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School of Industrial and Information Engineering

Master of Science in Mechanical Engineering

A technology-oriented framework to characterize energy efficiency measures in compressed air systems

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Sommario

L'efficienza energetica è riconosciuta come un elemento di fondamentale importanza nel panorama internazionale e politiche sempre più stringenti in termini di consumi e sostenibilità sono state varate dopo gli accordi di Kyoto. L'interesse generale, è volto alla diminuzione del consumo totale di energia tramite misure di efficientamento energetico ed in particolare al settore industriale, che assorbe più del 30% della produzione totale. Facendo riferimento alla situazione italiana si è deciso di investigare il mondo delle piccole medie imprese per due motivi fondamentali: il primo è che esse costituiscono l'ossatura portante del settore, con una percentuale del 98% nel contesto nazionale, la seconda ragione le vede portate più difficilmente ad investire in misure di efficienza energetica, frenate da mancanza di conoscenza e di pratiche sulla gestione dell'energia. Lo scopo del lavoro di ricerca è un'analisi che abbia una validità multi-settoriale e per questo motivo si è pensato ad un focus sulle tecnologie di servizio, cioè indipendenti dal processo di produzione. Nel dettaglio si analizzerà l'adozione degli interventi di efficienza energetica nei sistemi di aria compressa, mettendo in luce i fattori, legati alla tecnologia ed al funzionamento, che ne influenzano il tasso di implementazione.
In una prima fase si caratterizzano gli interventi di efficienza energetica. Lo studio si concentra poi sullo sviluppo di un framework orientato alla tecnologia, composto da tutti fattori da mettere in luce quando si adotta una misura di efficienza energetica nei sistemi di aria compressa, con le rispettive implicazioni che conseguono l'esecuzione dell'intervento nel contesto operativo. La validazione del modello consta di tre parti separate: (i) una è puramente teorica ed analizza ognuna delle implicazioni che una misura di efficienza comporta, (ii) segue la validazione sul campo del framework e degli elementi che lo compongono, in ultimo (iii) l'applicazione del modello proposta ad alcune aziende campione sulle misure di efficienza per valutarne lo sforzo e la facilità di utilizzo.

Abstract

Energy efficiency, is globally recognized as an element of utmost importance: as consequence, intensive policies in terms of consumption and sustainability have been launched after the Kyoto agreements. The general interest, is directed toward the total energy consumption reduction through energy efficiency measures, and in particular to the industrial sector, who takes up more than the 30% of the total production. Referring to the Italian situation, we decided to investigate the SMEs for two major reasons: firstly, they are composing the backbone of the sector, with a percentage of 98% of the total; secondly, they are less oriented in investing in energy efficiency measures, hindered by the lacking knowledge and practices on energy management. The objective of the research study is a multi-sectorial validity analysis, and for this reason we thought on a focus toward service technologies i.e. the ones independent to the production process. In detail, we are going to analyze the adoption of compressed air system energy efficiency interventions, to shed the light on technology and working process linked factors that have an influence on the implementation rate.
In a first step, the energy efficiency interventions are fully characterized. The study is then moved toward the development of a technology-oriented framework, composed by all factors to consider when a compressed air system energy efficiency measure is going to be adopted, with the corresponding implications of executing it in an operative context. The model validation is composed by three different parts: (i) the first, being purely theoretical, analyzes each of the implications coming from the efficiency measures adoption, followed by (ii) the on-field validation of the framework and of the elements composing it; lastly (iii) the model application is proposed to sample companies to evaluate the effort and user-friendliness in using the tool on single energy efficiency measures.

Table of contents

List of tables

List of figures

CHAPTER 1
Introduction: General outlook and reasons for investigation

The Paris agreement in December 2015 dramatically change the way we cope with the consumption and production of energy. Anyway, in many national realities, such a step forward requires a political before than a technical effort. In the modern times, a more and more dynamic and growing picture of the world stands in front of our eyes; a point of paramount importance is the growing of the population and the growing of services to deliver to that population, that is happening thanks to the reduction of the poverty. This automatically lead to a more energy demand and consumption in a global scale that from an emission perspective can seem harmful for the world itself.

The trade-off that arises in this situation is trivial to see but tricky to solve: a much more "energetic" world, that at the same time look for a lowering of the emissions and pollutants producing the same energy. The solution, despite not universal, but in some sense the starting point, is the concept of efficiency applied to the energy world; energy efficiency can help to move toward the right direction in terms of a sound and wise economic development.

