

4.2 Methodology

This section aims to develop a method usable as a guide for the enterprises that want to improve their CAS energy efficiency through a process of proposition of best practices and implementation of a set of guidelines adapted to their maturity level. To achieve this goal, this part consists on the development of the already mentioned set of guidelines starting from the aspects touched upon in the maturity model described in [75].

4.2.1 Information collection

Before suggesting the best practice and the suitable guidelines, it is necessary to collect some information about CAS management. In this phase two approaches are possible. The first is the administering of a maturity model which can provide important information about the company maturity about energy management. The second approach considers the possibility to collect information through surveys and direct contacts. Obviously, both approaches are usable to get more specific information.

Compressed Air System Energy Efficiency Maturity Model

The developers of the Compressed Air System Energy Efficiency Maturity Model (CASEEMM) have developed a self-assessment multiple choice questionnaire where the questions are organized according to a growing maturity level. The questions in the CASEEMM are grouped into 4 macro areas depending on the sector of interest called "dimensions" shown below.

- Awareness, knowledge and skills. This aspect represents a basic dimension of the energy efficiency of the CAS and, in general, of energy management. This dimension gathers: staff awareness of the importance of energy efficiency, technical and managerial knowledge useful for prevention, problem solving and identification of the best solutions through the use of Best Practices.

- Methodological approach. This dimension characterizes maturity levels more than other, especially in the energy sector. In fact, three main classes are well known from literature. Different methodological approaches can be grouped in: occasional reduction, systematic reduction, systematic and continuous reduction of consumption [5].

- Energy performance management. Energy management is a fundamental aspect, unavoidable to implement an efficient performance measurement system. Having a complex monitoring system could increase the costs for the necessary equipment and also requires the training of the personnel to manage the systems and set objectives to be achieved. For these reasons, the management method must be decided after careful cost and benefit assessments. The employees must be coordinated and must ensure communication between the various departments to create a synergy that helps the growth of the company.

- Implementation of Best Practices and adoption of Best Available Technologies. This dimension refers to the implementation of the BP and the adoption of the BAT for the CASs extrapolating from the scientific literature. There is no explicit reference about specific practices because of the variability of the plants and enterprises. For each indicated intervention, the maturity model does not simply evaluate the implementation, but it evaluates if the implementation is correct in energy and economic terms.

Therefore, CASEEMM includes all the aspects relating to the design, management of the CAS. It also includes all the aspects relating to internal organization, enterprise policies toward the energy efficiency improvement. The final result of the work is a questionnaire made of 34 questions divided into 4 dimensions, previously described, and on 5 levels (from 1 to 5) based on the maturity of the organization. The organization of the questions according to the analyzed dimensions and the level of maturity are collected in Table 4.1. The first level does not include questions because it is a "base" level, in which the dimensions are practically not developed. The administration of the CASEEMM to the companies allows to achieve an assessment of the level of maturity of the CAS with a completely autonomous approach and without any external conditioning in the choice of the responses. Each company, starting from the questionnaire results, can attest its own maturity level compared to what could be the desired level in the medium term. From this analysis, the company can define an intervention strategy based on the best practices and on the guidelines proposed in this work.

Table 4.1: *Description of the number of questions for each dimension (columns) and for each level of maturity (rows).*

	Dimension 1	Dimension 2	Dimension 3	Dimension 4	**Total for level**
Level 2	2	1	3	3	**9**
Level 3	2	2	4	4	**12**
Level 4	1	1	3	3	**8**
Level 5	1	1	2	1	**5**
Total for dimension	**6**	**5**	**12**	**11**	

Surveys

The constructive and managerial differences between the various production plants make necessary knowing each industrial case with a level of detail that is difficult to reach through summary descriptions or simple numerical consumption data. The knowledge of the plant characteristics and also of management policies are fundamental factors to better evaluate the process improvement potential. Furthermore, meetings with companies allow careful assessments of the compliance of the level of maturity that emerges from the application of the CASEEMM and the findings of the inspections. So, each inspection provides an overview of the plant and allows to establish more carefully what are the measures to be undertaken to raise the maturity level and improve the energy performance of the systems.

4.2.2 Best Practices selection

The best practices indicate procedures, behaviors, habits, etc., that might be taken as a reference to facilitate the achievement of the best results in business, engineering and so on. The definition, coined for the managerial field, refers to the techniques that allows to obtain the best results. The best practices can potentially constitute a system of rules whose observation helps the company to improve production methods becoming more efficient. Considering the interest that best practices have historically gained in organizations management, the development of a system of practices concerning the generation of compressed air can be considered an important step to develop a business activity aimed at energy efficiency. Therefore the best practices are considered as an objective to be reached and that must push the enterprise to continuous improvements.

To collect a sufficient number of best practices, a large and complex research activity is undertaken. This activity includes a specific bibliographic research of practices and customs that can be considered as best practices with regard to the field of generation and treatment of compressed air. The research concerns the study of scientific articles, conference publications, degree theses, technical manuals, etc. To complete the set, some best practices are developed on the basis of the acquired knowledge. The result of the research is a series of practices, about most of the aspects of the sector such as: generation, maintenance, transport, filtering, management, etc.

The analysis of literature about industrial energy efficiency leads to the identification of general best practices that can be suitable for compressed air systems. This research allows, also, to develop some specific best practices (never drafted up) before starting from available literature and author's experience.

The collected best practices represent a valid aid to define a result achievable in the short or medium term but do not provide further usable information to organize a work plan aimed at improving energy performance.

4.2.3 Guidelines drafting and application

As described above, the best practices represent the highest level of maturity. The achievement of the best practices level in one or more aspect can be considered the certainty of having performed a good job toward the desired objective. Companies should careful manage their efforts to achieve the level indicated by the best practices but it may be very difficult to do without a well defined strategy.

Considering the complexity of business dynamic, the companies certainly have to work hard to achieve the best practices level in a short time. For this reason, the best practices are not sufficient to support the companies through the process of efficiency improvement.

The guidelines could represent a more powerful tool for this activity. Following the guidelines, companies can outline a growth strategy in terms of energy efficiency, in most cases low-cost. The guidelines are not rules to be rigorously followed to get the desired results, but, in general, they may be useful to funnel the efforts towards a single direction indicated by them. So, the best practices are used as starting points for the development of several useful guidelines for improving the energy efficiency of the CAS.

From the company point of view, implementing the guidelines needs some requirements. First, the management and all the personnel should know the general and conceptual aspects of the guidelines, what they are useful for and how can they be implemented.

Their careful implementation enhances one of the most interesting aspects represented by the promotion of progressive improvements in terms of energy efficiency. This aspect is one of the cornerstones of the adoption of an integrated energy management system that meets the requirements of the ISO 50001 standard.

The wide range of energetic aspects concerning CAS requires to reach a sufficient knowledge about the system in exam. To develop set of guidelines defined for most of the aspects of compressed air production, the work has started with an analysis of technical and scientific literature to collect the best practices for energy efficiency improvement from. For each best practices (of groups of them) a suitable guideline is defined.

The process of developing a guideline is crucially important since each recommendation must be pertinent to the sector. Moreover, guidelines must be related to the level of performance sought and above all they must have the conditions to be of effective applicability. Essentially, each indication might be transferred to the company and adopted in common practice. The guidelines should indicate general aspects and suggest behaviours that lead to the improvement of the maturity. They do not indicate well defined technologies and tools but they have to represent a guide to be followed.

The analysis of the results of the CASEEMM and the criticalities highlighted during surveys allows the identification of the aspects in which the organization has a greater level of development and the aspects in which is more deficient. These results can be used to propose some strategies to improve the energy aspects.

After a careful analysis, the developed guidelines can be suggested to the company to propose some solutions to improve energy efficiency.

In order to permit companies to achieve the best results from guideline implementation, a procedure based on the administration of CASEEMM and a successive suggestion of the guidelines is developed.

It is important to note that the application of the guidelines is not always easy due to their variety and the wide range of interest. It is impossible for a company to implement all the defined best practices at the same time and reach the energy efficiency quickly. The process of energy efficiency improvement is usually quite long, it can be a source of considerable costs and, as already mentioned, it must involve every single business sector.

4.3 Results

This section collects the results of the best practices selection, guidelines development and the application of these after the administration of the CASEEMM and the surveys taking place.

Collected best practices

After a large and careful technical and scientific analysis, a set of best practices is collected. The available best practices, about technical and managerial aspects, represent the highest level of maturity achievable. All the collected best practices are listed below:

1. Leading an energy audit [30];
2. Using a high-efficiency motor to get energy saving [30];
3. Installation of motors with variable speed drive (VSD) to get energy saving; [30, 76, 14];
4. Leading actions to prevent compressed air leaks [30, 28, 77, 31, 78, 79];
5. Intaking of fresh air from the outside [30, 76, 78];
6. Reduction of pressure drops along the distribution line [30, 76, 78];
7. Recovery of compressors and dryers waste heat [30];
8. Use of efficient nozzles [30, 79];
9. Installation of variable displacement compressors [30];
10. Maintenance and cleaning of compressor and cooling surfaces [30];
11. Emission mitigation [30];
12. Use of software to estimate the efficiency improvement due to system changes [30];
13. Reduction or elimination of inappropriate uses [76, 28, 78, 80];
14. Managing of peak demand [28];
15. Pressure minimisation [28, 31, 78, 79];
16. Reduction of distribution inefficiencies [28];
17. Use of storage and automatic system controls to anticipate peak demands [31];
18. Evaluation of the possible alternatives to the compressed air [31, 78];
19. Evaluation of the compressor utilization coefficient [31, 81];
20. Evaluation of the contemporaneity coefficient of the compressors [31, 81];

21. Check the appropriateness of equipment used to control and deliver compressed air [31, 81];
22. Turn off the supply of compressed air at a process when it is not running [31];
23. Determining of the cost of compressed air for each machine or process [31];
24. Follow application of the preceding recommendations with a review of the number of compressors in operation and their control settings so that a corresponding reduction in energy is realized;
25. Make sure that the compressed air supply side personnel are involved in process and end-use related decisions [31];
26. Creation of a system pressure profile using pressure readings at key points throughout the system [31];
27. Control of the average flow [78];
28. Control of the air quality (pressure dewpoint for moisture, concentration limits for dirt and oil) [78, 82];
29. Control of compressor energy consumption [14];
30. Control of system load profile [78, 31];
31. Review the air receivers [14];
32. Maintainance of separators, filters, dryers and valves [14];
33. Selection of a suitable compressor [14];
34. Measurment of the improvement [14];
35. Analysis of compressed air uses [82];
36. Improvement of data measurement and recording [82, 76];
37. Optimization of the compressed air department based on the request [76];
38. Optimization of transport network [76];
39. Implementation of multiple pressure levels [76];

40. Installation of a heat economizer [76];
41. Replacement of obsoloete compressors with new and better machine(s) [76];
42. Placement of air tanks next to machines with high variation of the air required [76];
43. Removeing moisture content of compressed air with the proper type and size of dryers [83];
44. Removing condensate without loss of compressed air [83];
45. Control of air temperature [80, 84];
46. Implementation of a maintenance schedules;
47. Monitoring compressor performance (deterioration) [85];
48. Check drive belts (where fitted) [14];
49. Creation of organizational structure for implementation of the strategy [86];
50. Allocation and focusing of the resources towards strategic goals [86];
51. Galvanization of implementation of the chosen strategy [86];
52. Establishment of an internal administrative system for support [86];
53. Providing strategic leadership [86];
54. Minimization of pressure drops by calculating the equivalent lengths of fittings [14];
55. Dissemination of awareness of the importance of energy efficiency;
56. Dissemination of knowledge of analysis tools;
57. Establishment of a formal register of opportunities;
58. Enhancement of internal communication;
59. Identification and adoption of BAT;
60. Continuous training;
61. Forecasting of energy consumption;

Developed guidelines

As already mentioned, the procedure consists of the administration of the CASEEMM, the analysis of the results and the subsequent best practices proposition and guidelines suggestion. In the following, all questions of the CASEEMM are reported with the collection of the best practices and guidelines.

Question: 02:01 - Regarding the promotion of compressed air system's energy efficiency within the company:

Best Practices: 49, 50.

Guidelines:

- The company should encourage the systematic promotion of the energy efficiency and the improvement of energy performance through formal and informal contacts. The company should organize training activities and disseminate material (paper and computer equipment) to spread the awareness of the importance of the energy efficiency of the CAS. The employees, at every level, should know the principles of energy efficiency and promote them.

Question: 02:02 - Regarding the company's attitude towards energy efficiency opportunities, it is possible to state that:

Best Practices: 1, 34.

Guidelines:

- The company should introduce a systematic research of the opportunities to improve energy performance. It should inform suppliers of its interest for high efficiency solutions or systematically include requirements relating to the energy efficiency (ISO 50001 standard) in the technical specifications of the acquired equipment.
- The company should perform an adequate economic evaluation of all the opportunities through methods such as the Pay Back period when potential modifications of the plant are necessary and it should use the Life Cycle Cost analysis method for the evaluation of new purchases (eg. compressors, filters, etc.)

Question: 02:03 - With regard to the collection of data on costs and consumption of the compressed air system, it is possible to state that:

Best Practices: 36.

Guidelines:

- The company should consider the benefits of improving the measurement system. The installation of a continuous measurement system of energy consumption and compressed air flow would be advisable. If the installation is too expensive or technically impossible, the company could think using temporarily flow meters and portable ammeters to monitor the production of compressed air and the energetic consumption during certain periods. Continuous or periodic measurements allow depicting a better picture of the situation than the one outlined through the consumption analyses derived from the electricity service invoices.

Question: 02:04 - Regarding compressed air leaks in the distribution network:

Best Practices: 4, 16, 27.

Guidelines:

- Air leaks represent the most important form of reduction of the energy efficiency of the compressed air system. The company should assess the amount of compressed air lost along the distribution network. To achieve this objective, the company should develop a leak detection strategy that can be implemented through on/off tests in a preventive way, and subsequently through inspections and instrumental surveys (using ultrasound instruments).

Question: 02:05 - Level of technical knowledge (design, maintenance, management, use of compressed air, innovative technologies) related to energy aspects of the personnel responsible for the management of the plant:

Best Practices: 49.

Guidelines:

- The company management should create a strategy-oriented structure. In this way, continuous technical training activities can be proposed, at every company level, regarding the energy efficiency measures of the compressed air department. All personnel should be constantly informed about the possibilities of increasing the efficiency of the compressed air generation system through all the available tools (courses, meetings, paper material, etc.). All aspects concerning this sector should be dealt with in depth, from design to maintenance, from management to equipment renewal.

Question: 02:06 - The person responsible for the energy efficiency of the compressed air system:

Best Practices: 53.

Guidelines:

- The company should work for the training of an energy efficiency manager, which should positively impact on the plant energy consumption. The manager should work toward the efficiency improvement process. His action should be taken into consideration by the management and could have a strong impact on the company. The absence of a reference figure can lead the company to make wrong decisions or to concentrate its efforts on a strategy that does not bring the desired results. Where the productions are huge, it would be advisable to identify specific indicators for monitoring the energy performance (electricity used correlated to the quantity of compressed air supplied to the users) and the amount of compressed air used in the production section (amount of compressed air compared to production volumes).

Question: 02:07 - Regarding improper use of compressed air:

Best Practices:13, 18, 20, 22.

Guidelines:

- The company should evaluate and eliminate the improper uses of compressed air. The absence of a procedure to shutdown the air supply for equipment that is currently not used and the improper use of the air (for example for blowing operations) can lead to a deterioration of energy performance. The company should define procedures for controlling the switching on and off of the equipment, stopping the supply of air (when compressed air is not needed) and above all assessing the replacement of equipment powered by compressed air with others that use other energy carriers. The introduction of low pressure blowers and electrical equipment can lead to improve energy efficiency.

Question: 02:08 - Analysis of costs and consumption data of the compressed air system:

Best Practices:

Guidelines:

- The company should monitor costs and energy consumption related to the compressed air production plant. Periodic analysis of system performance allows benchmarking against internal and external references. The monitoring of consumption and production allows to highlight any operating anomalies and it encourages employees to carry out analyses and investigations to find the causes.

Question: 02:09 - The positioning of the air intake to the compressors:

Best Practices:5, 16.

Guidelines:

- The company should verify the correct placement of the air intake of the CAS. A lowering of the intake air temperature by 3° C allows to reduce the consumption of the CAS by about 1%. For this reason, the air intake should be situate in an external position, exposed to the north (and therefore sheltered from direct sunlight), at a sufficient altitude to avoid dust suction.

Question: 03:01 - The company staff (and in particular those involved in the compressed air system management):

Best Practices: 55.

Guidelines:

- The company management should spread the awareness of the importance of energy efficiency at every level. Energy efficiency must be an objective pursued in every aspect of the company, both in production and in utilities use. The impact of consumption for compressed air can be reduced in every aspects: design of CAS, operation and maintenance. Everyone should be able to evaluate and propose new ideas that can increase efficiency. To validate the work, the personnel should demonstrate the effects of energy efficiency through tables, graphs and periodic reports.

Question: 03:02 - Systematic and documented diagnosis of the compressed air system (i.e. energy audits), aimed at identifying opportunities for energy savings conducted also through the analysis of available data and inspections that may also include measurement campaigns ...

Best Practices:1, 23.

Guidelines:

- The company should manage systematic and documented diagnosis of the compressed air system, aimed at identifying energy saving opportunities (energy audits). The energy audit allows the company to identify all the energy flows in a service, quantify the energy use and propose energy saving measures. The company should periodically conduct systematic diagnoses to highlight (through subsequent measurements and assessments) all the possibilities for efficiency improvement and how to implement them.

Question: 03:03 - Development of a consumption measurement system (definition and use of a measurement plan that identifies the quantities to be measured, the measurement frequency and the measuring instruments):

Best Practices: 12, 26, 30.

Guidelines:

- The company should define a measurement plan and implement a measurement system that monitors the compressed air production and the related energy consumption with the appropriate sampling frequency. A well-designed measurement system enables performance monitoring, failure detection and definition of benchmark analysis. If it is not possible to install a fixed measurement system, the company may consider using temporary flow meters to monitor the production of compressed air and its use during certain periods and ammeters to measure electric energy consumption.

Question: 03:04 - As regards the compressor regulation system (on/off, vacuum/load, inverter):

Best Practices: 26, 2, 3.

Guidelines:

- The company should evaluate in economic terms the use of an optimized regulation system. The adoption of variable speed compressors through the use of inverters can help improving energy efficiency. The company should evaluate the inclusion of inverter control systems on its compressors if it only has compressors with a load/unload control logic available.

Question: 03:05 - Level of managerial knowledge related to energy aspects (economic-financial evaluation of energy projects, energy audits, methods and tools for the consumption analysis and control, information systems for energy management, energy management systems, tools for financing innovative technology) of the personnel responsible for the management of the plant:

Best Practices: 56.

Guidelines:

- The company personnel involved in improving energy performance should increase its own knowledge about management tools for improving energy performance, including: economic and financial evaluation of energy projects (estimate of plant and operating costs, amortization calculation, pay back times and other useful economic-financial indicators), analysis of consumption data (statistical tools for the analysis of historical data, the definition of baseline, the identification of behavioral anomalies, etc.), energy audits (organization of a diagnosis, energy services offered by ESCOs, etc.).

Question: 03:06 - Energy saving opportunities register:

Best Practices: 57.

Guidelines:

- The organization should have a formal register that collects the opportunities for efficiency improvement identified after conducting surveys and energy audits. Anyone who notices a savings opportunity can fill in the register. In addition to the opportunities, the register can be used to take note of the summary assessment about the economic impact of the interventions and possibly forecasts for future activities.