1.1 Energy consumption

Generally, when taking about countries, the concepts of energy efficiency and consumption are related: the energetic intensity of a country is often used as a proxy indicator of energy efficiency. This is an approximative measurement of the energy required to satisfy energy services demanded, and moreover, this indicator is easily available and can represent a comparative measure across countries (1). This does not imply a perfect correspondence between an efficient use of energy and a low consumption of the same, but all in all, is the best measure as a first estimate to compare international and national situations.

To clarify what is the situation about the final consumption of energy all around the world and the paramount importance of the industrial sector in the global sectors scenario, two key statistic follows. First of all, the global trend of consumption is going to increase by 49% in the horizon 2011-2035.
Dealing with the consumption, the IEA statistics gives a primary classification of OECD countries and non-OECD ones. The former are members of the international organization of economic studies, that are developed countries with a common democratic government system and a market economy. In this sense, there is a network they are embedded in, for the ongoing development of policies (both local and international), commercial practices and resolution of common problems. For the statistics, tons of oil equivalent are used as unity of measure.

As the pictures below show, OECD countries were responsible for most consumption until 1974. In the 2015 the situation is deeply changed: despite a higher consumption of OECD countries, (2810 Mtoe vs 3619 in 2014) their share in a global perspective is lowered by a 21,9%, mainly due to the industrialization of the China and other Asian countries (mostly India, with the only negative trend of Japan).

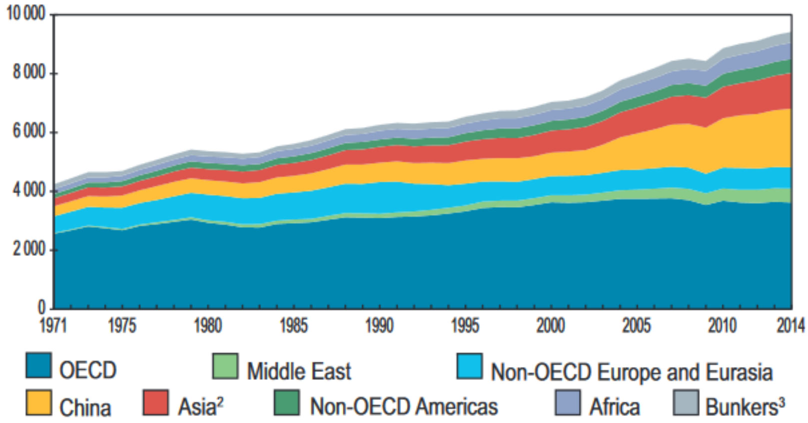

Figure 1: World total final consumption from 1974 to 2014 by region

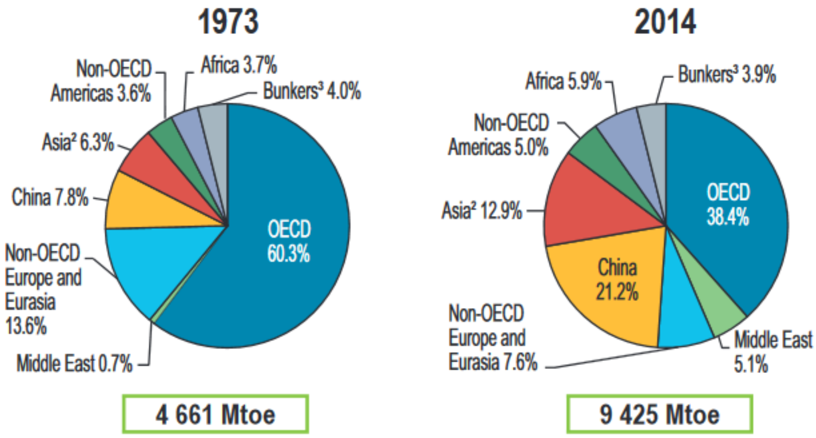

Figure 2: 1974 and 2014 regional shares of total final consumption

Generally, classifying energy by sectors, provide four main groups:

- Transport;
- Residential;
- Services;
- Industry;

In this sense, the second key statistic to note, is the consumption trends on the perspective of the sectors involved: a sectorial consumption gives a comprehensive review of how the energy is delivered and what is the consumption by fuels. On a global perspective, the industrial sector owns the 29.2% of the total consumption, with coal having the biggest share, being comprehensive of peat and oil shale; shares of natural gas and other types of fuel are very high for this sector as well (others comprise heat, solar, wind, trade electricity and geothermal sources).

SUPPLY AND CONSUMPTION	Coal[1]	Crude oil	Oil products	Natural gas	Nuclear	Hydro	Biofuels and waste[2]	Other[3]	Total
TFC	**1075.42**	**17.57**	**3743.64**	**1419.98**	**-**	**-**	**1151.86**	**2016.21**	**9424.69**
Industry	858.49	6.80	294.67	548.54	-	-	193.52	849.15	2751.17
Transport [5]	2.86	-	2426.33	97.90	-	-	73.89	26.04	2627.02
Other	155.39	0.18	424.53	613.41	-	-	884.45	1141.03	3218.98
Non-energy use	58.68	10.60	598.11	160.13	-	-	-	-	827.52

Figure 3: Simplified world energy balance table

More interesting in our perspective, are the shares among the IEA counties[1]. IEA members should have some prerequisite, aiming at the easy coordination of members' energy policies to ensure stability of energetic sources procurement to sustain economic development. In the last years, efforts are being made also for sustainability goals.

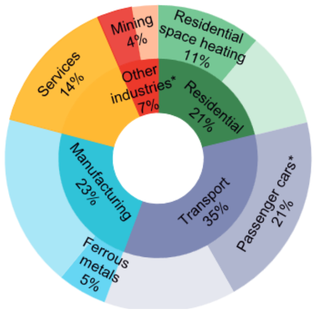

Figure 4: IEA shares of energy consumption by sectors

On this scenario the global industry shares are higher and reach the 30% of the total consumption, being outclassed only by the transport sector.

In parallel with the energy consumption, the world is going to became more and more efficient: the energy intensity (that, by definition, is the consumed energy for a GDP unit) trend is going to decrease by 1,8% on average each year in the next 20 years. The first reason behind this trend, is the increasing of many resources price level, running towards market logic aiming the adoption of innovative solutions for the efficiency. The prices in the last years have been influenced a lot by many regions in the world, giving much more importance to solutions in substitution or reduction of consumption (2).

1.2 The importance of energy efficiency

Efficiency is quantified as the output delivered by a process over the input needed to produce it; a lot of terms influence these values, that can be expressed in purely economic terms or in heat equivalent units with reference to energy measures. In this latter case, the problem of quality of energy arises, since not all forms of energy perform in the same way (3).

[1] To be a IEA member country, is necessary being part of OECD nations. However, membership of OECD does not automatically result in membership in IEA: Iceland, Slovenia, Israel, Chile and Mexico are OECD currently non being part of the IEA (the last two are candidates for the membership).

Energy efficiency, as defined by IEA (4), is the thrust for changing in policies and practices approaching the energy world. In the 450 scenario[2], indeed, is necessary the change in the decarburization and in the level of energy efficiency improvements implementation velocity.

Subsidies for the fossil fuels are a smaller fraction of the total energy research funds in the planned 2015-2030 horizon, giving the signal that the policy is shifting the objective in a future perspective, investing in research and development plans. The new allocation of investments has a cumulative amount of investments for procurement of energy reaching 44k billions of US dollars, which shares are 60% in extraction and production of oil, gas, carbon, and the 20% dispatched in renewables. An additional amount of 23k billion dollars is necessary for the enhancement of energy efficiency. Just thinking on the 2000-2015 period, where more of the 70% was accrued by fossil fuels, this represent a net reallocation of capital, moreover considering that for the renewables cost, is expected an ongoing decrease along years (4).

Step forwards for a faster spread diffusion of energetic goals was also planned in the Junker plan in EU28 (EFSI), that aims to overcome the present market barriers in energetic terms by addressing market gaps and mobilizing the commitment private investments. To cope with sustainability goals, low carbon competitive economy is set up for the economic development, since it leads to lower energy consumption, lower material consumption, lower pollution and emissions as well.
Pushing frontiers of technology and knowledge put the contact between the energy consumption and efficiency with the industrial sector that will be the one of our interest, for the high potential of savings that, at the present, can widely be improved.