Question: 03:07 - Measurement of energy factors (factors influencing energy consumption such as production volumes, compressed air production, hours worked, etc.):

Best Practices: 24, 25, 29.

Guidelines:

- Changes in processes, operating conditions and the final use of compressed air can cause strong impacts on the energy performance of the CAS. The organizations should carefully assess which operating parameters they might appropriately measure (eg. volumes of compressed air produced/used, work pressures, environmental conditions, production volumes or working hours of the departments/machinery using compressed air, etc.), at what level of detail (eg. single compressor/single machine or entire department) and how often data needs to be analyzed (monthly, weekly, daily ... up to the quarter hour). An optimized measurement system should allow to evaluate the energy performance both of the entire plant and the single sections. Furthermore, it should allow to monitor the natural changes of the boundary conditions being able to distinguish and intercept inefficiencies and waste, even temporary. This characteristic permits to obtain significant savings characterizing for example, an unjustified increase in working pressure, significant absorption by utilities that should be switched off, incorrect maintenance interventions, etc. To summarize, an adequate monitoring system will also make it possible to subsequently develop consumption baselines and control the factors that influence consumption and the systems performance in real time, allowing the early identification of lack of performance.

Question: 03:08 - Regarding compressors maintenance planning:

Best Practices: 10.

Guidelines:

- The company must consider creating a regular and well-organized maintenance program. Following a rigorously organized maintenance program enables the company to maintain high performance of the compressed air production system. A good maintenance program that contains interventions both on the motors and on the filters allows to limit faults, avoid unwanted service interruptions and reduce system management costs. The filtering system must be maintained to keep minimum localized pressure loss (source of energy efficiency loss) and guarantee good filtration levels.

Question: 03:09 - As regards analyses carried out using energy consumption data collected, it is possible to state that:

Best Practices: 34, 36.

Guidelines:

- The availability of measured data about energy consumption allows the organization to assess the energy performance of its CAS and to state whether the measured energy consumption is justified by the operating conditions. This operation can be performed at the entire system level (for example by comparing the kWh absorbed by the compressed air production plant to the volumes produced by the plant) or by subsystems (for example, by comparing the electric energy consumption of the compressors with the volumes of compressed air, for the entire group or the single compressor, and comparing the volume of compressed air used to the production volumes produced by the entire production site or by the single department). Such analysis can be made more effective by developing baselines through the use of statistical models obtained by linear regression. In this phase, it is possible to take into account the inevitable scale effects that occur when operating conditions change (for example air volumes). The use of this approach, on an ongoing basis, allows the definition of standard energy performance and the identification of system behavior deviations due to various types of inefficiencies (ignition rules, failures that have not yet caused the system failure, air leaks, plant modifications, etc.), to accurately assess their impact in terms of additional energy consumption. Thus it allows to establish the most convenient intervention methods and times.

Question: 03:10 - Regarding the verification of the correct design of the system and its elements:

Best Practices: 2, 21, 28, 24.

Guidelines:

- The organization should verify that the working plant is in line with the times and its performance are enough to meet the needs. Beyond the natural technological development that makes compressors and other plant components (filters, dryers, etc.) capable of ensuring ever better energy performance (high efficiency motors, inverters, magnetic levitation bearings, etc.) it is important to note that the needs of an industrial site can vary greatly during the life cycle of a CAS. An old compressed air plant can be obsolete in terms of modulation capacity, compressor size, pipe diameters, supply pressure and air usage, etc. For these reasons, past choice can influence and severely penalize CAS performance.
  Any plant modification generally requires significant investments but it could have return times compatible with company strategies. For example, the purchase cost of a compressor typically represents

less than 10% of the life cycle cost determined by the compressor itself, resulting in energy costs over 80%.

- The quality parameters for compressed air are the dew point as regards the presence of humidity, and the concentration of particles such as dust or oil. Unlikely all the equipment, connected to the compressed air distribution, need the same air quality. Some of them could have less stringent requirements that lead to fewer treatments and lower costs for compressed air generation. These differences should be considered during design phase together with the maintenance plan.
  Since an excessive level of air cleaning leads to excessive pressure losses due to the passage of air through filters and dryers, it is necessary to assess the extent of air treatments. The organization should therefore evaluate the various types of applications and the level of air quality required; if required quality is very different from one user to another it might be efficient to have two different circuits with different types of treatment.

- Considering the energy saving, the enterprise should review whether the number of active compressors is correct for the level of service required. For a good operation without energy waste it would be advisable to also review the positioning of the compressors and the configuration of the system.

Question: 03:11 - Internal communication:

Best Practices: 58.

Guidelines:

- The enterprise should promote internal communication between the various levels regarding the energy efficiency process. It should enhance the exchange, even informal, of information between those responsible for energy efficiency in the various sectors and at all levels. The exchange of information can take place through periodic meetings in which the various strategies for improving the efficiency of the various systems can be discussed formally or informally.

Meetings must take place on a regular basis and efficiency measures must be proposed at each meeting so they can be discussed and extended to other enterprise departments. For example, difficulties or lack of communication between the staff responsible for evaluating consumption data and production personnel precludes the possibility of acting on many types of waste and identifying generally very profitable interventions (waste avoided through behavioral changes and therefore at almost zero cost). Only periodic communications between the parties makes possible to limit the waste, monitoring the obtained savings and therefore encourage the development of corporate awareness of energy saving opportunities.

Question: 03:12 - Regarding the adoption of automatic control systems for modulation:

Best Practices: 3.

Guidelines:

- Many CAS are designed to operate at maximum load conditions. The organization, during the design phase or during the renewal phase of the department, should evaluate the profile of use of the compressors and evaluate the introduction of variable speed compressors equipped with inverters. The efficiency of the system can be improved by varying their capacity to meet the actual load requirements. However, a variable speed motor with an inverter has a non-zero base load and the efficiency is not at maximum level for each load condition. When the load could not be fully choked the compressed air production can also be optimized thanks to the use of control units controlled by special software capable of autonomously managing the switching on and off of the various compressors in the department. This type of management leads to the shutdown of the compressors in the event of non-use and consequent limitation of the absorbed power.

Question: 04:01 - Regarding the involvement of personnel in the energy efficiency improvement process:

Best Practices: 51.

Guidelines:

- Organization management should provide the right motivation to organizational units and individuals to achieve energy efficiency. It should create working conditions in which the staff is encouraged to support the strategy and it is involved in its implementation. The achievement of good results must be a goal continually sought by all organization levels and it must be encouraged by the organization. The achievement of the expected results must be appropriately rewarded by the enterprise.

- Organization management should prepare a system that allows anyone within the organization to report an opportunity to save energy or to propose an intervention that can improve the organization energy performance. The personnel responsible for the operation and maintenance of the plants, for example, if appropriately involved can provide very interesting ideas. This type of approach also favors the development of energy sensitivity at all levels of the organization.

Question: 04:02 - Definition of energy efficiency specifications for the design and retrofitting of the system or its components:

Best Practices: 59.

Guidelines:

- The organization should promote research and the application of Best Available Technlogies. During design or redesign phase, the enterprise should already be aware of the BAT and should apply them to the whole procedure. When the search identifies an applicable BAT, the company should allow its application and measurement of the performance achieved with it. Monitoring becomes a fundamental activity for the characterization of the effectiveness of the technologies installed. The organization should therefore evaluate the opportunity to establish technical specifications relating to energy efficiency to be applied for new plants and for the replacement of components (eg. energy efficiency class of electric motors, presence of inverters, energy meters) electricity or energy factors, etc.).

Question: 04:03 - Use of methods for predicting energy consumption:

Best Practices: 61.

Guidelines:

- Before being able to implement this guideline, the organization must be equipped with an efficient system for measuring energy consumption for the production and use of compressed air. It should also measure the main factors that can influence energy consumption (eg. volumes of compressed air and/or volumes of production of the departments served). Starting from reliable data, the organization should have tools for forecasting energy consumption (baseline) based on statistical models developed through the use of historical data (for example through regression analysis). In this way, starting from the expected production volumes, it may be possible to predict the need for compressed air and/or energy consumption for the CAS. The early knowledge of consumption also allows you to manage control strategies (for example ignition) of the most efficient compressors and to control consumption over time. The comparison between the expected consumption with the actual one can be used to identify possible anomalies.

Question: 04:04 - Pressure drops in the compressed air distribution system:

Best Practices: 6, 16.

Guidelines:

- The company should assess the amount of wasted energy in the compressed air generation systems due to not optimal installation and inadequate maintenance. A good practice for raising energy efficiency is the regulation of compressed air pressure at the minimum functional level that the production equipment requires. In order to satisfy this requirement a well designed air distribution system is necessary, the diameters of the pipes are sized based on the flow speed and on the present pressure losses. The company should therefore monitor pressure drops at the end of the line and plan corrective actions such as replacement of network parts and elimination of localized pressure drops.

Question: 04:05 - Permanent consumption control (data acquisition, comparison with prediction model, variance analysis, reaction):

Best Practices: 36.

Guidelines:

- In the presence of significant energy consumption due to the compressed air production, the enterprise should carefully evaluate the possibility to install continuous control systems able to monitor energy performance over time. These systems, starting from the historical data, are able develop a statistical method to calculate the standard energy performances of the system (baseline) and allow to analyze the system performance in real time with very high frequencies. Output data can be analysed through automatic systems (eg. control charts with automatic alerting systems). In this way it is possible to promptly identify consumption anomalies and also obtain clues about their nature (sporadic, continuous, still present, growing, etc.). Moreover, control systems allow to determine the impact in terms of additional energy consumption in a very precise manner. To summarize, these systems are able to identify "unwanted" improvements and standardize them as well as verify the actual impact of interventions made on the existing plant.

Question: 04:06 - Regarding the compressed air supply pressure:

Best Practices:15.

Guidelines:

- The company should minimize the compressed air supply pressure. For this reason it should analyze the need for compressed air in different parts of the network and then organize interventions that can minimize the supply pressure. Studies can be conducted based on the daily use (for example by differentiating weekdays and holidays) and on the request for different pressures by individual users. The results should lead to a redesign of the CAS which could involve the subdivision of the plant based on the necessary pressure level by adopting compressors and boosters for the production of compressed air with differentiated pressure.

Question: 04:07 - Identification of responsibilities for the energy efficiency of the compressed air system:

Best Practices: 25.

Guidelines:

- The energy performance of the CAS is generally determined by a multitude of actors: supervisor for the plant design and purchase decisions (also in relation to the modifications), supervisor for the management and maintenance of the production and distribution system, supervisor of the maintenance of machinery, etc. The organization should identify all personnel capable of influencing the energy performance of the plant, make sure of its awareness and training on the subject of energy efficiency and define specific responsibilities in terms of energy efficiency.

Question: 04:08 - Regarding the compressed air demand profile:

Best Practices: 14, 27, 30.

Guidelines:

- The company must evaluate the demand profile of compressed air and be able to better manage the peaks in demand. It is necessary to verify the correct sizing of the tanks to allow good responses to the demand peaks without causing the compressors overloads. Furthermore, the installation of appropriate control systems allows monitoring the pressure of each tank and automating the sequence of start of the compressors to avoid peaks of electricity absorption. Finally, the company should think to obtain the load profile by measuring the air flow coming out of the compressor and at various points of the distribution network for a sufficiently long period of time.

Question: 05:01 - With regard to continuous training on energy efficiency, it is possible to state that:

Best Practices: 60.

Guidelines:

- The management should push towards a continuous training process regarding energy efficiency. The training programs, besides being shared at all organization levels, should be periodically reviewed and updated with the aim of keeping up with the times in terms of energy efficiency.

Question: 05:02 - With regard to new technologies:

Best Practices: 59.

Guidelines:

- The organization should promote research and the application of Best Available Technologies. When designing or redesigning the systems, the company must already be aware of the BAT and must apply them on the whole procedure. In the event that the search identifies an applicable BAT, the company should allow its application and measurement of the performance achieved with it. Monitoring becomes a fundamental activity for the characterization of the effectiveness of the technologies installed.

Question: 05:03 - With regard to the information system for the system's energy consumption management:

Best Practices: 12.

Guidelines:

- The organization could exploit the potential of a specific software for estimating savings in the event of modifications of the plant. Some software are designed to visually display the measured energy parameters and/or pressure values. After calibrating the system, the parameters can be changed to simulate the expected performance of the compressor in various conditions and the savings can be estimated as the difference between the current and expected use of the compressor energy. The use of specific software for compressed air systems is therefore similat to the use of software for simulating energy consumption in the event of changes in buildings. The possibility to choose the time interval of the data is fundamental to model the actual loading/unloading or modulation events, which typically occur in the order of seconds or minutes.

Question: 05:04 - Regarding the implementation of the Best Practices and the adoption of BATs for the energy efficiency of the compressed air system:

Best Practices:59.

Guidelines:

- The organization should achieve the optimization of the compressed air system through the implementation (or evaluation of applicability) of all BP and BAT on any aspect of the system. During design phase it should consider the energy efficiency for the main plant components and also consider the installation of advanced solutions for energy recovery through heat recuperators or inter-refrigeration stages.

Question: 05:05 - Concerning the integration of the energy management system within the organization's strategy:

Best Practices:59.

Guidelines:

- The management should raise awareness of the importance of energy efficiency to each lower level. Performance management should be a goal pursued in every aspect of the organization, both in the industrial production and in the generation of compressed air. The impact of consumption for compressed air can be reduced in every aspect through a continuous action of identification and implementation of ad hoc measures. The actions taken should have high success rates both in economic and environmental impact terms.

4.3.1 Application of developed method

This phase concerns the application of the developed method on real case studies. In all of the proposed case studies the administration of the CASEEMM takes place only after a careful survey of the industrial plant. The compiling of the CASEEMM does not take place in self-assessment modality by the company, but with the help and the supervision of an expert of the questionnaire. In this way, it is easier for the company to resolve some doubts related to the formulation of the questions and on the other that it is possible for the authors to gather useful feedback on them. This procedure allows to get in touch of an objective and unambiguous assessment of the company's level of maturity. Moreover, the analysis serves as a test bench to verify:

- The easy application of the CASEEMM that proposes questions that company personnel involved in energy management can easily answer;

- The entirety of the model that is suitable to being applied regardless of the size of the company, the characteristics of the plant and the level of maturity of the organization;

- The ability of the model to differentiate the different levels of corporate maturity;

- The model's ability to analyze the company from different points of view corresponding to the 4 dimensions that contribute to effective and efficient energy management (Awareness, knowledge and competence; Implementation of "Best Practices" and adoption of "Best Available Technologies"; Approach methodology; Energy performance management);

- The possibility to provide a starting point for developing a "customized" growth plan for companies, identifying the best technical or management practices to implement prior to a technical-economic assessment supported by the guidelines developed in the project.

The companies whose results are reported as the most significant are:

- Two companies operating in pharmaceutical production;

- A company engaged in the production of paper;
- A company operating in the food sector;
- A company engaged in plastic processing.

For each company the efficiency improvement opportunities are systematically searched starting from the answers and referring to the associated best practices.

Pharmaceutical company (#1)

The first case study is given by a pharmaceutical company. The administration of the CASEEMM allows to assess the level of maturity of the company and to compare the results achieved with those deriving from a survey. The interview is useful to examine the situation and evaluate the proposals to improve the coverage of every levels and of each dimension. The results of the maturity model assessment is coherent with the survey result, some particular are reported below.

- Syntetic maturity indicator. The indicator is attested on 2.48 on a scale from 0 to 4. The reached value indicates a medium-high level and attests that the company is structured and well moving towards improving the good management of CAS. The target value for the synthetic indicator is 2.69 and, as expected, it does not differ much from the current level. This result is due to the recent evolution of the company and the need to consolidate procedures and methodologies before seeking further improvement.
- Degree of coverage of levels. The highest coverage value belongs to level 3 (81%), very close to level 2 (75%) and level 4 (72%), the last level has a scarce coverage (20%). For a correct development of a compressed air energy consumption management system, it is desirable to cover approximately $85 \div 90\%$ of the lower level before implementing the next level tools. The results indicate that the company has a good level of development and that is working constantly and methodically to achieve good results in general. As can be guessed, the company has almost completed the process for completing the knowledge of level 3 and is undertaking the growth of level 4. The company structure can therefore reach the knowledge of the last level in a short time. In Figure 4.1, the results are

collected. Considering the desired coverage, the estimated growth of the various levels turns out to be very homogeneous even if the optimal growth would be represented by the full achievement of a level before intervening on the aspects of the next level. However, in the near future the company would achieve a good level of development for level 2, the optimal level for level 3 and, for this reason it would also enhance aspects of level 4.

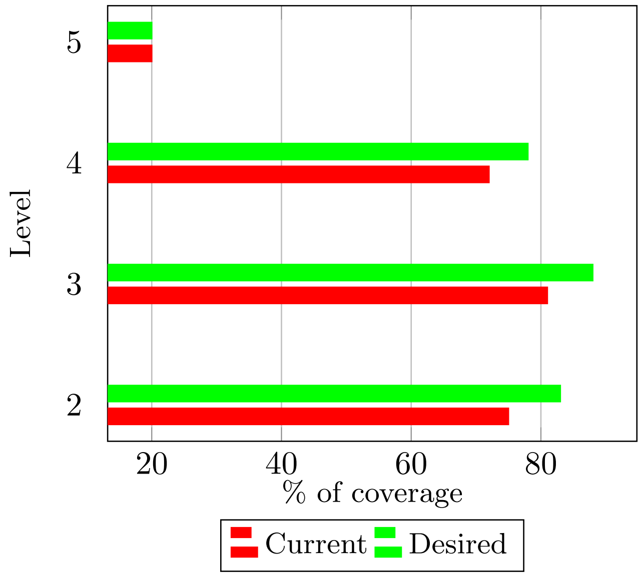

Figure 4.1: *Degree of coverage of different levels (current and desired values) for company 1.*

- Development of the four dimensions. The growth of the management system should envisage a substantially balanced development of the different dimensions, represented in the RADAR diagram shown in Figure 4.2. The difference between the development of the methodological approach dimension and the remaining three is greater than 20%. This aspect represents an anomalous behaviour that should be consider. In general, pronounced differences in the coverage of the various dimensions indicate that the company does not have a well developed plan to examine in dept all the aspects concerning the improvement of energy efficiency but concentrates its efforts on some aspects rather than others. In particular, the low level of the methodological approach indicates that the company should investigate some aspects concerning the analysis of data coming from measuring instruments, it should better organize possible interventions and evaluate possible effects. For this reason, the efforts in terms of staff training and technological development may actually be ineffective for achieving the intended purpose. Analyzing the growth objectives of the 4 dimensions in the medium term, the company is once again moving in the right direction focusing on the development of the methodological approach in a much higher way than the others to decrease the excessive difference between the various quotas. In particular, the company's diligence will be shifted towards careful data analysis and the growth of a performance monitoring system.