To clarify the concepts, in the next two paragraph the attention is moved on on the importance of considering the industrial sector.
Moreover, dealing with energy efficiency concepts, they are supposed to be crucial to the strategic governance of any country or region; this implies a deep knowledge and

[2] which assumes that strong policy measures are implemented to keep long-term greenhouse-gas-induced temperature changes to 2° Celsius

application of policies tending to stimulate the technical progress and speed up the technological learning processes (5).

1.3 The importance of the industrial sector

Heterogeneity of industrial sectors is a key factor to analyze when thinking on the common solutions for the diffusion of Energy Efficiency Measures, especially in that enterprises that face problems of low adoption. The medium-small enterprises, face the lack of standard procedures and have the additional problem of misfits in internal competences to walkthrough a sound decision-making process. The light, nowadays, is not shed enough towards the energy efficiency measures; this happens for the difficulties in quantifying in real terms what energy efficiency is potentially able to provide. Many studies have been performed along the years for the energy efficiency potential adoption and actual use, giving attention on the gap between the two (3), and as consequence, in the last years, the attention has been given to the need for a new taxonomy in defining the market barriers of energy efficiency and main drivers to focus on for the spread diffusion of such measures.

Energy is the “air” for industries, whose lungs are the indoor processes of the enterprise itself, that through transformations can generate goods or services, but anyway a tangible output that ensure its survival or success on the market. Markets are extremely dynamic worlds, where the needs of end-users are drivers for a facility, and not the other way, both in technological and in energy efficiency use terms. This reversal of perspective from a facility to a consumer point of view was clarified more than 20 years ago from Eric Von Hippel, that gave a new framework for the development of innovations.

1.3.1 *The industrial sector in Italy*

Industrial sector in Italy is highly diversified and the presence of Small Medium Enterprises is spread all along the Peninsula, whose share exceeds the 99% of the total, employing more of two thirds of the workers in the non-financial business economy (6).

In the international energy efficiency picture, Italy represents a good example, having -14% of primary energy intensity with respect to the average in Europe in 2010; this led to the recognition by the ACEEE[3] as the third country in the national effort for the enhancement of energy efficiency levels (7). These data are in conflict with actual problems faced by the country in in economic terms, because of the scarce competitiveness due to high energy prices and the high dependence on importations (7).

Let's now take a look on the Italian energetic consumption and on the SMEs characteristics.

1.3.1.1 General outlook of Italy consumption

Italy objectives in terms of energetic goal are to exceed the EU 2020 environmental and decarbonization objectives and to have a leading role in implementing the EU roadmap 2050 (2).

Step forwards in the energy policies have been established since 2013, when the development of the National Energy Strategy was the result of a debate between the energy sector and the interested stakeholders. The NES set the goals in terms of reduction of energy costs, meeting of environmental targets for the emission reduction, increasing of renewable sources and energy efficiency.

The actual consumption, in terms of total final consumption for energetic use is 116.6 Mtoe (7). The major share is given by the heat consumption (final use of energy for environmental heating and cooling) which represent the 45% of the total, followed by the transportation with the 32%. From the sectoral point of view the transport represents the highest part of the total being followed by the industrial sector, with a share exceeding the 25%. In the picture, the cross-diagram with sectoral and gross final use of energy in Italy.

The Small Medium Enterprises consumptions, which specific features are showed in 1.3.1.2 section, are showed in the following table.

[3] American Council for an Energy-efficient Economy

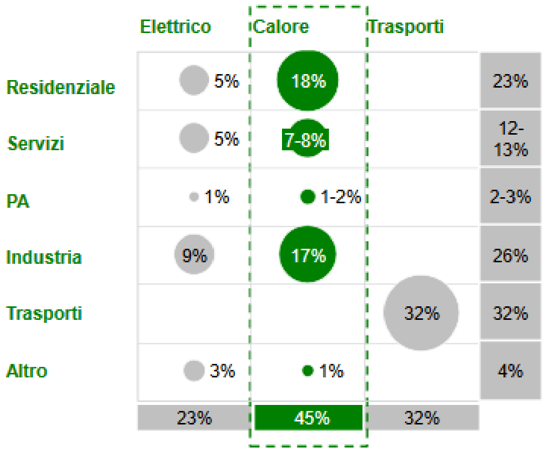

Figure 5: Shares of consumption of Italian SMEs. Evidence of sectors and energetic source

From an energy efficiency point of view, the Italian situation is quite comfortable, being one of the first countries for energy intensity in Europe, with a level 14% lower than the average consumption. Consider also, that these results are obtained even though the manufacturing sector has a higher weight with respect to the Europe average.