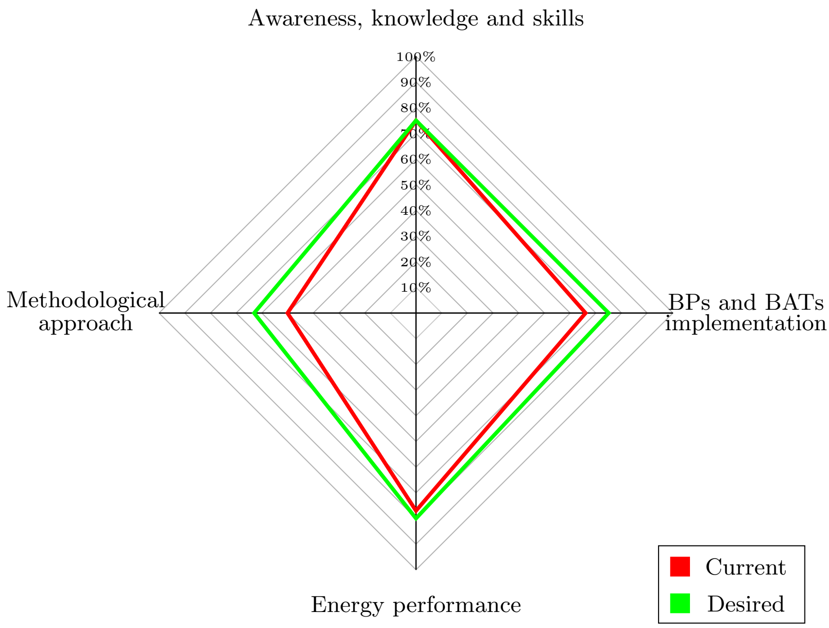

Figure 4.2: *Development of dimensions (current and desired) for company 1.*

Criticalities and suggestions for improvement. Some solutions for improving the energy efficiency have been identified based on the guidelines previously defined and starting from the results coming from the CASEEMM administration and the survey. The company has shown a very careful CAS management. For example, leak detection campaigns and a performance measurement have been carried out in previous years.

Moreover, the attention of the company toward the energy management is demonstrated by the decision to employ its resources to the achievement of ISO 50001 certification relating to the Energy Management System. In general, some solutions are consolidated and any interventions on these are not considered, others have already been identified or budgeted, others can still be proposed and evaluated. The solutions whose use is consolidated over time include:

- The use of compressors with load-unload control strategies rather than more modern variable speed compressors managed by an inverter.
  Considering the specific stability of the load over time, the company prefers to use air compressors with the traditional simple control strategy instead of variable speed compressors. Furthermore, the staff considers that inverters are unreliable and could potentially cause undesired service interruption.

- The maintenance of the systems follows the times and methods suggested by the manufacturer that consists in a preventive maintenance strategy.
  For the general maintenance of lines and systems, the company has defined some control procedures that must be daily carried out to ensure the proper functioning of the equipment. The company considers satisfactory the level of reliability of the maintained systems thus does not intend to change the methodology in the near future.

- The presence of a consolidated practice of monthly analysis of all the system control variables (pressure, flow rate, power) to highlight and evaluate the differences in behavior of the systems over time.

- The use of periodic detailed analyzes on the compressors performance through the application of thermographies and vibrational analyzes.
  The company considers sufficient the commitment on this front and it does not intend to invest additional resources for this type of action.

- The gradual replacement of some compressed air end users with others electrically operated.

The solutions that have already been identified are:

- The possibility to evaluate compressed air losses more frequently than the previous 2 years.
  The company has confirmed that during the time span of 2 or more years between two consecutive evaluations, the distribution system can be modified according to need and any addition of fittings and pipes could lead to the creation of new compressed air leaks.
- The possibility of replacing its older compressor, in use since 1983, with a more recent one.
  The company is evaluating the economic convenience of replacing a working compressor but with several years of use with a more modern one with different performances.
- The possibility of renewing those parts of the distribution network whose modification, change of position and expansion have made them subject to excessive losses.

Possible improvements are:

- The installation of equipment for controlling the electricity consumption and the flow rate supplied by each compressor.
  Currently, the company measures only the production and consumption of the entire CAS. As suggested by many texts in technical and scientific literature, continuous or periodic measurement allows us to take a picture of the situation. Results are surely better than the one outlined through the analysis of consumption derived from electricity service bills. The improvement of performance control occurs only if the energy consumption measurement is supported by a careful analysis of the performance over time, for example using the KPIs of the sector. Data measurement allows to characterize the presence of out-of-control signals due to deterioration in performance, breakdowns and malfunctions. It also allows to objectively evaluate the results of the application of energy efficiency opportunities.
- Minimize set point pressure.
  Considering the vastness of the plant and the large number of connected users (the air is necessary for the processes but also for the actuation of the servo-valves and for the displacement of the

material), the company tends to produce air with a slight pressure higher than the minimum necessary to avoid malfunctions and blockages of the equipment. The company may consider conducting some functional tests with slightly lower system operating pressure than the current one. This practice would reduce the costs for the production of compressed air while still keeping the risk of malfunctioning low.

- Evaluation of pressure losses at the end of the line.
  Considering the vastness of the plant and the continuous modifications to which the network has been subjected, the company should evaluate the possibility of measuring the end-of-line pressure drops due to non-optimal network dimensions. This evaluation allows to calculate the costs and benefits of a possible modification of the air transport network to optimize the diameters of the pipes and minimize the pressure losses, sources of energy waste.

- The use of a tool for the estimation of compressed air leaks and the assessment of the need for maintenance intervention.
  Compressed air leaks are the most important cause of energy waste. The search for leaks is the first action in order to improve the energy efficiency of the CAS. In this plant, the vastness of the network implies numerous difficulties, especially in terms of time search for losses. For this reason, the estimation of the amount of compressed air leaks can be both technically and economically advantageous. Measurements can be done through empty tests on the system, for example by calculating the tank emptying time.

- The use of tool to collect information and suggestions about CAS energy efficiency.
  The company should have a formal register that collects both the opportunities for efficiency identified during surveys and campaigns to search for losses and above all during the daily use of the systems. The formal register can be filled in by anyone who notices a saving opportunity. In addition to the opportunities, summary assessments of the economic impact of the intervention and provisions for future activities should also be noted in the register.

Paper production company

The company in exam is a paper mill engaged in the production of numerous types of products from common paper to furniture covering. The administration of the CASEEMM has made possible to assess the level of maturity and compare the results with those deriving from direct knowledge. During the survey, the improvement intentions of the company were also investigated and reformulated in terms of improvement objectives by level and size. The outcome of the evaluation carried out by the maturity model was fully consistent with the impression derived from the survey. The results are reported below:

- Syntetic maturity indicator. The value of the indicator is 2.05. This value represents an average level and fully summarizes the situation of the company. The level of organization is good and the average value indicates that the organization is moving towards improving its efficiency by increasing the organizational awareness about CAS necessities. The target value of 3.06 is a fairly high level, certainly it is challenging in the short term and can be reached only through a well-organized work following the dictated guidelines.

- Degree of coverage of levels. The highest value of coverage is about level 3 (63%), level 2 is slightly lower (56%), level 4 (47%) and level 5 (40%) are moderately distant. The homogeneity of this values indicates that the company has not worked trying to complete the lower levels and move on to the next. This would indicate a non-consistent development, in fact the organization should focus its efforts on completing a lower level before moving on to the upper one. This methodology would lead to concentrate efforts on more aspects leading to homogeneous growth throughout the organization. As regards the desired coverage of the various levels, the growth of the company in the medium term leads to still homogeneous results by increasing the values by approximately 13%, reaching the coverage of 69% for level 2, 77% for level 3, 40% for level 4 and an optimistic 100% for level 5. The analysis of these results confirms that company desires to obtain considerable improvements but, at the same time, does not have a clear perception of its maturity level. Moreover, the company probably has a lack of awareness about what it should do to complete the coverage of the lower levels. Being able to cover the highest levels without having completed most of the lower levels can indeed be downright inefficient, if not impossible. The results are collected in Figure 4.3.

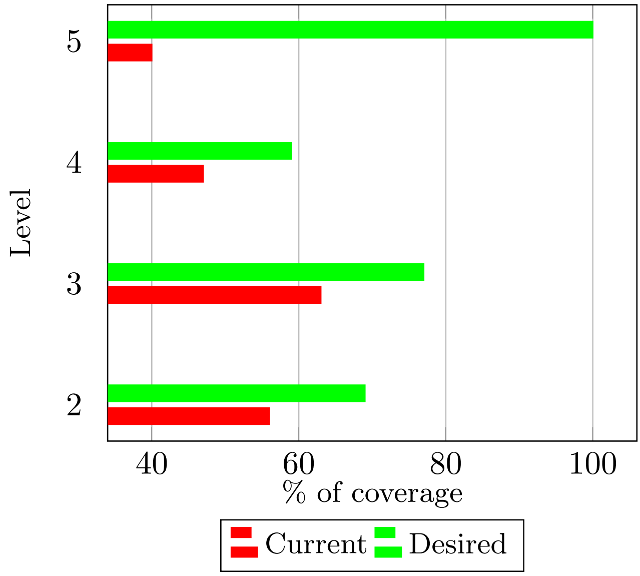

Figure 4.3: *Degree of coverage of different levels (current and desired values) for company 2.*

- Development of the four dimensions. The development of the management system should be substantially balanced for each different dimension. The difference between the dimension of the energy performance and the other three is larger than 20% (Figure 4.4). This represents an anomaly to be considered. In particular, this difference is mainly due to the lack of a compressed air measurement system (there is only one measurement device for electricity consumption). Instead, the desired development shows how the general situation leads to a certain balance of the growth of the various aspects, showing attention to the aspect of energy performance. The company therefore would install flow and consumption meters to monitor the energy performance of the system.

Criticalities and suggestions for improvement. The company) has proven to be very careful about the energy management of CAS. The company is certified according to ISO 50001 standards and there is an energy manager within the personnel. Despite the efforts, some

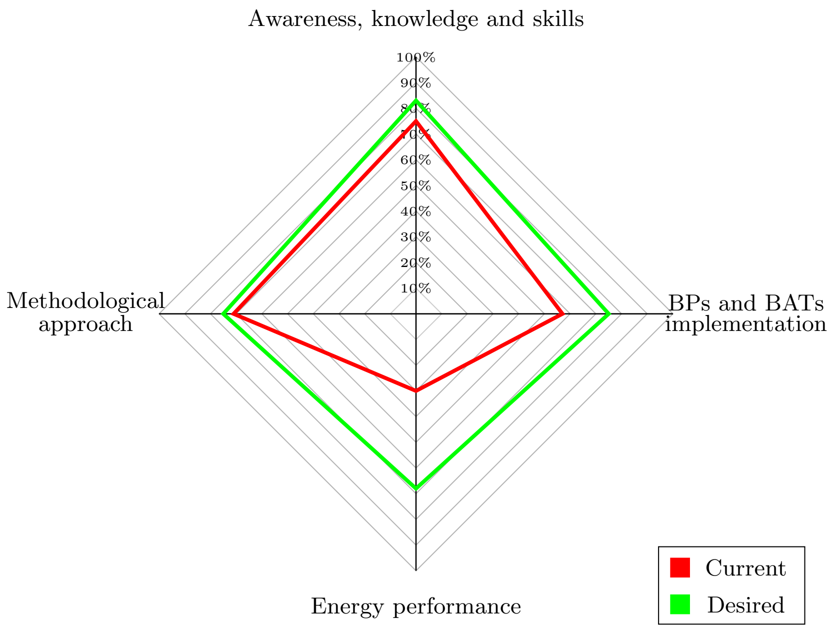

Figure 4.4: *Development of dimensions (current and desired) for company 2.*

problems were encountered mainly due to the low importance of the CAS consumption compared to the overall plant consumption. In this perspective, some solutions are consolidated and any interventions on these are not considered, others can be proposed and evaluated. Within the consolidated solution there is:

- The use of compressors with load-unload control strategies rather than more modern variable speed compressors managed by an inverter.
  The trend of compressed air requirements is quite stable over time, with some exceptions represented by few temporary peaks due to some particular processes. This stability makes the traditional solution prefer to the one that uses a variable speed compressor. The adopted solution sometimes turns out to be unsuitable, causing the company to risk blocking or slowing down the activities, however the possibility of installing variable speed compressors managed by an inverter is not considered due to the high investment prices which could have too long pay-back (o repayment) times.

- The belief that the energy consumption has little influence on the total system consumption.
  The CAS is not very energetically important compared to other productions, for this reason large investments in the department are not considered.

- The possibility of using low-cost energy.
  The company is equipped with a co-generative system capable of producing the triple of the electricity needed for the plant and also generating part of the steam needed for the processes. This solution allows to reduce by one third the costs related to the supply of electricity compared to the withdrawal from the network. This convenience makes efforts to improve the efficiency of the CAS very unattractive.

Among the solutions that can be proposed and evaluated are:

- The launch of a campaign for the research of the compressed air leaks.
  Air leaks are the most important cause of energy waste and often lead to significant increases of energy consumption for compressed air production. The preliminary assessment of leaks and the search for leaks through the use of ultrasound tools are therefore the first activities to be undertaken to improve energy efficiency. The economic and technical difficulties of a leaks research campaign may suggest the calculation of losses by indirect methods through the evaluation of the tank emptying time for switched off end users.

- The installation of flow meters to measure the amount of produced compressed air and of ammeters for the energy used by the compressors.
  This installation would simplify the analysis of energy consumption and facilitate the process of reduction of it. Currently, the control only takes place on the electrical consumption of the department. The availability of continuous or periodic measurements would allow to have a first level of control as regards the energy efficiency of the system. The availability of continuously or periodically measured data can help the company to define a consumption baseline, display the deviations and possibly define an intervention strategy. In the

event that the installations are too expensive or technically difficult, the company might think to temporarily use portable meters.

- The installation of a blower to replace some users supplied with compressed air.
  The company needs air for cleaning some equipment, replacing the compressed air at 7 bar with air coming from a blower ($1 \div 1.7$ bar) reduces the costs related to excessive compression of the air flow rate for use.

- Review of network diameters.
  The distribution network has been subject to modifications over time. For this reason, it would be advisable to review the diameters and the lengths of the pipes according to the flow rates required for the various sections of the plant. A wrongly designed network could lead to excessive load losses if the diameters are too small and condensation problems in the case of excessive diameters. The evaluation of the costs and benefits of such interventions is easily implemented.

- Evaluation of load losses at the end of the line.
  Considering the vastness of the plant and the continuous modifications to which the network has been subjected, the company should evaluate the possibility of measuring the end-of-line pressure drops due to non-optimal network dimensions. This measurement would allow to evaluate the costs and benefits of a possible modification of the air transport network to optimize the diameters of the pipes and minimize the load losses sources of energy waste.

- Sectioning of the network.
  The company should evaluate the sectioning of the network in several parts to exclude some of the branches that are temporarily not used. In this way, only the section with connected and in operation users would be kept in pressure, decreasing the possibility of air leaks in the sections with not used utilities.

Pharmaceutical company (#2)

The third case study is provided by a pharmaceutical company. The administration of CASEEM has allowed to evaluate the maturity level and compare the results with those deriving from a survey. The outcome of the evaluation carried out by the maturity model has been fully consistent with the impression derived from the interview with the company, providing in particular the following results:

- Syntetic maturity indicator. The value of the indicator is 2.79. The high value indicates that the company is well improving the management of the CAS and that is now structured and well operating. The target value is 3.24, a significant improvement that appears to be within the organization scope.

- Degree of coverage of levels. The highest coverage value belongs to level 3 (81%), but the other levels are also very close: 75% for level 2, 63% for level 4 and 60% for the last level. For a correct development of a plant energy consumption management, it is desirable to complete about $85 \div 90\%$ of the lowest level before implementing the tools of the next level and in this aspect the results are excellent. The achievement of this coverage is an indication of the constant dedication of the company to improve all aspects with a method to reach high levels. The company therefore has a high level and can easily aspire to reach the set thresholds before developing the knowledge of the last level. In Figure 4.5 the summary of the results are collected.

- Development of the four dimensions. The development of the management system should be substantially balanced for each of the different dimensions. Radar diagram in Figure 4.6 represents the current situation. The difference between the awareness dimension and the other three is considerable. In general, marked differences in the maturity level of different dimensions indicate that the company does not move in an organized manner, enhancing the knowledge about some aspects rather than others. However, the level above the average indicates that the company is well aware of the importance of energy efficiency and tries in every way to achieve this goal. By analyzing the growth objectives of the four dimensions, in the medium term, once again the company one again wishes to move towards increasing awareness and energy performance. This aspect makes the development less homogeneous and suggests to the company to shift its efforts towards the implementation of BP and towards BAT research.

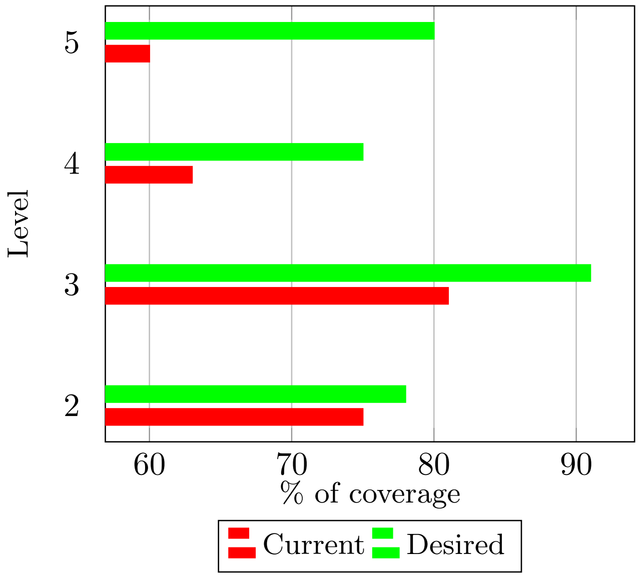

Figure 4.5: Degree of coverage of different levels (current and desired values) for company 3.

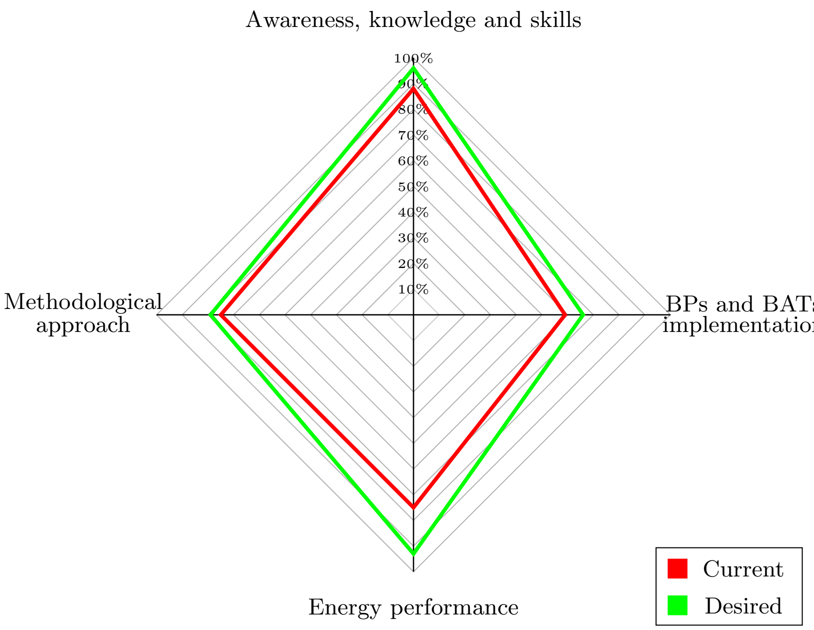

Figure 4.6: Development of dimensions (current and desired) for company 3.

Criticalities and suggestions for improvement.

Some remarks can be reported both regarding CAS energy efficiency. In this perspective, some solutions are consolidated and any interventions on these are not considered, others can be proposed and evaluated. The first are:

- The adoption of an internal incentive system for the discovery of losses.
  In addition to the planned leaks research campaign carried out through the use of ultrasound instruments, encourages its employees through incentives to find the leakages and to report them to the energy manager.

- Installation of variable speed compressors.
  The production of compressed air has a rather variable trend over time, for this reason a mixed load-unload and inverter control strategy is used. The base load is produced through compressors with load-unload regulation, the variable part is produced with variable speed compressors. Start and operation of all the compressors are regulated by a control unit produced by the compressor manufacturer. This adjustment is optimized based on historical data.

- More frequent consumption analysis comparing with the billing period.
  The company has a performance monitoring system that makes weekly performance reviews possible.

The proposals for improvement include:

- The implementation of a campaign to search for compressed air leaks.
  Air leaks are the most important cause of energy waste and often lead to significant increases of energy consumption for compressed air production. The preliminary assessment of leaks and the search for leaks through the use of ultrasound tools are therefore the first activities to be undertaken to improve energy efficiency. The company has already budgeted for a leak search for the near future.

- The installation of a measurement system for each production unit.
  The production system is made up of many units work at the

same time. This peculiarity makes it advisable to install a flow rate measurement and electricity consumption system for each compressor. This installation would make easier the analysis of energy consumption and facilitate the process of reducing it. The availability of data measured continuously or periodically could help the company to define a consumption baseline, display the deviations and possibly define an intervention strategy. If the installations are too expensive or technically impossible, the company might install temporary portable meters to at least outline the situation.

- Evaluation of pressure losses at the end of the line.
  Considering the vastness of the plant and the continuous modifications to which the network has been subjected, the company should evaluate the possibility of measuring the end-of-line pressure drops due to non-optimal network dimensions. This measurement would allow to evaluate the costs and benefits of a possible modification of the air transport network to optimize the diameters of the pipes and minimize the load losses sources of energy waste.

- Use of multi-pressure systems.
  The compressed air plant requires different supply pressures; the company should measure or estimate the amount of compressed air used for each pressure level and evaluate the technical and economic possibility to divide the system in two sections powered by more compressors working at different pressures.

- The implementation of a campaign to search for compressed air leaks.
  The last leaks analysis campaign was carried out many years ago; it is necessary to reorganize a leaks measurement campaign also considering the changes brought to the plant over the years.

Food production company

The company in exam belongs to the food industry sector, in particular it deals with the processing and sale of milk and derivatives. The CASEEMM administration has evaluated the maturity level and the collected results have been compared with those deriving from a survey. CASEEMM results indicate:

- Syntetic maturity indicator. The value of the indicator is 2.58. The value corresponds with a medium-high maturity level and indicates that the company is moving towards the improvement of the correct CAS management. To reach the target value of 3.06, the company has to significantly improve its performance. This appears rather challenging for the company in the short term, but certainly feasible in a slightly longer period.

- Degree of coverage of levels. The highest coverage value belongs to level 3 (81%), but the other levels are also very close: 75% for level 2, 63% for level 4 and 60% for the last level. This is an indication of a development of the organization that has worked constantly to improve all aspects with a method to reach high levels. In Figure 4.7 the summary of the results. Considering the desired coverage, the estimated growth of the various levels turns out to be very homogeneous, the optimal growth would be represented by the full achievement of a lower level before intervening on the aspects of the next level. However, in the near future the company would increase all the quotas in order to reach over 80% coverage for the first levels and considering being able to operate on the last level for a further development over time.

- Development of the four dimensions. The development of the management system should provide for a substantially balanced development of the different dimensions, represented in the RADAR diagram shown in Figure 4.8. The difference between the awareness dimension and the other three is considerable. In general, marked differences in the development of maturity with respect to the various dimensions indicate that the company does not move in an organized manner, trying to deepen all the aspects that lead to an improvement in energy efficiency but deepens some aspects rather than others. In this case, however, the level above the average indicates that the company is well aware of the importance of energy efficiency and tries in every way to achieve this goal. Analyzing the development objectives of the 4 dimensions in the medium term, we can see how the organization is well moving trying to bring all dimensions to the same level of coverage. This aspect would make the development homogeneous and well defined.

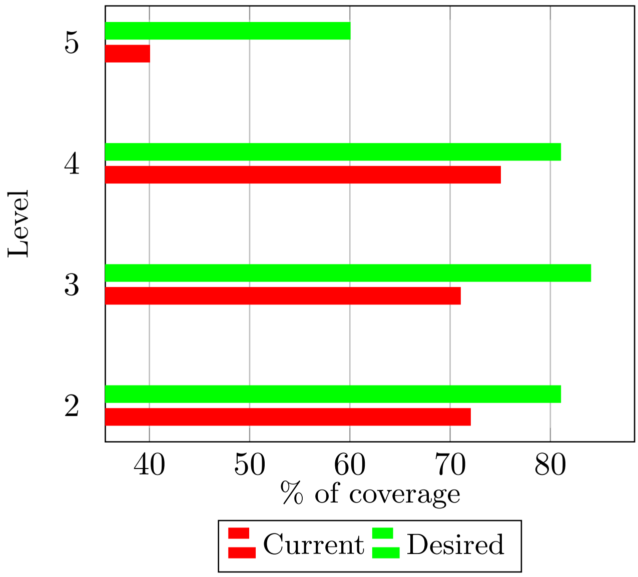

__Figure 4.7:__ Degree of coverage of different levels (current and desired values) for company 4.

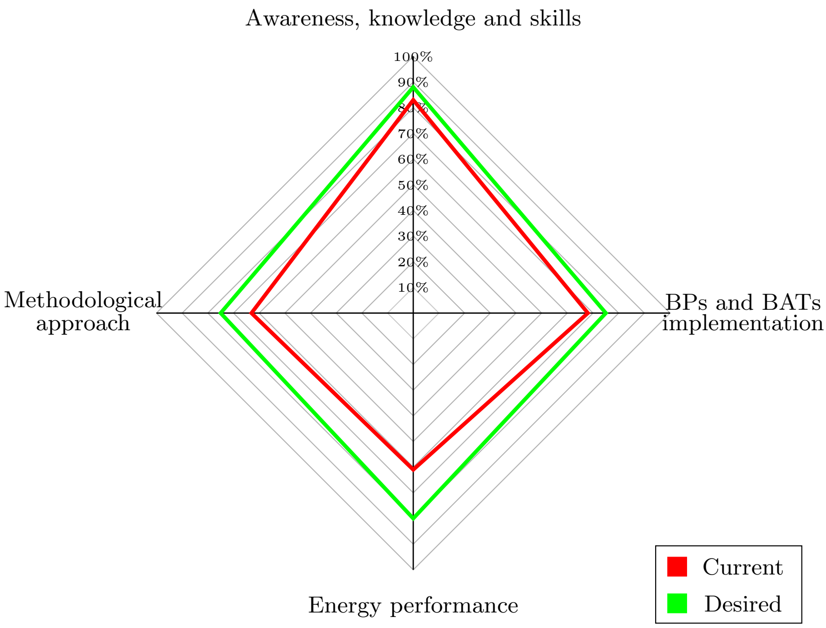

__Figure 4.8:__ Development of dimensions (current and desired) for company 4.

Criticalities and suggestions for improvement. The consolidated solutions for which no changes are needed are:

- Use of the available capillary monitoring system.
  The company should monitor flow rates and all energy consumptions of every compressors. This is the optimal configuration for monitoring energy performance.

- Evaluation of air leaks.
  As already mentioned, air leaks are the most important problem for achieving energy efficiency. In recent periods, the company has considerably limited them through a widespread measurement campaign of leaks. Further investments in terms of resources would lead to insignificant results.

- Replacement of compressed air tools with other electrically powered ones.
  A cause of loss of efficiency is represented by the use of compressed air for tools that can be powered with other forms of energy. This leads to suggest the replacement of pneumatic instruments with electric ones with consequent minimization of the length of the compressed air networks and the limitation of the possibility of air leaks.

Among the latter we find:

- Check of the suitability of the compressor load management programs.
  The incorrect activation of the compressors leads to energy losses due to the increase in absorption during the transient phases.

- Changes to the micro-layout in some departments have made unused some branches of the network.
  The possibility to isolate these branches from the main network should allow to eliminate any air leaks inside the branches that would remain under pressure even if not used.

- Minimization of set point pressure.
  Because of the installation of a new machine, the set point pressure has been raised to allow the machine to work properly. The insertion of a system to raise the local pressure upstream of the

machine operating at higher pressure could save the energy spent to unnecessarily raise the pressure of the entire system.

- Optimization of the control system based on hourly consumption. The air demand profile has changed considerably in the last period and the management system is based on the concept of dividing the operating hours of all the compressors equally. For this reason, it could be suggested to the company an alternative management system that also considers the yields of the machines and the management costs by optimizing the scenario.

Plastic production company

This company belongs to the plastic processing sector for the production of bottles and containers. The CASEEMM has allowed to evaluate the maturity level and compare the highlighted aspects to the results with those directly noticed through the survey. The results are shown below:

- Syntetic maturity indicator. The value of the indicator is 2.82. The value indicates that the company is improving the system management and that is now structured. The target value is 3.27. A significant improvement that appears rather challenging for the company in the short term but certainly within the organization's reach in a slightly longer period.

- Degree of coverage of levels. The highest coverage value belongs to level 2 (83%), but the other levels are also very close: 81% for level 4, 77% for level 3 and more distant level 5 to 40%. These are some indications of a well planned development of the company that has worked constantly to improve all aspects related to CAS energy efficiency. For a correct development of a system of management of plant consumption it is desirable to complete about $85 \div 90\%$ of the lowest level before implementing the tools of the next level. In this respect the results are excellent. The company has therefore worked toward the efficiency, first achieving excellent results in the lower levels. In Figure 4.9 the summary of the results. Considering the desired coverage, the estimated growth of the various levels proves to be ideal, achieving completeness for level 2. Levels 3, 4 and 5 should homogeneously grow and would lead to the full completion of all levels even if a progressive intervention on the lower would be desirable.

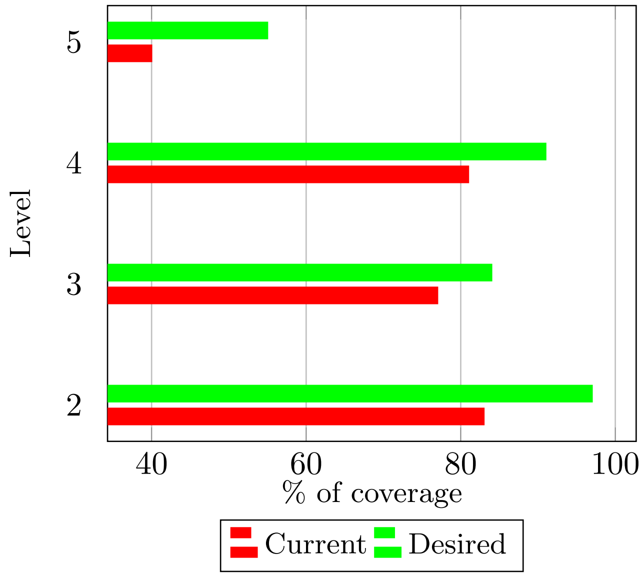

Figure 4.9: *Degree of coverage of different levels (current and desired values) for company 5.*

- Development of the four dimensions. The growth of the management system should consider a balanced development of the different dimensions, represented in the RADAR diagram shown in Figure 4.10. From the results, the difference between the dimension of the methodological approach and those of the implementation of BAT and BP is considerable. In general, marked differences in the coverage levels of the various dimensions indicate that the company does not adopt an organized procedure. In this case, the results show some criticalities in the management of the pressure level and in the evaluation of the processed flow rates. Considering the objectives for the development for the next period, the company intends to adopt solutions capable of increasing the dimensions in a differentiated manner to reach a more homogeneous development level than the current one.

Criticalities and suggestions for improvement. The consolidated solutions for which no changes are needed are:

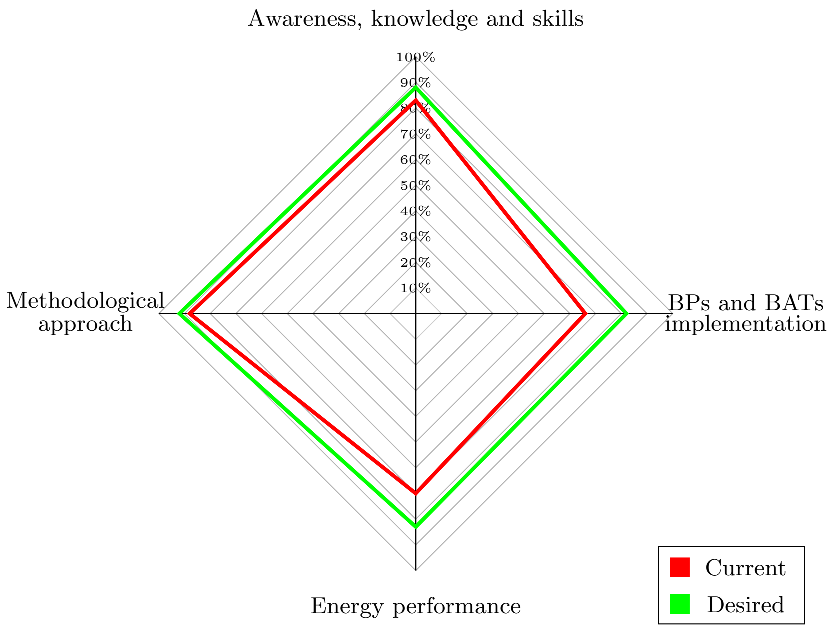

Figure 4.10: *Development of dimensions (current and desired) for company 5.*

- Measurements of consumption and plastic production are daily monitored.
  This data allow to define a consumption baseline and evaluate the daily deviations. The company considers sufficient the information provided by the collected data and therefore does not consider further implementations of its own measurement system.

- The compressed air leaks are monitored.
  The first reason for wasting energy have been carefully monitored through a campaign of inspections which allowed for a 14% reduction in electricity consumption.

- Network diameters optimization.
  The network has been revised in the diameters that have been optimized in the last year according to the new needs. In fact, the new machinery requires a greater quantity of compressed air. In this way it has been possible to limit the pressure losses at the end of the line and reduce the air supply pressure.

- Use and continuous BAT research.
  The compressor inventory is equipped with motors with levitation supports that represent the BAT of the sector. In this way energy consumption can be reduced.

The development already considered is::

- Use of and continuous BAT research. The compressor range is equipped with machines with levitation supports that represent the BAT of the sector. In this way energy consumption can be reduced to the advantage of efficient management.

The proposals for improvement include:

- Considering the continuous innovation of the production system and the continuous modification of the equipment connected to the network, some tests could be carried out by decreasing the operating pressure of the systems. It is possible to verify the presence of a possible margin of reduction of energy consumption due to air compression at excessive pressure.

- The installation of a flow measurement system should allow the control of consumption and the identification of malfunctions and compressed air losses. Continuous or periodic measurement gives a good picture of the situation.

4.3.2 Conclusions

In this chapter a methodology to improve CAS energy system has been developed. To performance evaluation and decision support tool for the efficiency of compressed air systems, a sample of Italian industrial enterprises has been used as case studies. The tool used to evaluate energy efficiency was the CASEEMM with which organizations can independently assess their maturity in terms of energy efficiency. This phase has involved numerous Italian industrial enterprises that responded with great availability and openness. The activity therefore concerned a first contact with the organization,getting knowledge of their characteristics and problems and the assessment of the level energy efficiency through the CASEEMM. From the information obtained, different situations emerged relating to different ways of using compressed air and different ways of managing its production. The common element to all companies is the attention to energy efficiency that is sought to be achieved through numerous solutions. Therefore, practices have been defined for each company visited to achieve the sector's energy efficiency.

Chapter 5

Decision Support Tools

Introduction

Through the application of the CASEEMM, a company can assess its maturity level and define the objectives to achieve in the short-medium term. The described activity regards the application of the CASEEMM to some companies and the development of a system of guidelines useful to improve the energy efficiency of industrial CASs. So, a two-phases methodology has been developed: the first phase allows the assessment of the maturity level about CAS energy efficiency, the second provides useful suggestions on the procedures to be adopted in order to raise the level of efficiency.

The last part of the work concerns the evaluation of the efficiency improvement possibilities through the development of decision support tools. These tools are important to characterize the efficiency measures at a technical-economic level and provide companies with feedback on the efficiency potential deriving from a possible action.

The development of the decision support tools follows four phases. The first is the definition of the possible options, the second one is the characterization of the options based on the difficulty of application and implementation, the third phase is the choice and the last phase concerns the final development of the tools. The tools are grouped according to the increasing level of maturity indicated by CASEEMM.

The procedure therefore suggests the application of tools related to each level of maturity to achieve greater coverage of maturity levels. All the tools have been developed and collected in a suite called CAEESuite

(Compressed Air Energy Efficiency Suite) available for free to be more usable and representing the last step for the completion of a methodology that can be easily used by companies to identify, enhance and improve the energy efficiency of their air production systems compressed.

All the activities related to the evaluation of DSSs and their development and implementation into the suite is lead by the author.

5.1 Background

Several studies have been led to evaluate the energy consumption related to each phase of the industrial processes and to propose some modifications to them [87]. Such changes could impose significant investments as they would entail radical changes in the production process [88]. Less expensive solutions could be represented by little modifications of some production settings; although several studies focus on these changes [88], these usually concern specific processes and may have side effects such as a decrease in the quality level of the product [89].

Before modifying cycles and systems, numerous evaluations must be made on the most convenient alternatives to choose, often from an economic point of view. For characterizing the technical-economic feasibility of the choices, it is often necessary to quantitatively evaluate the benefits and costs of each alternative. Numerous companies have already developed good energy management skills, however most of them are limited to monitoring and do not consider to predict and simulate alternative scenarios [25]. In order to evaluate possible choices and evaluate the possible impact on systems and plants energy efficiency, the scientific literature provides numerous tools called Decision Support Systems (DSSs). According to [90] the DSSs are tools that began their development with the arrival and spread of minicomputers.

DSSs can be grouped in 6 categories:

- communication-driven;
- data-driven;
- document-driven;
- knowledge-driven;
- model-driven;

- web-based systems.

The typologies of analysis can be referred to 3 methodologies:

- Life Cycle Analysis (LCA) in which the environmental impact of a product, a process or an activity is analyzed throughout its life cycle. The analysis identifies and quantifies used energy, materials and waste released into the environment. It, also, assesses the economic and the environmental impact of those.

- Cost-benefit analysis (CBA) offers an alternative way of summarizing performance in different evaluation aspects by transferring all impact categories into monetary terms. This approach offers the possibility of providing results on a scale compatible with the market mechanism and more understandable for decision-makers. Cost-benefit analysis involves comparing the total costs and benefits associated with a project or a policy.

- Multi-Criteria Decision Making (MCDM) are techniques used in sustainable energy management which provide solutions to problems involving conflicting and multiple objectives. They use different methods based on weighted averages, prioritization, overshoot, fuzzy principles and their combinations to plan energy management decisions. MCDM applications include energy policy analysis, electricity planning, technology choice and project evaluation and environmental impact analysis.

From their introduction, DSSs are widely used in many applications concerning the manipulation of quantitative models, the analysis of large amounts of data and the support in decision-making process. Dozens of documents in scientific literature attest to the development and application of DSSs to the most varied fields of application. Some examples are collected in Table 5.1.

Scientific literature does not collect many documents about industrial CAS management. Some example are reported in Table 5.2.

Although, as seen, there are some works concerning DSS, according to the author's knowledge there are no detailed decision support procedures to increase CAS energy efficiency. For this reason, in this section, the procedure of development of a series of DSS is described. The DSS tools want to represent a method for solutions comparisons based on the performance guaranteed by the systems.