The macroeconomic indicator of energy efficiency is the energy intensity, which has a very good value for the nation. Indeed, is one of the lowest among the IEA members with a value of 0.08 Toe/USD PPP[4].

The attention to the energy efficiency topics has been increased in the last five years, also thanks to the energetic audit diffusion, compulsory for big enterprises and high energetic consumers. The 80% of enterprises prefer to undergo with internal intervention in 2016; the low percentage to external investment origin from mistrust of external experts and willingness to protect the internal know-how, when the efficiency measure is related to the core processes and may threaten critical processes (8).

1.3.1.2 Small medium enterprises

What is clear from general insights about industrial world, but sometimes is not taken into account at all, is that the majority of the enterprises are Small or Medium in size. They

[4] The energy intensity is measured as the ratio between the Total Primary energy Supply by real GDP adjusted taking into account the purchasing power value.

involve more of the 99% of the total of enterprises both in the global perspective but in the majority of the national frameworks as well, being Italy one of them. As consequence, this sheds the light on the energy use perspective, but also for economics terms and as drivers for innovation.

From the high amount of enterprises embedded in the national panorama, some diversifying characteristics of SME are advised, and a prior classification can be performed on the energy-use: ranging from non-energy intensive companies to the energy-intensive ones (usually manufacturing plants fall in this category), which threshold is defined as the energy costs not above the 3% of the added value. The SMEs are, by the definition provided from the EU Commission, enterprises employing less than 250 people and with an annual turnover that is not exceeding 50 million €. A classification based on the number of people involved ranges from 10-49 for the small enterprises, 50-249 for the medium.

In the analysis, the focus will be towards the SMEs, basically because industrial SMEs face extensive challenge in improving their energy efficiency, due to the lack of knowledge and deep structural practices of energy management, as well as a lack of resources. On our perspective, we can argue that the SMEs are an easier target for industrial energy program rather than wider industrial contexts, just because most of the energy consumed by SMEs and in non-energy intensive industries will be probably used in support processes.

The steps for an effective change in the way of facing energy problems in an industrial contest, especially in these smaller realities, is to implement energy audit programs (5). These programs are systematic, documented and periodic procedures to undergo for the improvement of organizational procedures, that can be performed by internal and external figures to the firm adopting them. Along with being the means for achieving the UNI ISO 50001:2011 certification, the results on adoption of sound engineering procedures with the audit permits the individuation of intervention for technological retrofits, and a preliminary technical-economic feasibility study. This means that the audit is of utmost importance for the SMEs in understanding and overcoming some of the barriers hindering the measures for their improvement in energetic terms.

What is lacking usually the SME is not the energetic audits information source, but the continuity of their communication process; simple methods as reminding of simple routines or energy use procedures can produce good results in the long-term run (5).

1.3.2 *Process and cross cutting technologies*

Since the industrial world is widespread and heterogeneous, a comprehensive view on energy efficiency in the Italian industrial sector seems impossible to outline. Remaining in the industrial sector, the only way to cope with this methodological issue, is to arouse the interest toward homogeneous sources of energy (that are common to the most of industries): the solution was found in the cross-cutting technologies, that are not directly linked to the production process (or at least not exclusively) but on the surrounding services.

As consequence, an analogy may be found on the consumption in non-residential sector, in which are encompassed the buildings providing services, commercial area and public administration.

One may think that this is worst solution, since this method is not comprehensive for the major part of the intensity used in energy; this is even worse talking about energy intensive industries[5], where a high amount of energy is used to feed production processes. So, why to undergo with such analysis, considering only some percentage of the energy produced by companies? The answer is that, being the core processes part of the production, is quite obvious that the energy efficiency efforts are already done, leaving very few potential enhancements of the current situation. In reality, the support processes may be implemented at an operational level, while the production process related are more dealing with a strategic activity, thus a different type of effort is required, as highlighted by the study of Thollander (5).