Table 5.1: Examples of decision support tools

Reference	Description
[89]	The work presents a review of previous studies concerning the use of spatial analysis in the implementation of renewable energy policy and a proposal for the use of the multi-criteria spatial DSS based on geographic information systems.
[91]	The document presents a DSS for planning and optimizing the use of a hydroelectric plant. The use of the software can significantly improve production and daily energy revenues.
[92]	The document describes a DSS to choose the optimal position of photovoltaic plants. This is a combination of multicriteria and hierarchical analysis taking into account also environment, orography, location and climatic factors.
[93]	The document presents a tool for the development, the assessment and the classification of domestic water heating systems with the lowest economic, environmental and social impact (more sustainable). A multi-criteria decision analysis is used to ascertain which heating system is the most sustainable in each application with defined climatic radiation.
[94]	The development of a decision support tool with a hybrid approach that provides support for energy management in public buildings is described.
[95]	The document proposes a DSS for the optimization of a long distance heat transport system.
[96]	The document describes a toolbox for decision support that allows farmers to upload their data, use different methods of analysis and have their own results.

Defined tools propose alternative solutions whose implementation could lead to the improvement of energy efficiency. All the solutions and output data from the tools are general evaluations that consider the systems in their optimal configuration, the assessments on the technical and economic feasibility of the interventions must be made separately, considering all the singularities of the case.

5.2 Methodology

The following DSSs implementation is based on the hypothesis that the process of the maturity level increasing should be gradual starting from the achievement of a good knowledge of the basic applications. This allows to achieve the level dictated by the Best Practices and by the use

Table 5.2: Examples of decision support tools for CASs

Reference	Description
[97]	AIRMaster+ is a free online software tool that helps CAS manager in energy use analysis and savings opportunities evaluation. It can be used to evaluate improvements of the existing system and to evaluate energy and economic savings due to the increase in energy efficiency.
[98]	The work describes a tool capable of determining the best configuration of the compressed air production system with the aim of saving energy.
[99]	The work proposes an instrument capable of simulating the on/off control of a group of compressors working in parallel. The tool is intended to help the company to define the best control strategy in order to minimize energy consumption.
[100]	The work describes the development of a tool for simulating and optimizing the position of the compressed air production plant in an industrial plant based on the shape of the network and the needs of the users.

of the Best Available Techniques.

The tools developed are grouped according to the level of maturity to which they refer with the aim of proposing the characterization at an energy and economic level of some technical solutions that serve to increase the maturity of the organization with respect to a specific area.

The development of the tools involves several phases starting from the identification of the problems, passing through the qualitative assessment of the difficulties of implementation and use of the tool up to the choice of the most effective tools and their development and their use.

5.2.1 Choice of tools to implement

In order to establish the most important aspects to be evaluated, all the problems that cause the loss of energy efficiency are collected from the technical literature. The list of issues to be addressed is defined on the basis of best practices already analyzed and extent through a careful further research.

The possible solutions are evaluated using a method based on the evaluation of the difficulties of development, implementation and application of the tools to asses the potential energy efficiency improvements. The used evaluation method is developed as follows:

- For each problem, the list of parameters to be used for its implementation and application is drafted and assessed with grades from 1 to 5 both regarding the difficulty of data collection by the company, and regarding the possibility of being implemented within a model.

- The result is multiplied by a value on a scale from 1 to 5 which also takes into account the technical and economic feasibility of the suggested efficiency improvement intervention.

In Table 5.3 an example of tool evaluation is reported. Data for the evaluation are organized in columns as follows:

- The first contains a short description of the problem;
- In the second, the necessary data are collected;
- In the third, the evaluations of the difficulties to collect the necessary data are resumed;
- In the fourth, there is the assessment of the difficulty of developing the tool;
- In the fifth, there is the evaluation of the complexity of carrying out the intervention in organizational, technical or economic terms;
- In the sixth, there is the synthetic final judgment on the tool.

Table 5.3: *Example of the use of the evaluation method*

Problem	**Needed info**	**Difficulty of finding data**	**Difficultys of tool develop.**	**Difficulty of implem.**	**Final judgment**
Problem 1	Data 1	1	3	3	12
	Data 2	2	4		
	Data 3	1	2		

The final judgment is calculated as follows:

$$\overline{Difficulty}\ \overline{of}\ \overline{finding}\ \overline{data} \times \overline{Difficulty}\ \overline{of}\ \overline{tool}\ \overline{development} \times \overline{Difficulty}\ \overline{of}\ \overline{implementation} = Final\ rating$$

The tools with the lowest synthetic judgments are those deemed most valid from an implementation and use point of view by the end user.

5.2.2 Tools development

The development phase of the tools is the longest and most complex. The implementation followed a multi-step methodology.

- Analysis of the problem. Each previously defined problem is analyzed in detail and the physical relationships that govern the phenomenon described are defined for each of them. When a physical model is not available because of the difficulties a specific relationship elaborated between energy input and output, statistical models are taken into account.

- Implementation of the program. The defined relationships are used in writing programs. Once the routines have been implemented, simple graphical interfaces are developed to facilitate use by the external user.

- Test the program. Each program is tested by entering values relating to possible scenarios and assessing the actual compliance of the output data.

5.2.3 Results

Choosing of the tools to be implemented

The methodology highlights the possibility to evaluate 19 situations for improving CAS performance. In the following list all problems and motivations of possible solutions are collected.

1. Change of intake and compressor position. The position of the outdoor air intake is an important factor to increase the system performance. Lowering the inlet temperature allows to increase the compression efficiency and therefore decrease electricity consumption. From the physics of the problem, it is shown that by decreasing the suction temperature by 3 °C it is possible to save 1% of the electricity [30, 28]. By installing an external air intake system where not present, it is possible to keep at minimum the air temperature. The external intake should be oriented north and not exposed to direct sunlight. In calculating the performance of the new solution, attention must be paid to the possible increase in pressure drops due to the possible extension of the air intake ducts.

2. Installation of an intercooling system. Compressors with intercooling system have better performance compared to compressors that do not have them [76]. Such a modification should be evaluated in economic terms.

3. Multiple pressure levels. All the tools connected to compressed air network do not require the same pressure level. In some cases the pressure is raised up to the maximum required level causing a loss of performance. The installation of local boosters could decrease the pressure set point of all the system and leads to the improvement of energy efficiency [76]. To provide such an evaluation it is necessary to know the air needed.

4. Optimization of pipes diameters. Old distribution plants modified over time with additions and exclusions may not be optimized for the current compressed air requirement. A non-optimized network leads to excessive pressure drops which are usually overcome by raising the operating pressure of the system, therefore increasing consumption for the production of compressed air [28]. A tool for the evaluation of the correct shape and size of the network would have a significant impact on service management. To create a tool, and for its possible use, it would be necessary to have available data relating to the position, diameters, lengths and singularities of the entire network. This factor would make the use of the tool very complex.

5. Optimization of the diameters of the first section of the network. A non-optimized network leads to excessive pressure drops which are usually overcome by raising the operating pressure of the system, therefore increasing consumption for the production of compressed air [28]. A tool for reviewing the diameter of the entire network would be very complex to use, however the optimization of the first section of the network and the main ring would be a first step towards optimizing the system.

6. Filtering system management. The treatment of compressed air, realized through passages in filters and dryers, entails the creation of even large pressure drops [101]. Checking and replacing the filters could decrease the pressure drops due to the accumulation of impurities on the surfaces to be crossed and therefore save energy. The tool should evaluate the convenience of replacing a filter

with a new one and define the optimal time between maintenance interventions in which a filter does not significantly degrade system performance.

7. Modulation control. In most cases, compressed air requirement is variable over time. In order to minimize consumption over time, it is possible to define a strategy for controlling the switching on and off of the compressors. In the presence of inverters, the tool should be able to modulate the compressor power based on the load required by the system at each time interval [30].

8. Replacement of compressed air with other forms of energy. In many cases, compressed air may not be the best source of energy for powering machines [80]. The replacement of equipment powered by compressed air (also based on the characteristics of the air and the position in the network) with other electrically powered could help the company to reduce energy consumption.

9. Air quality control. The treatment of compressed air, carried out through passages in filters and dryers, entails the creation of even large pressure drops [101]. The use of lower quality compressed air entails less filtration and fewer treatments to lower the dew point. The tool is used to evaluate the possibility of decreasing air quality in such a way as to reduce pressure drops and decrease costs for the maintenance of air treatment systems.

10. Heat recovery. Compressing air necessarily involves producing heat at low temperature. The company could use this type of heat especially if in large quantities and with continuous flow over time [30]. The tool would help the company calculating the amount of available heat and performing a cost-benefit analysis on the possible installation of a heat recovery system through exchangers.

11. Air demand profile and tanks optimization. The variability of the demand for compressed air by the users entails the occurrence of numerous cycles of activation and shutdown of the compressors (in the case of load-unload management) and load modulation (in the case of management via inverter) [31]. The use of storage tanks could limit these cycles and decrease consumption. The tool could

calculate the optimal volume of the tank based on the demand of the users.

12. Base load reduction and consumption forecasting model. The variability of the demand for compressed air by the users entails the occurrence of numerous cycles of activation and shutdown of the compressors (in the case of load-unload management) and load modulation (in the case of management via inverter) [31]. Knowing the load profile or, alternatively, the dependence of compressed air consumption on the main production, can help to better manage the load and reduce the basic load to a minimum. The tool could identify the dependencies of compressed air consumption on time and on the main productions and optimize the load of the compressors by minimizing consumption.

13. Monitoring systems implementation. The implementation of a performance measurement and trend analysis system is the first step towards improving energy efficiency [79]. The tool should be able to analyze consumption data and define out of control events through the use of regression analysis, Cusum control charts and deviation maps for performance analysis and alerting.

14. Installation of high efficiency motors (BAT, inverters, levitation bearings). High efficiency motors equipped with inverters for load regulation and rotating on magnetic levitation bearings represent some of the sector BAT. The introduction of this type of technology involves reducing the energy consumption of the systems [76]. The support tool could help the organization to choose which BAT to install based on the definition of the current position, analyzing the costs and benefits of this installation.

15. Adaptation to the new needs of the system. The great dynamism of the market and industries involves constant changes within them and makes continuous updates of industrial plants necessary. However, updates do not always entail effective redesigns and system optimizations. In the case of old plants, it is possible that the systems work in different conditions from the optimal performance since they are never adequate for the change (e.g. oversized compressors, inadequate network, excessive treatment, etc.). The support tool should analyze the current situation by defining a

framework and proposing a better solution that reduces energy consumption.

16. Air leaks evaluation. Air leaks are the main cause of increase in energy consumption of the systems however the search for leaks through ultrasound instruments is a very efficient but also very time-consuming practice especially for large-scale systems [76]. The possibility of estimating losses through an indirect measurement method could represent a starting point for the assessment of the need to control losses. By measuring the pressure of the tank, the tool could provide a first estimate of the air leaks within the distribution network.

17. Maintenance planning. Maintenance is a source of significant costs for systems management [80]. Optimal maintenance management helps to minimize costs and keep systems efficient. The tool could help define maintenance deadlines, highlight costs and possible benefits.

18. Comparison between ideal and actual performance. Compressed air systems can decrease their efficiency with use. The tool could simulate the installed system and thanks to the theoretical performances, establish the deviation with the real performances. This method could be useful for assessing and locating energy losses and help suggest possible changes to the system.

19. Life cost analysis. The Life Cost Analysis (LCA) allows to evaluate all costs relating to a specific component or system, from design to disposal. In fact, initial costs (purchase, installation, etc.), management costs (energy costs, maintenance, financial charges, etc.), up to the disposal and recovery costs are taken into consideration. The tool could help the organization to consider the total costs of the system and motivate the purchase of new and more efficient parts through an economic evaluation.

Each listed tool is evaluated based on the variables to be used and the difficulty of development. Results are in Table 5.4.

Table 5.4: List of defined tools, quantities to be considered and final judgment

Problem	Needed info	Difficulty of finding data	Difficultys of tool develop.	Difficulty of implem.	Final judgment
1	External temperature	2	1	3	**6.7**
	Pressure	1	1		
	Operating time	2	2		
2	Size	2	2	5	**20**
	Flow rate	2	2		
	Pressure	2	2		
3	External temperature	2	1	3	**8**
	High pressure	1	1		
	Low pressure	2	1		
	Operation time	2	2		
	Flow rate	2	2		
	Percentage of HP on total	4	1		
4	Flow rate	2	2	4	**40.3**
	Speed	4	2		
	Length	5	2		
	Number of singularities	5	2		
	Type of singularities	5	4		
5	Flow rate	2	2	4	**17.3**
	Speed	4	2		
	Length	2	2		
	Number of singularities	2	2		
	Type of singularities	2	4		
6	Flow rate	2	2	3	**15.2**
	Pressure	2	2		

Table 5.4: List of defined tools, quantities to be considered and final judgment

Problem	Needed info	Difficulty of finding data	Difficultys of tool develop.	Difficulty of implem.	Final judgment
	Operating time	2	2		
	Filter substitution interval	3	4		
	Filter cost	1	1		
	Delta P substitution	3	3		
7	Flow rate	2	2	1	**4.7**
	Pressure	2	2		
	Type and size of compressor	2	1		
	Pressure levels	2	5		
	Tank	1	3		
	Load profile	4	1		
8	Distance from main ring	4	4	4	**17.1**
	High pressure	1	1		
	Low pressure	1	1		
	Operation time	2	2		
	Flow rate	2	2		
	Percentage of HP	4	1		
9	Flow rate	2	2	2	**24.5**
	Pressure	2	2		
	Type of users	3	4		
	Presence of dust	5	5		
	Air humidity	5	5		
	Intake position	1	4		

Table 5.4: *List of defined tools, quantities to be considered and final judgment*

Problem	Needed info	Difficulty of finding data	Difficultys of tool develop.	Difficulty of implem.	Final judgment
10	Flow rate	2	2	5	**38.4**
	Pressure	2	2		
	Available heat	5	5		
	Need of heat	2	3		
	Available space	1	4		
11	Flow rate	2	2	5	**35.6**
	Pressure	2	2		
	Pressure levels	5	5		
	Available space	1	1		
	Type of users	5	5		
	Type of network	1	1		
12	Main production	3	2	2	**16.3**
	Flow rate	2	2		
	Pressure	2	2		
	Type and size of compressor	2	2		
	Air quality	3	4		
	Production plan	5	3		
	Electic consumption of CAS	4	4		
13	Resources availability	1	1	3	**22.5**
	Skills	4	5		
14	Resources availability	1	1	5	**27.1**
	Flow rate	2	2		
	Pressure	2	2		

Table 5.4: List of defined tools, quantities to be considered and final judgment

Problem	Needed info	Difficulty of finding data	Difficultys of tool develop.	Difficulty of implem.	Final judgment
	Load profile	4	2		
	Type and size of compressor	2	2		
	Electic consumption of CAS	4	4		
15	Flow rate	2	2	4	**26.8**
	Pressure	2	2		
	Load profile	4	2		
	Type and size of compressor	2	2		
	Electic consumption of CAS	4	4		
16	Size of tank	1	1	4	**11.2**
	Max pressure	1	1		
	Min pressure	1	1		
	Emptying time	5	2		
	Power of compressor	2	2		
17	Type of maintenance	4	5	3	**48**
	Maintenance costs	4	3		
	Required quality	3	4		
	Presence of dust	5	4		
18	Ideal performance	5	4	2	**18.8**
	Flow rate	2	2		

Table 5.4: *List of defined tools, quantities to be considered and final judgment*

Problem	**Needed info**	**Difficulty of finding data**	**Difficultys of tool develop.**	**Difficulty of implem.**	**Final judgment**
	Pressure	2	2		
	Required quality	4	4		
	Load profile	4	2		
	Type and size of compressor	2	2		
	Pressure levels	2	5		
	Pressure losses	4	2		
	Operating time and on/off	3	2		
19	List of the equipment	5	5	3	**75**
	Assessment of all productions	5	5		

The developed tools are those with the lowest final judgment. Implemented tools are:

- Tool for the evaluation of pressure drops in compressed air distribution;
- Tool for assessing pressure drops in the external air intake phase;
- Tool for evaluating the filter management system;
- Consumption calculation tool when using 2 pressure levels systems;
- Tool for evaluating the position of the compressor air intake;
- Tool for the evaluation of air leaks indirectly;
- Tool for the control of the modulation of compressors with inverter.

5.2.4 Subdivision of tools based on maturity level

The chosen tools are divided according to the area of interest selected on the basis of the indications provided by the maturity model in order to define a methodology capable of suggesting appropriate tools to improve the levels of maturity.

- Level 2:
    1. Tool for evaluating the position of the compressor air intake;
    2. Tool for the evaluation of air leaks indirectly.
- Level 3:
    1. Tool for evaluating the filter management system;
    2. Tool for the control of the modulation of compressors with inverter.
- Level 4:
    1. Tool for the evaluation of pressure drops in compressed air distribution;
    2. Tool for assessing pressure drops in the external air intake pipe;
    3. Consumption calculation tool when using 2 pressure levels systems.

5.2.5 Developed tools

This section describes the tools developed and the reasons. All developed tool are available within a standalone application called CAEESuite.

Tool for evaluating the position of the compressor air intake

The energy consumption of CAS could be reduced by suctioning fresh air from outside rather than from inside. The easiest and the cheapest way to suck air at the lowest temperature is to position the air intake facing north, possibly not exposing it to direct sunlight and raised above ground level. An empirical evaluation suggests that reducing the inlet temperature by 3 °C decreases the compression work by 1% [30, 76]. This reduction is easily explainable through thermodynamic considerations.

The developed tool allows to evaluate the possibility to reduce the energy consumption through the good positioning of the air intake.

The tool operation is based on the thermodynamic analysis of air compression. To estimate the energy consumption of compression phase, thermodynamic cycles have been implemented in the tool using the most common efficiency parameters for industrial air compressors.

The results provided allow to evaluate costs, energy consumption and savings related to temperature drops of 3, 6 and 9 °C compared to the present solution.

To use this tool it is necessary to know:

- External temperature (°C);
- Pressure level (bar);
- Number of compressor stages;
- Compression ratio of the first stage ;
- Intercooled air temperature (°C);
- Flow rate (Nm^3/h);
- Annual operating time (h);
- Energy cost (€/kWh).

The graphical interface of the tool is represented in Figure 5.1.

Tool test

The tool is tested using a simulated scenario where the temperature of intake air can be decrease until 9 °C. The used scenario is an industry where:

- The compressor processes an average flow rate of 500 Nm^3/h. The pressure is set at 10 bar. The compressor has two stages, the first has a compression ratio of 3 and the intercooled air has a temperature of 30 °C;
- External temperature is 20 °C.
- The compressor is used for 3500 h/year;

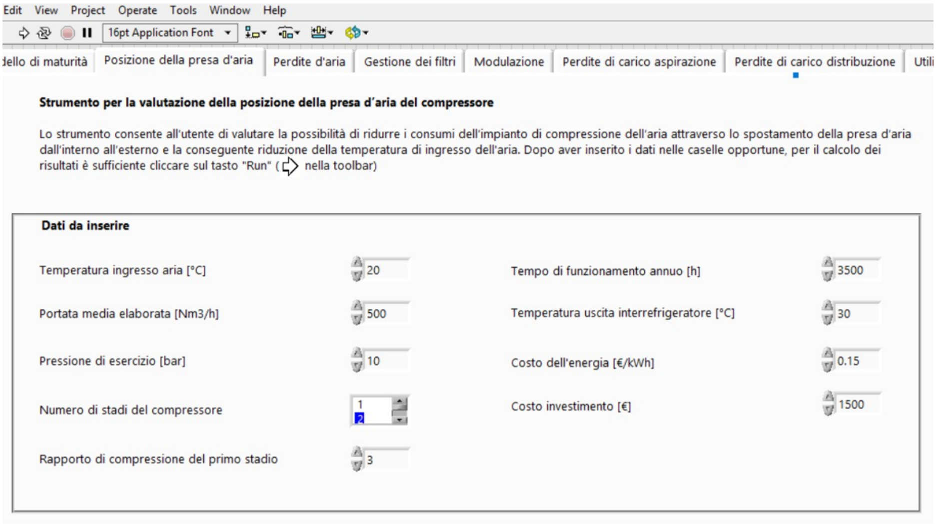

Figure 5.1: *Graphical interface of the tool*

- Electric energy costs 0.15 €/kWh.

The economic saving is calculated decreasing the air temperature from 3 to 9 °C. The results should be compared with the cost of a system modification. The summary of the results of the tool simulation are available in Figure 5.2.

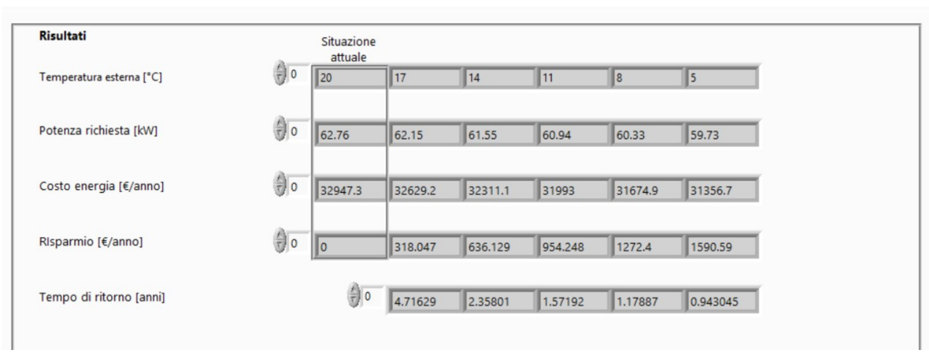

Figure 5.2: *Summary of the results of the simulation*

Tool for the evaluation of air leaks indirectly

Air leaks are the most important problem to solve for improving CAS energy efficiency. Some studies affirm that, on average, each

CAS dissipates 20% of the flow rate [30, 28]. Moreover, air leaks can make network-connected equipment less efficient and adversely affect production, reduce equipment life, make necessary additional maintenance and unscheduled downtimes.

Therefore leaks control is the first step to define an energy efficiency strategy for CAS. However, carrying out a capillary check is a very complex activity that can entail significant costs for the company. The research and the evaluation of air leaks are usually carried out directly by analyzing the network sections with a portable sound level meter able to find the leaks thanks to the typical ultrasound emission. It is possible to estimate in advance, through the control of consumption, the quantity of compressed air lost and therefore assess the need for monitoring and leaks detection.

The developed tool is used to assess the quantity of compressed air lost from the network in advance and provide a first evaluation of the cost of the problem. The operation of the tool is based on the calculation of the flow rate lost by the system through the assessment of the time lapse of the tank pressure drops. To measure the losses, it is therefore necessary that all the users connected to the network are turned off and that the pressure is at the set point. Starting from knowing the tank capacity and the time lapse for the pressure drop, it is possible to have an estimate of the lost flow rate and the energy consumed due to the losses. To calculate the energy consumption the tool operates simple thermodynamic evaluation starting from input data.

In Figure 5.3 the graphical interface is represented.

To use the tool, the following data have to be inserted:

- Volume of tank (m^3);
- Maximum pressure (bar);
- Minimum pressure (bar);
- Time interval to pass from maximum pressure to minimum pressure (min).

Through the use of this tool it is possible to evaluate the economic sustainability of a campaign of leaks research and maintenance.

Tool test

The tool is tested on a simulated scenario where:

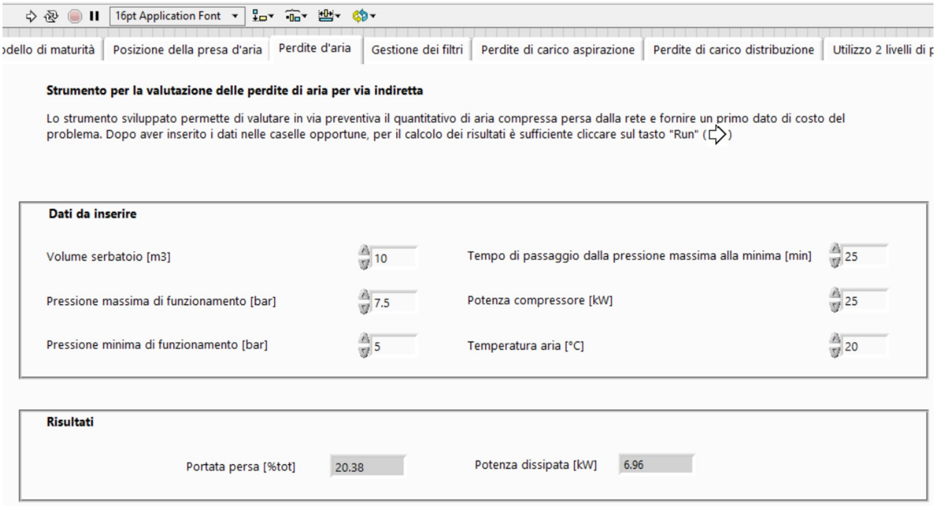

Figure 5.3: *Graphical interface of the tool*

- There is a 10 m^3 tank;
- The maximum pressure is 7.5 bar and the minimum is 5 bar;
- The time lapse to pass from maximum to minimum pressure is 25 minutes;
- The compressor power is 50 kW.

The tool calculates that 10% of total flow rate is lost and about 7% of power is wasted. These results allow to evaluate the convenience of a leak search campaign.

Tool for evaluating the filter management system

Dozen of studies have been published regarding filtration systems and their clogging [101, 102]. A clogged filter provides a low air filtering and, above all, can cause an excessive pressure drop. Moreover, the excessive pressure drop causes the increase of energy consumption to compress the air. The cleaning of the filters is, therefore, a fundamental aspect for a good functioning of the systems and for energy saving.

The clogging speed of the filters depends substantially only on the amount of impurities in the form of dust and steam which remains suspended in the air and on how much air passes through the filtering surfaces. From Figure 5.4 it is possible to notice how the pressure drop, due to the clogging of the filters, does not follow a linear trend and therefore can lead to a consequent deterioration of the performances. For this reason, it is advisable to replace or maintain the filter before the pressure drop is excessive.

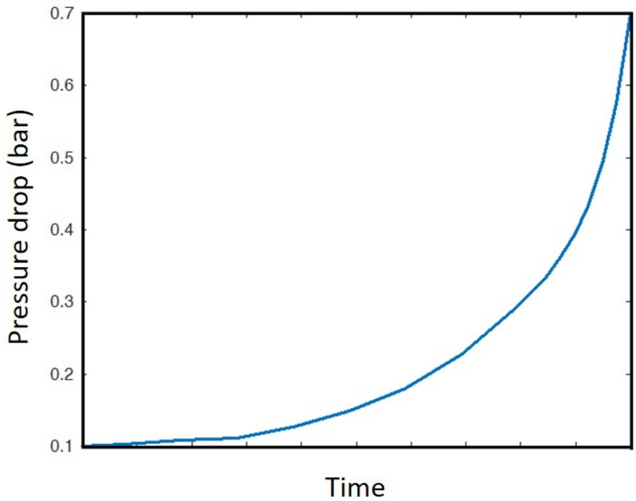

Figure 5.4: *Pressure drop over time*

The tool aims to help the organization in defining the best strategy for filter maintenance. In other words, the developed tool compares the costs derived from current filters management (energy + filter substitution) with the possible costs that the company would bear by increasing the frequency of the maintenance interventions, thus decreasing the average pressure drop during the operation of the system. The tool is based on the concept according to which decreasing the time of use of the filter, it is possible to keep the pressure drop low and decrease energy consumption. On the other hand, a too frequent filter replacement strategy would entail excessive maintenance costs.

The tools operation is based on the comparison between the actual adopted solution (in term of pressure drop) and some alternative solutions. The tools, using thermodynamic principles, is capable to calculate energy consumption of the air compressor in each situation using the common efficiency data.

To use the tool, the following data have to be available:

- Operating time (h/year);

- Time between filters changes (h);
- Intervention cost (€);
- Average flow rate (Nm^3/h);
- Maximum ΔP for filter replacement (bar);
- Pressure of system (bar).

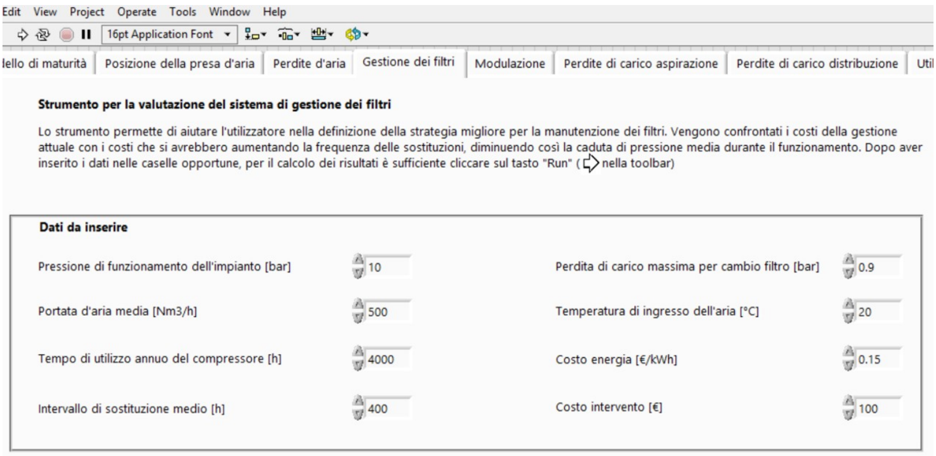

Figure 5.5: *Graphical interface of the tool*

In Figure 5.5 the user interface is shown.

<u>Tool test</u>

The developed tool is tested on a simulated scenario where:

- The compressor processes an average flow rate of 500 Nm^3/h at 8 bar;
- The compressor is used for 2500 h/year;
- The filters are maintained on average every 400 h of use which is the time in which the pressure drop reaches 0.9 bar;
- A maintenance intervention costs 50 €;
- Electric energy costs 0.15 €/kWh.

It is possible to calculate the energy saving due to the changes of the maintenance of filtering system. In particular, by decreasing the maximum pressure drop from 0.9 to 0.6 bar, the time interval between two consecutive maintenance operations is reduced by 23%. Although the annual maintenance costs are proportional to the number of interventions, the lower pressure drop allows to decrease the energy costs by an amount larger than the increase in maintenance costs. The savings achievable with this scenario is therefore around 300 € per year. Details of the results are collected in Figure 5.6.

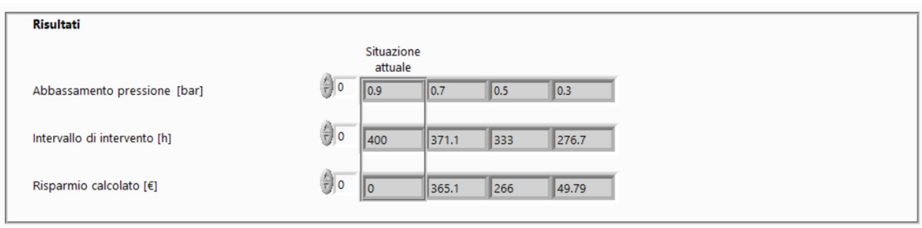

Figure 5.6: *Graphical interface of the results provided by the tool.*

Tool for the control of the modulation of compressors with inverter

Compressed air demand is often not stable over time. This variability could make the air compressors with load/unload control policy not suitable for providing the needed amount of compressed air. Moreover, frequent switching on/off could deteriorate the compressors early. The installation of a large tank could reduce the problem uncoupling the air demand from air production.

Scientific literature considers the installation of variable speed compressors, through the use of inverters, very suitable to decrease energy consumption and reduce problems related to switching on and off.

The operation of this tool is based on the monitoring of the pressure and the flow rate of the system, more in detail:

- The signal from the pressure sensor on the tank relating to period n is subtracted from the signal relating to the set point pressure set;
- The pressure difference is sent to a PID-type regulator which transforms the signal into a power signal to be sent to the compressor.

- At period n the compressor produces the quantity of air which brings the tank back to the set point pressure.

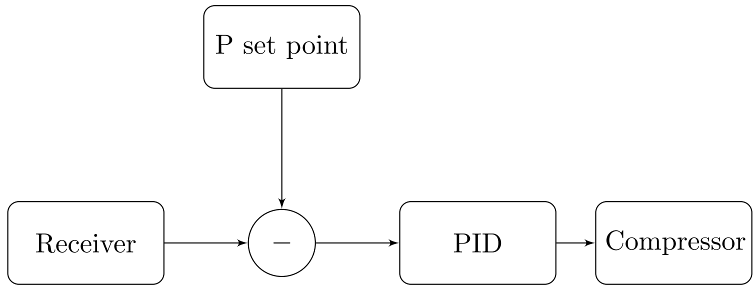

Figure 5.7: *Flow chart of the instrument operation.*

The operation of the tool needs a data-set composed of the following information:

- Tank set point pressure (bar);
- Minimum tank pressure (bar);
- External temperature (°C);
- Compressed air load profile (Nm$^3/h$);
- Volume of the tank (m^3);
- Electric load profile (kWh).

The program defines an alternative load profile to the actual based on the simulation logic previously adopted, and allows to view and compare the obtained through possible application of the method with those deriving from actual operation.

The results provided are:

- Graphical comparison over time of the flow rate profile produced according to the defined logic and that produced with the management system used by the company;
- Graphical comparison over time of the trend of the compressor load according to the defined logic and the compressor load assessed according to the actual management logic;

- Graph of the tank pressure trend over time according to the management system developed;
- Numerical indicator of the savings on consumption achieved by using the system.

Validation of the tool through a test case

The developed tool is validated through the application on a case study provided by an Italian industrial company belonging to the food sector.

The available data refer to one week of operation of the 3 compressors that make up the CAS. Data include:

- Date and time;
- External temperature (°C);
- Relative humidity of the environment (%);
- Flow rate of each compressor (Nm^3/h);
- Electrical power of each compressor (kW);
- Pressure of produced air (bar);

Data about the compressor with inverter are analysed to get some information about the compressors operation.

The tool provides the following results (Figure 5.9):

- Visualization of used data;
- Histogram of pressure;
- Diagram of flow rate over time;
- Diagram of pressure over time.

From the load analysis it is possible to notice that, despite the use of variable speed compressor, it works at maximum for most of the time. This is an important element to consider. In Figure 5.9 the comparison between actual flow rate and provided one is reported (central graph).

The tool provides also the pressure level over time (the bottom part of Figure 5.9).

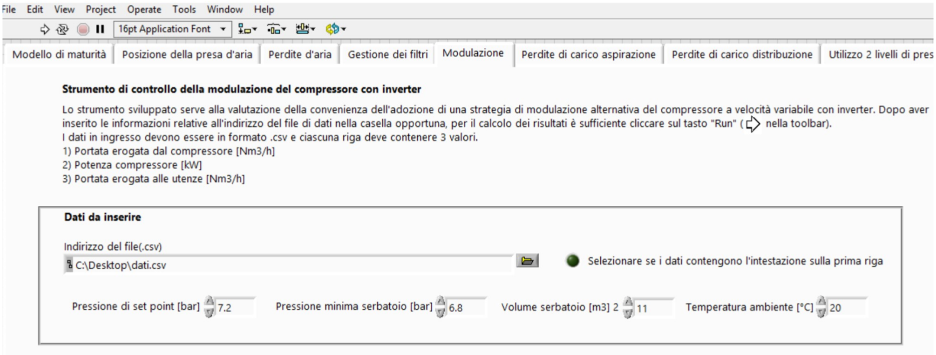

Figure 5.8: *Graphical interface of the tool*

Using the parameters detected by the monitoring system during a week of ordinary operation, it is possible to simulate the operation of the developed program and evaluate the actual improvement in performance. It should be noted that the variable speed compressor is inserted in a department with 2 other machines and it does not work for the whole time but it is managed according to a logic of uniform distribution of the load between the machines. The developed program is able to read the data measured by the various instruments installed on the air production system and subsequently, based on the required load, simulate the presence of a compressor with a different type of regulation. The results achieved by using the program show significant margins for improvement as regards the management system of the compressor power regulation. As can be seen from the central graph of Figure 5.9, the flow rate that the system produces (green curve) is particularly stable over time, reaching the maximum level for many minutes. The sudden changes in load are not indicative of the proper functioning of the compressor equipped with the inverter. In fact, this technology would allow the load to be adjusted more closely to the needs by dividing the power and the consequent flow rate delivered by the compressor. Furthermore, the distance between the required flow curve (blue curve) and the green curve indicates that, for a long time, the system produces more compressed air than necessary and during the rest it drastically decreases the production if the required flow is lower. The flow rate curve that the system would produce using the developed system should be closer to the real need of the system and this is a first indication of a possible improvement in system performance. As can be easily guessed, the simulation program satisfies the partial loads quite well,

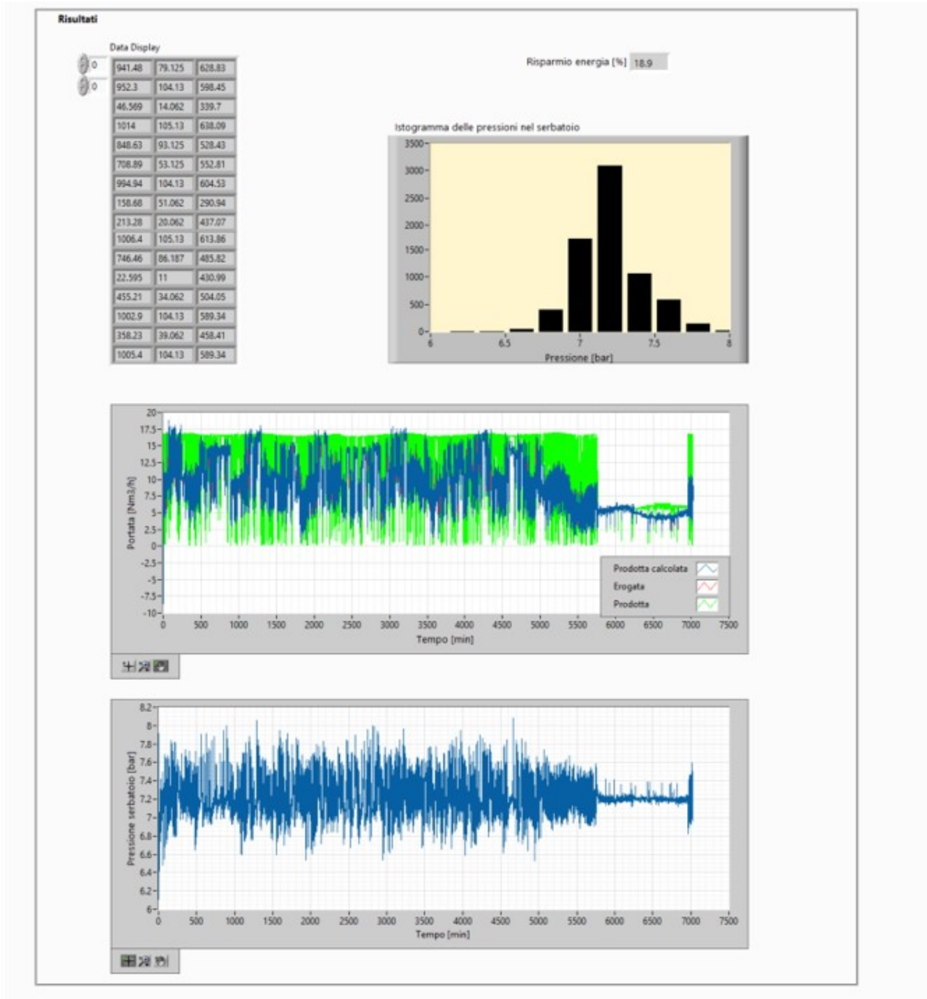

Figure 5.9: *Graphical interface of the results provided by the tool*

limiting the difference between the delivered flow rate and the required one.

The analysis of the tank pressure shows that the trend is fairly constant over time and stands very close to the level indicated by the 7.2 bar set point. In Figure 5.9 (lower graph) the representative curve of the pressure trend is reported. Even by reporting the data in a histogram as a function of the pressure, it is possible to note that the most numerous range of values as regards the pressure of the tank is close to the set point set at 7.2 bar.

The last and perhaps most important consideration should be made on the power used by the system. The analysis of energy consumption shows that using the implemented method saves 18% of the energy used by the compressor.

Tool for the evaluation of pressure drops in compressed air distribution

This tool provides an assessment of the good design of the first section of the network and of the branch which connects the compressor room with the main backbones. The evaluation is made on the basis of the possible pressure drop along the section in exam by calculating the length of the branch and the presence of various singularities (valves, curves, etc.). The tool is also useful for evaluating any other branch of the distribution network.

The data that the user must enter for the evaluation are:

- Flow rate of compressed air through the section (defined in Nm^3/h);
- Air inlet temperature (°C);
- Compressed air pressure (bar);
- Difference of air temperature between inlet and outlet compressor sections (°C);
- Desired air velocity in the pipe section (m/s);
- Length of the section (m);
- Piping diameter (inches);
- Number of singularities including:
  - Globe valves;
  - Diaphragm valves;
  - Rolling shutters;
  - Angle pipes;
  - Curve (radius equal to the diameter);
  - Curve (radius equal to twice the diameter);
  - "T" intersections;
  - Diameter reductions.

For the calculation of head losses the empirical formula (5.1) was used and implemented:

$$\Delta P = 1.6 \cdot 10^8 \cdot (Q^{1.85} \cdot L)/(d^5 \cdot p_0) \tag{5.1}$$

In which: ΔP is the pressure drop expressed in bar, Q is the air flow in Nm^3/min; d is the internal diameter of the pipes expressed in mm; p_0 is the pressure of the compressed air in kg/cm^2; L is the equivalent length of the pipe considering also the presence of singularities (m). Therefore, the tool presents itself as a simple interface in which the previously defined data must be entered. Figure 5.10 shows the graphical interface of the tool.

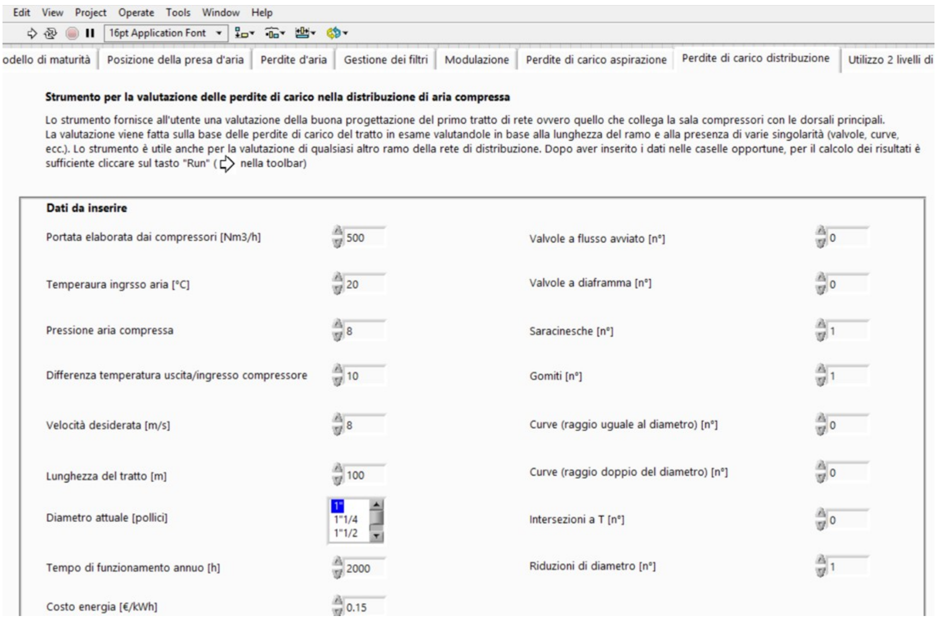

Figure 5.10: *Graphical interface of the tool*

The results made available the comparison between the current solution and two alternative solutions with a commercial diameter immediately smaller and immediately greater than the optimal one. For each solution, data are therefore made available on:

- Diameter of the pipes (expressed in inch and mm);
- Reynolds number;
- Total pressure drops of the line (bar);

- Annual energy cost of current operation (€);
- Possible annual saving (€).

The tool therefore provides valuable support for evaluating the sizing of the network. By providing two output values, the user is left with the possibility of choosing which solution is better, being able to evaluate them both in terms of flow speed and in terms of total pressure drops.

Test of the tool

The tool has been tested on an hypothesized scenario in which there are:

- A compressor which processes a flow rate of 500 Nm^3/h;
- Length of the piping 100 m;
- Optimum speed in the tube of 8 m/s;
- Presence of a gate valve, an angle curve and a reduction along the pipe;
- Current pipe diameter of 4".

Using the tool, it is possible to calculate the pressure drop of the existing pipe and estimate the pressure drop that would be obtained by optimizing the diameters. The results collected in Figure 5.11 show that, for the defined scenario, the optimal diameter which allows the optimization of the air speed and the minimization of pressure drops is 2"1/2. The solution obtained from the reported test also shows that an alternative solution in which the diameter of the pipe is smaller than the optimal by increasing the pressure drops but decreasing the purchase costs can be chosen. The final assessment of the convenience of the intervention remains the prerogative of the organization.

Tool for assessing pressure drops in the external air intake pipe

The implementation of this tool aims to provide an assessment of the good design of the compressor suction duct or the section of pipe that connects the compressor with the outside. The evaluation of the pressure drop is made by evaluating the length of the branch and the presence of various singularities (valves, curves, etc.). The variables that the user must enter for evaluation are:

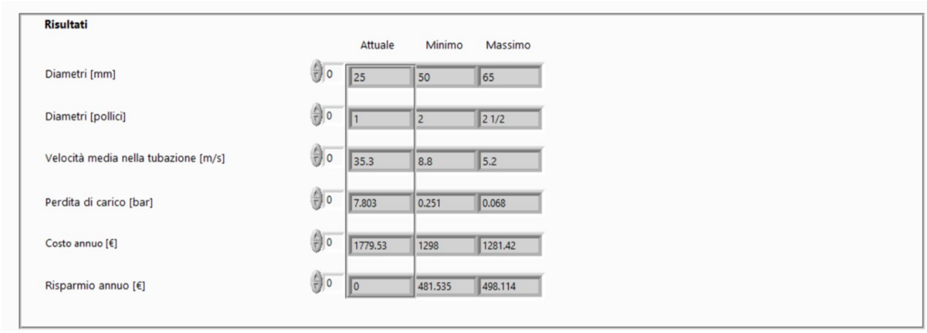

Figure 5.11: *Graphical visualization of the results*

- Flow rate of compressed air through the section (defined in Nm^3/h);
- Air inlet temperature (°C);
- Compressed air pressure (bar);
- Difference of air temperature between inlet and outlet compressor sections (°C);
- Desired air velocity in the pipe section (m/s);
- Length of the section (m);
- Piping diameter (inches);
- Number of singularities including:
  - Globe valves;
  - Diaphragm valves;
  - Rolling shutters;
  - Angle pipes;
  - Curve (radius equal to the diameter);
  - Curve (radius equal to twice the diameter);
  - "T" intersections;
  - Diameter reductions.

For the calculation of the pressure drop, (5.1) is taken as reference. Figure 5.12 shows the graphical interface of the tool.

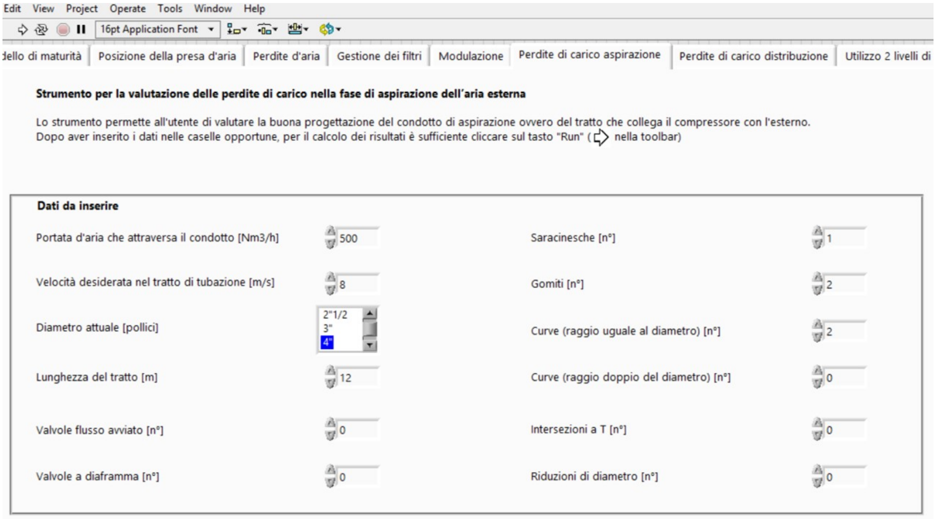

Figure 5.12: *Graphical interface of the tool*

The provided results compare the current solution with two solutions using different commercial diameter immediately smaller and immediately larger than the optimal one. For each solution, data are therefore made available on:

- Diameter of the pipes (inch and mm);
- Air speed (m/s);
- Reynolds number;
- Total pressure drops of the line (Pa).

The tool, therefore, provides valuable support for evaluating the sizing of the network. By providing two output values, the user is left with the possibility of choosing which solution is better, being able to evaluate them both in terms of flow speed and in terms of total pressure drops.

Test of the tool

The tool is tested regarding the operation and the calculation of the pressure drops. A scenario is hypothesized in which:

- The compressor processes a flow rate about 500 Nm^3/h;

- Pipe is 15 m long;
- Optimum speed in the tube of 8 m/s;
- There is a gate valve, two elbows and two curves along the pipe;
- Current pipe diameter is 4”.

Using the tool, it is possible to calculate the pressure drop of the present pipe and estimate those that would be obtained by optimizing the diameter. The results collected in Figure 5.13 show that for defined scenario, the optimal diameter to minimize the pressure drop and optimize the air speed is 6”. The solution obtained from the reported test also shows that the company can also choose a solution in which the diameter of the pipe is smaller than the optimal, increasing the pressure drops but plausibly decreasing the costs for the purchase. The final assessment of the convenience of the intervention remains the prerogative of the organization.

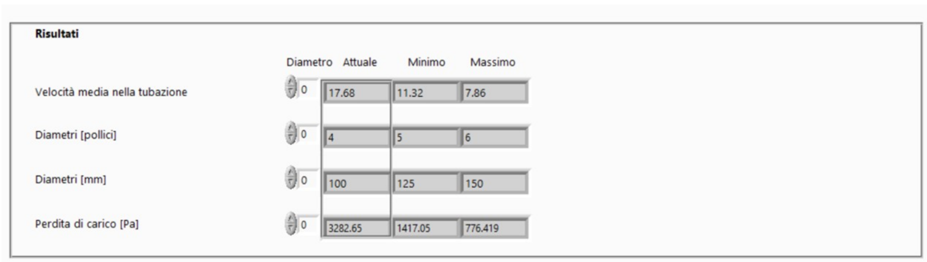

Figure 5.13: *Graphical visualization of the results*

Tool for consumption calculation of systems with 2 pressure levels

The equipment installed inside an industrial plant and connected to the compressed air distribution network must not all be fed at the same pressure. In cases where the network and the compressor are unique, the pressure set point of the CAS is set to the maximum level necessary for the users. In this way, precautionary behavior is adopted. The risk of malfunction is minimized but the energy consumption significantly increases. If users need significantly different operating pressure (differences higher than 0.5 ÷ 1 bar) and the flow rates are mostly used by the tools with lower operating pressure, it could be convenient to evaluate the adoption of a system with two pressure levels.

The developed tool is useful to help the organization in assessing the convenience of adopting a multi-level pressure system by comparing two scenarios. The first in which the entire flow has a single pressure level, the second in which a part of the flow is processed at a lower pressure. Energy consumption of both the scenarios are calculated. The tool simulates the different scenarios through the calculation of the air compression work using simple thermodynamic considerations. To use the tool, the values to be entered are:

- Required compressed air flow rate (indicated in Nm^3/h);
- High pressure (bar);
- Low pressure (bar);
- Annual operating time (h);
- Ratio between the high pressure flow rate and the total flow rate (indicated in %);
- Air intake temperature in the compressor (°C).

With these data, the tool allows to evaluate the current consumption for the production of compressed air and the energy consumption if a two pressure levels system would be installed. In Figure 5.14 is represented the tool interface.

<u>Test of the tool</u>

The tool is tested as regards operation and the calculation of economic savings due to the possibility of using systems with 2 pressure levels instead of a system with regulation on maximum pressure. A scenario is hypothesized in which:

- There is a compressor that processes an average flow rate of 500 Nm^3/h with a pressure that varies from 4 to 10 bar. In particular, 70% of the flow rate is intended for users powered at 7 bar while the remaining 30% is for users that need a pressure of 4 bar;

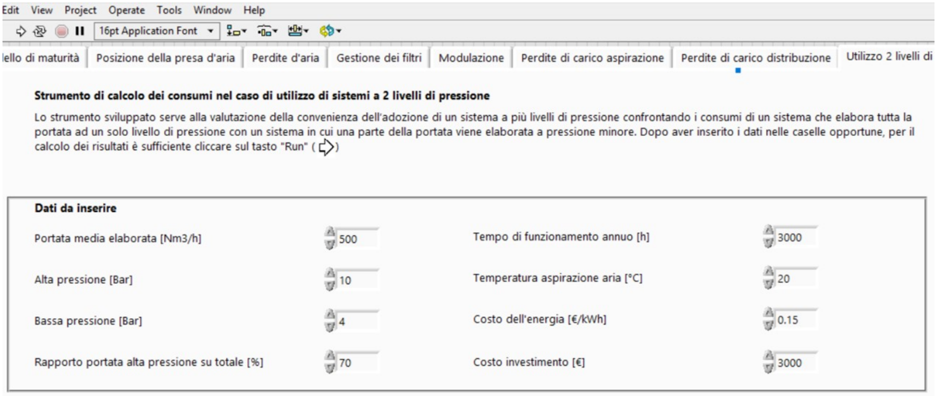

Figure 5.14: *Graphical interface of the tool*

- The external temperature is 20 °C;
- The compressor is used on average 3000 h/year;
- The supply of electricity costs 0.15 €/kWh.

Starting from these data, the instrument assesses the economic savings that would be introduced by introducing a low pressure air compression system for the flow rate that requires 4 bar and a separate compression system for the higher flow rate. In particular, the tool estimates that current consumption can be decreased by 15% using a 2 pressure level system. The economic savings from one solution to another is considerable and is about 4200 €. Details of the results are shown in Figure 5.15

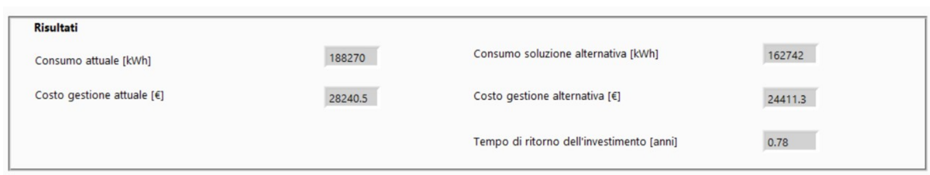

Figure 5.15: *Graphical visualization of the results*

5.2.6 Conclusions

In this chapter, 7 tools have been introduced to support decisions in terms of managing compressed air systems with the aim of improving energy efficiency. These tools allow assessing the economic convenience of the adoption of some efficiency measures. In order to develop these tools, it is necessary to characterize the problems and identify their importance through a research phase in technical-scientific literature. After defining all the tools that could be developed, the best tools are chosen and developed. All the tools are collected in a Suite easily usable and available for free.

For all of them, the development phase is followed by a test phase on simulated scenarios. For one tool, relating to the control of the compressor load, it is possible to test its operation on consumption data from the monitoring system of a company belonging to the food sector. The test characterizes its good functioning and shows that by using this tool it is possible to guarantee the company a 15% saving in costs relating to the energy used by the compressor.

Conclusions

The lack of well organized procedures to increase energy efficiency of CASs gave the input for the development of a large research activity about industrial compressed air use and performance improvements. This thesis summarizes all the activities undertaken during 3 years of doctoral course.

The main objective of the work is the development of a well structured methodology which can be easily used by industrial companies to assess CAS energy efficiency and decrease energy consumption.

The work has first concerned a careful analysis of the situation with regard to the use of the CAS and then went on to identify the possibilities for defining strategies and developing methodologies to improve energy performance. So, starting from the scientific literature research and available dataset about energy consumption of more than 1500 industries belonging to 9 Italian industrial sectors, a benchmark analysis has been carried out to get in touch and assess the energy performance of Italian industrial sector. Results have shown that, on average, $10 \div 15$ % of industrial electric energy consumption is due to CAS operation and that there are a lot of differences between the performance of different industrial sectors, for this reason is quite difficult to compare all the achieved results. Furthermore, too many industries have not a performance measurement system. To get more information about CAS management, a short questionnaire composed of 12 questions have been administrated to many companies belonging to different sectors. The results of the questionnaire have been used to characterize the criticalities and have been useful to develop the following phases of the work.

In order to propose a procedure capable to help companies to improve their efficiency, during the work a series of best practices and guidelines have been developed. Taking into account the results of the administration of the CASEEMM (a maturity model about compressed air systems), best practices and guidelines have been suggested to the company to decrease energy consumption for CAS.

The last part of the method concerns the proposition of a set of 7 decision support tools developed during the last year. The application of these decision support tools is useful to propose a summary evaluation of the potential performance improvement and evaluate the cost and benefit of some implementations.

In this way, a complete methodology was developed that starts from data analysis and ends with the proposal of some solutions to improve energy efficiency.

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[1] A. Kluczek and P. Olszewski, "Energy audits in industrial processes," Journal of cleaner production, vol. 142, pp. 3437–3453, 2017.

[2] M. S. Rahman, A. H. M. Noman, F. Shahari, M. Aslam, C. S. Gee, C. R. Isa, and S. Pervin, "Efficient energy consumption in industrial sectors and its effect on environment: A comparative analysis between g8 and southeast asian emerging economies," Energy, vol. 97, pp. 82–89, 2016.

[3] Y. Wang, X.-l. Ge, J.-l. Liu, and Z. Ding, "Study and analysis of energy consumption and energy-related carbon emission of industrial in tianjin, china," Energy Strategy Reviews, vol. 10, pp. 18–28, 2016.

[4] E. Parliament, "Directive 2012/27/eu of the european parliament and of the coucil of 25 october 2012 on energy efficiency; 2012. oj l315/1," Official Journal of the European Union, 2012.

[5] V. Introna, V. Cesarotti, M. Benedetti, S. Biagiotti, and R. Rotunno, "Energy management maturity model: an organizational tool to foster the continuous reduction of energy consumption in companies," Journal of cleaner production, vol. 83, pp. 108–117, 2014.

[6] H. A. ElMaraghy, A. M. Youssef, A. M. Marzouk, and W. H. ElMaraghy, "Energy use analysis and local benchmarking of manufacturing lines," Journal of cleaner production, vol. 163, pp. 36–48, 2017.

[7] J. K. Kissock and C. Eger, "Measuring industrial energy savings," Applied Energy, vol. 85, no. 5, pp. 347–361, 2008.

[8] M. Benedetti, V. Cesarotti, and V. Introna, “From energy targets setting to energy-aware operations control and back: An advanced methodology for energy efficient manufacturing,” Journal of Cleaner Production, vol. 167, pp. 1518–1533, 2017.

[9] E. Worrell, “Energy efficiency improvement and cost saving opportunities for the us iron and steel industry an energy star (r) guide for energy and plant managers,” 2011.

[10] E. Worrell, K. Kermeli, and C. Galitsky, “Energy efficiency improvement and cost saving opportunities for cement making an energy star® guide for energy and plant managers,” 2013.

[11] https://www.enea.it/it.

[12] S. Salvatori, M. Benedetti, F. Bonfà, V. Introna, and S. Ubertini, “Inter-sectorial benchmarking of compressed air generation energy performance: Methodology based on real data gathering in large and energy-intensive industrial firms,” Applied energy, vol. 217, pp. 266–280, 2018.

[13] R. Marshall, W. Scales, G. Shafer, P. Shaw, P. Sheaffer, R. Stasyshan et al., “Improving compressed air system performance: A sourcebook for industry v3,” Lawrence Berkeley National Laboratory, Resource Dynamics Corporation, Tech. Rep., 2016.

[14] Compressed air manual - 8th edition, 8th ed., Atlas Copco, 2010.

[15] N. Edomah, “Governing sustainable industrial energy use: Energy transitions in nigeria’s manufacturing sector,” Journal of cleaner production, vol. 210, pp. 620–629, 2019.

[16] R. Mahamud, W. Li, and S. Kara, “Energy characterisation and benchmarking of factories,” CIRP Annals, vol. 66, no. 1, pp. 457–460, 2017.

[17] J. P. Hughes, “Regulatory treatment of uneconomic power plants,” The Electricity Journal, vol. 29, no. 6, pp. 28–32, 2016.

[18] D. W. Kim, Y. M. Kim, and S. E. Lee, “Development of an energy benchmarking database based on cost-effective energy performance indicators: Case study on public buildings in south korea,” Energy and Buildings, vol. 191, pp. 104–116, 2019.

[19] E. P. Piening and T. O. Salge, "Understanding the antecedents, contingencies, and performance implications of process innovation: A dynamic capabilities perspective," Journal of Product Innovation Management, vol. 32, no. 1, pp. 80–97, 2015.

[20] T. Koc and C. Ceylan, "Factors impacting the innovative capacity in large-scale companies," Technovation, vol. 27, no. 3, pp. 105–114, 2007.

[21] M.-J. Li and W.-Q. Tao, "Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry," Applied Energy, vol. 187, pp. 203–215, 2017.

[22] D. Moya, R. Torres, and S. Stegen, "Analysis of the ecuadorian energy audit practices: A review of energy efficiency promotion," Renewable and Sustainable Energy Reviews, vol. 62, pp. 289–296, 2016.

[23] D. D'Agostino, B. Cuniberti, and P. Bertoldi, "Energy consumption and efficiency technology measures in european non-residential buildings," Energy and Buildings, vol. 153, pp. 72–86, 2017.

[24] G. May, B. Stahl, M. Taisch, and D. Kiritsis, "Energy management in manufacturing: From literature review to a conceptual framework," Journal of Cleaner Production, vol. 167, pp. 1464–1489, 2017.

[25] K. Bunse, M. Vodicka, P. Schönsleben, M. Brülhart, and F. O. Ernst, "Integrating energy efficiency performance in production management–gap analysis between industrial needs and scientific literature," Journal of Cleaner Production, vol. 19, no. 6-7, pp. 667–679, 2011.

[26] Z. G. Babel'ová, M. Kučerová, and M. Homokyová, "Enterprise performance and workforce performance measurements in industrial enterprises in slovakia," Procedia Economics and Finance, vol. 34, pp. 376–381, 2015.

[27] M. Benedetti, I. Bertini, V. Introna, S. Ubertini et al., "Explorative study on compressed air systems' energy efficiency in production and use: First steps towards the creation of a benchmarking system for large and energy-intensive industrial firms," Applied Energy, 2017.

[28] J. R. Neale and P. J. Kamp, "Compressed air system best practice programmes: What needs to change to secure long-term energy savings for new zealand?" Energy Policy, vol. 37, no. 9, pp. 3400–3408, 2009.

[29] P. Radgen and E. Blaustein, "Compressed air systems in the european union," Stuttgart: LOG_X, 2001.

[30] R. Saidur, N. Rahim, and M. Hasanuzzaman, "A review on compressed-air energy use and energy savings," Renewable and Sustainable Energy Reviews, vol. 14, no. 4, pp. 1135–1153, 2010.

[31] Introduction to best practices for compressed air systems, Compressed Air Challenge , n.a.

[32] Z. Ge, "Review on data-driven modeling and monitoring for plant-wide industrial processes," Chemometrics and Intelligent Laboratory Systems, 2017.

[33] X. Feng, D. Yan, C. Wang, and H. Sun, "A preliminary research on the derivation of typical occupant behavior based on large-scale questionnaire surveys," Energy and Buildings, vol. 117, pp. 332–340, 2016.

[34] D. Viesi, F. Pozzar, A. Federici, L. Crema, and M. S. Mahbub, "Energy efficiency and sustainability assessment of about 500 small and medium-sized enterprises in central europe region," Energy Policy, vol. 105, pp. 363–374, 2017.

[35] H. Kanneganti, B. Gopalakrishnan, E. Crowe, O. Al-Shebeeb, T. Yelamanchi, A. Nimbarte, K. Currie, and A. Abolhassani, "Specification of energy assessment methodologies to satisfy iso 50001 energy management standard," Sustainable Energy Technologies and Assessments, vol. 23, pp. 121–135, 2017.

[36] A. Ozawa, Y. Kudoh, and Y. Yoshida, "A new method for household energy use modeling: A questionnaire-based approach," Energy and Buildings, vol. 162, pp. 32–41, 2018.

[37] M. Nakajima, A. Kimura, and B. Wagner, "Introduction of material flow cost accounting (mfca) to the supply chain: a questionnaire study on the challenges of constructing a low-carbon supply chain

to promote resource efficiency," Journal of Cleaner Production, vol. 108, pp. 1302–1309, 2015.

[38] W. Cai, F. Liu, O. Dinolov, J. Xie, P. Liu, and J. Tuo, "Energy benchmarking rules in machining systems," Energy, vol. 142, pp. 258–263, 2018.

[39] J. Ke, L. Price, M. McNeil, N. Z. Khanna, and N. Zhou, "Analysis and practices of energy benchmarking for industry from the perspective of systems engineering," Energy, vol. 54, pp. 32–44, 2013.

[40] G. Festel and M. Würmseher, "Benchmarking of industrial park infrastructures in germany," Benchmarking: An International Journal, vol. 21, no. 6, pp. 854–883, 2014.

[41] C.-F. Lindberg, S. Tan, J. Yan, and F. Starfelt, "Key performance indicators improve industrial performance," Energy Procedia, vol. 75, pp. 1785–1790, 2015.

[42] A. Juaidi, F. AlFaris, F. G. Montoya, and F. Manzano-Agugliaro, "Energy benchmarking for shopping centers in gulf coast region," Energy policy, vol. 91, pp. 247–255, 2016.

[43] W. Chung, "Review of building energy-use performance benchmarking methodologies," Applied Energy, vol. 88, no. 5, pp. 1470–1479, 2011.

[44] D. Phylipsen, K. Blok, E. Worrell, and J. De Beer, "Benchmarking the energy efficiency of dutch industry: an assessment of the expected effect on energy consumption and co2 emissions," Energy policy, vol. 30, no. 8, pp. 663–679, 2002.

[45] M. A. Mirzakhani, N. Tahouni, and M. H. Panjeshahi, "Energy benchmarking of cement industry, based on process integration concepts," Energy, vol. 130, pp. 382–391, 2017.

[46] S. Nadolski, B. Klein, A. Kumar, and Z. Davaanyam, "An energy benchmarking model for mineral comminution," Minerals Engineering, vol. 65, pp. 178–186, 2014.

[47] S. Longo, B. M. d'Antoni, M. Bongards, A. Chaparro, A. Cronrath, F. Fatone, J. M. Lema, M. Mauricio-Iglesias, A. Soares, and A. Hospido, "Monitoring and diagnosis of energy consumption in wastewater treatment plants. a state of the art and proposals for improvement," Applied energy, vol. 179, pp. 1251–1268, 2016.

[48] K. Mui, L. Wong, and L. Law, "An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates," Applied Energy, vol. 84, no. 1, pp. 89–98, 2007.

[49] S. S. Asl, N. Tahouni, and M. H. Panjeshahi, "Energy benchmarking of thermal power plants using pinch analysis," Journal of cleaner production, vol. 171, pp. 1342–1352, 2018.

[50] J. Ahn, S. Cho, and D. H. Chung, "Development of a statistical analysis model to benchmark the energy use intensity of subway stations," Applied energy, vol. 179, pp. 488–496, 2016.

[51] L. K. Sahoo, S. Bandyopadhyay, and R. Banerjee, "Benchmarking energy consumption for dump trucks in mines," Applied energy, vol. 113, pp. 1382–1396, 2014.

[52] W. Chung, Y. Hui, and Y. M. Lam, "Benchmarking the energy efficiency of commercial buildings," Applied energy, vol. 83, no. 1, pp. 1–14, 2006.

[53] B. Ang, "Monitoring changes in economy-wide energy efficiency: from energy–gdp ratio to composite efficiency index," Energy Policy, vol. 34, no. 5, pp. 574–582, 2006.

[54] T. W. Anderson and D. A. Darling, "Asymptotic theory of certain" goodness of fit" criteria based on stochastic processes," The annals of mathematical statistics, pp. 193–212, 1952.

[55] K. Cullinane, T.-F. Wang, D.-W. Song, and P. Ji, "The technical efficiency of container ports: comparing data envelopment analysis and stochastic frontier analysis," Transportation Research Part A: Policy and Practice, vol. 40, no. 4, pp. 354–374, 2006.

[56] J. Chen, Y. Wu, M. Song, and Z. Zhu, "Stochastic frontier analysis of productive efficiency in china's forestry industry," Journal of Forest Economics, vol. 28, pp. 87–95, 2017.

[57] S. Carlson and A. Walburger, Energy index development for benchmarking water and wastewater utilities. American Water Works Association, 2007.

[58] E. Commission, "Reference document on best available techniques for energy efficiency," pp. 1–430, 2009.

[59] I. N. d. S. Sistema Statistico Nazionale, "L'ambiente di codifica automatica dell'ateco 2007." [Online]. Available: https://www.istat.it/it/files/2014/04/metenorme0941ambiente_codifica_automatica_ateco07.pdf

[60] P. Rohdin, P. Thollander, and P. Solding, "Barriers to and drivers for energy efficiency in the swedish foundry industry," Energy Policy, vol. 35, no. 1, pp. 672–677, 2007.

[61] P. G. Sassone and M. V. Martucci, "Industrial energy conservation: the reasons behind the decisions," Energy, vol. 9, no. 5, pp. 427–437, 1984.

[62] E. Sardianou, "Barriers to industrial energy efficiency investments in greece," Journal of Cleaner Production, vol. 16, no. 13, pp. 1416–1423, 2008.

[63] J.-C. Brunke, M. Johansson, and P. Thollander, "Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the swedish iron and steel industry," Journal of Cleaner Production, vol. 84, pp. 509–525, 2014.

[64] K.-H. Lee, "Drivers and barriers to energy efficiency management for sustainable development," Sustainable Development, vol. 23, no. 1, pp. 16–25, 2015.

[65] T. F. Burgess, "A general introduction to the design of questionnaires for survey research," UK: University of Leeds, 2001.

[66] W. Foddy and W. H. Foddy, Constructing questions for interviews and questionnaires: Theory and practice in social research. Cambridge university press, 1994.

[67] V. Cesarotti, S. Deli Orazi, and V. Introna, "Improve energy efficiency in manufacturing plants through consumption forecasting and real time control: Case study from pharmaceutical sector," in International Conference on Advances in Production Management Systems (APMS 2010), Cernobbio, Como (Italy), 2010.

[68] S. Project, "The sigma guidelines: putting sustainable development into practice-a guide for organizations," 2003.

[69] A. G. Chofreh, F. A. Goni, J. J. Klemeš, M. N. Malik, and H. H. Khan, "Development of guidelines for the implementation of sustainable enterprise resource planning systems," Journal of Cleaner Production, p. 118655, 2019.

[70] A. Hasanbeigi and L. Price, "Industrial energy audit guidebook: Guidelines for conducting an energy audit in industrial facilities," Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), Tech. Rep., 2010.

[71] B. Stawicki, B. Lozo, and B. Lajic, "Energy management guidelines in pulp and paper production," Cellulose Chemistry & Technology, vol. 44, no. 10, p. 521, 2010.

[72] J. Carvalho Filho, T. V. Nunhes, and O. J. Oliveira, "Guidelines for cleaner production implementation and management in the plastic footwear industry," Journal of Cleaner Production, 2019.

[73] A. Brent, C. Silinga, and N. Sanetra, "Guidelines for energy management in the south african wine industry," Journal of Energy in Southern Africa, vol. 27, no. 4, pp. 53–63, 2016.

[74] B. H. Roberts, "The application of industrial ecology principles and planning guidelines for the development of eco-industrial parks: an australian case study," Journal of Cleaner Production, vol. 12, no. 8-10, pp. 997–1010, 2004.

[75] M. Benedetti, F. Bonfà, I. Bertini, V. Introna, S. Salvatori, S. Ubertini, and R. Paradiso, "Maturity-based approach for the improvement of energy efficiency in industrial compressed air production and use systems," Energy, vol. 186, p. 115879, 2019.

[76] R. Dindorf, "Estimating potential energy savings in compressed air systems," Procedia Engineering, vol. 39, pp. 204–211, 2012.

[77] S. Mousavi, S. Kara, and B. Kornfeld, "Energy efficiency of compressed air systems," Procedia Cirp, vol. 15, pp. 313–318, 2014.

[78] Energy Efficiency Best Practice Guide, Sustainability Victoria , 2002.

[79] Il manuale delle migliori prassi per l'efficienza energetica, CARE +, 2010.

[80] A. McKane, "Improving energy efficiency of compressed air system based on system audit," 2008.

[81] R. Cipollone and D. Vittorini, "Energy saving potential in existing compressors," 2014.

[82] "D.lgs. 4 luglio 2014, no. 102. attuazione della direttiva 2012/27/ue," Gazzetta Ufficiale della Repubblica Italiana, 2014.

[83] D. M. McCulloch, F. Moskowitz, and R. Marshall, "The 14 rs of compressed air efficiency," 2014. [Online]. Available: www.plantservices.com/articles/2014/the-14-rs-of-compressed-air-efficiency/?show=all

[84] C. Beals, J. Ghislain, H. Kemp, and D. McCulloch, "Improving compressed air system performance," US Department of Energy, 2003.

[85] I quaderni dell'Aria Compressa, Friulair, 2014.

[86] M. Radovanović, S. Popov, and S. Dodic, Sustainable Energy Management. Academic Press, January 2013.

[87] Y. Sakamoto, Y. Tonooka, and Y. Yanagisawa, "Estimation of energy consumption for each process in the japanese steel industry: a process analysis," Energy conversion and management, vol. 40, no. 11, pp. 1129–1140, 1999.

[88] Z. Bi and L. Wang, "Optimization of machining processes from the perspective of energy consumption: A case study," Journal of manufacturing systems, vol. 31, no. 4, pp. 420–428, 2012.

[89] C. Pach, T. Berger, Y. Sallez, T. Bonte, E. Adam, and D. Trentesaux, "Reactive and energy-aware scheduling of flexible manufacturing systems using potential fields," Computers in Industry, vol. 65, no. 3, pp. 434–448, 2014.

[90] D. J. Power, "A brief history of decision support systems," DSSResources. com, vol. 3, 2007.

[91] R. Sharma, N. Chand, V. Sharma, and D. Yadav, "Decision support system for operation, scheduling and optimization of hydro power plant in jammu and kashmir region," Renewable and Sustainable Energy Reviews, vol. 43, pp. 1099–1113, 2015.

[92] J. A. Carrión, A. E. Estrella, F. A. Dols, M. Z. Toro, M. Rodríguez, and A. R. Ridao, "Environmental decision-support systems for evaluating the carrying capacity of land areas: Optimal site selection for grid-connected photovoltaic power plants," Renewable and Sustainable Energy Reviews, vol. 12, no. 9, pp. 2358–2380, 2008.

[93] M. del Mar Casanovas-Rubio and J. Armengou, "Decision-making tool for the optimal selection of a domestic water-heating system considering economic, environmental and social criteria: Application to barcelona (spain)," Renewable and Sustainable Energy Reviews, vol. 91, pp. 741–753, 2018.

[94] F. Lolli, A. Ishizaka, R. Gamberini, B. Rimini, E. Balugani, and L. Prandini, "Requalifying public buildings and utilities using a group decision support system," Journal of Cleaner Production, vol. 164, pp. 1081–1092, 2017.

[95] P. Hirsch, M. Grochowski, and K. Duzinkiewicz, "Decision support system for design of long distance heat transportation system," Energy and Buildings, vol. 173, pp. 378–388, 2018.

[96] M. Kukar, P. Vračar, D. Košir, D. Pevec, Z. Bosnić et al., "Agrodss: a decision support system for agriculture and farming," Computers and Electronics in Agriculture, vol. 161, pp. 260–271, 2019.

[97] AIRMaster+, Office of Energy Efficiency and Renewable Energy, 2014.

[98] P. Pondrano, N. Anglani, and G. Petrecca, "Simulation planning and control of a central compressed air plant for a more efficient energy use," in 6th Annual International Conference on Industrial Engineering Theory, Applications and Practice, 2001, pp. 18–20.

[99] S. Murphy and J. K. Kissock, "Simulating energy efficient control of multiple-compressor compressed air systems," 2015.

[100] J. Zahlan and S. Asfour, "A multi-objective approach for determining optimal air compressor location in a manufacturing facility," Journal of Manufacturing Systems, vol. 35, pp. 176–190, 2015.

[101] D. Thomas, P. Penicot, P. Contal, D. Leclerc, and J. Vendel, "Clogging of fibrous filters by solid aerosol particles experimental and modelling study," Chemical Engineering Science, vol. 56, no. 11, pp. 3549–3561, 2001.

[102] S. Calle, P. Contal, D. Thomas, D. Bemer, and D. Leclerc, "Description of the clogging and cleaning cycles of filter media," Powder Technology, vol. 123, no. 1, pp. 40–52, 2002.