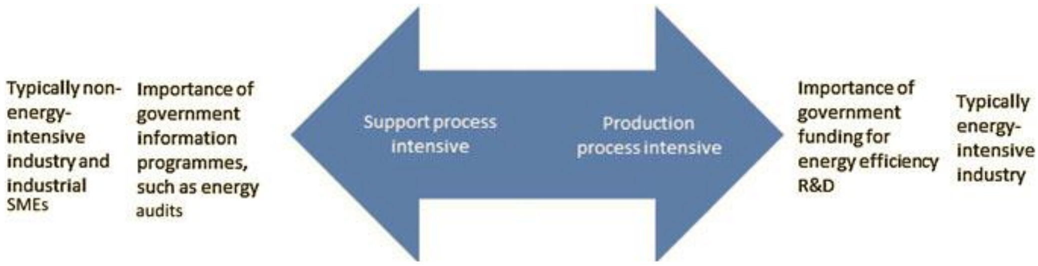

Figure 6: How energy efficiency measures are dependent on whether they apply to a support process

As evidenced by literature studies (6) (5) a thorough energy management procedure should encompass the usage of energy that is not linked to the core processes but that, in any case

[5] Energy-intensive are defined as companies in which energy costs exceed the 2% of the turnover

have an influence in terms of energy consumption and for which one may find the greatest potential for energy savings.

The most common support processes are revealed to be:

- Electric motors;
- Compressed air system;
- Lightning;
- HVAC Systems

The spread of such EEM depends on the type of industry and is revealed to be easier in the non-energy intensive ones.

1.3.3 *The relevance of Compressed Air Systems*

Among the four aforementioned systems, the electric motors are of course the major source of potential since the electric power is widespread in industry and a very high amount of electric power is used to fed motors. In any case, the literature has many studies that give a comprehensive view of the situation, being defined the efficiency classes under an international standard (IEC 60034-30:2008), for the substitution of all national systems (9) as well as studies on efficiency measures and policies to apply (10) and a development of a framework to understand the factors hindering measures of energy efficiency in that systems (11). On the other hand, the HVAC systems were approached both by simulation tools studies (12), (13) and theoretical manuals (14). Lightning systems does not need a comprehensive systemic view because, despite owing high potential for energy savings, the reasons for low implementation are not related to the low awareness towards the technology.

For this reason, the work aims to give attention to cross-cutting technologies that have high potential for savings and low adoption rate. Compressed air systems have electric driven power[6], and have the highest potential for the implementation of efficiency measures, because they are not implemented as expected. The low adoption rate is investigated in the

[6] The driver of the air compressor is electric, as well as the pumps and refrigerant compressor used to the heating and cooling cycle for a comfortable environment, or the centrifugal fan's source. Refer to Chapter 2 25for further details.

study of Cagno and Trianni on the barriers hindering the adoption of energy efficiency measures. This exploratory study in cross-cutting technologies barriers (6), gives a strong connotation to some barriers for the compressed air. This system seems to have slightly less investment problems with respect to electric motors, but the issue of implementing the interventions without any external support is the most influential problem arose. The awareness and investment costs are revealed to be the second and third in importance.

1.4 Efficiency and consumption of selected technology

After the introduction of the selected system under the scope of this study, is important to clarify the importance of efficiency opportunities for the retrofit/substitution of equipment, as well as organizational and best energy practices. Energy efficiency measures are an ongoing effort in the industrial contest because of the dynamic nature of the technology, because of the lesson learnt from previous efficiency measures and last but not least for the price changing in time.

Compressed air machines can be characterized basically with the introduction of 3 indexes, that are:

- FAD (free air delivery) that gives information about the flow rate at reference conditions of 20° and 0,1 MPa for the pressure;
- Power of the compressor, that indicates the nameplate rating of the driving electric motor;
- Relative pressure (difference) with respect to a reference usually indicated as the atmospheric pressure; the pressure ratio from output to the input is used in some cases, though.

The second index of course is the one used for the consumption information, referring to the electric power taken from an electric source.

The estimates give a total compressed air consumption of approximately 80 TWh in EU (15), and the potential savings coming from an EU study were supposed to be more than 30%. The market of compressed air systems is almost stable in Europe with a growth from 1 to 2% per year and Italy have the third higher stock in Europe with a total amount of more or less 200 thousand machines (excluding piston compressors of little dimensions) with a total energy consumption of 16 TWh/year (16).

Compressed air is chosen for a series of reasons, but owns a high not exploited efficiency potential in the industrial context. The compressed air, known as the fourth utility, owns some characteristics that may, at least partially, explain the low adoption rate:

1. It is used mainly as a service;
2. It's not a productive output;
3. It's present in almost all the production industries (17);

Radgen and Blaustein (18) recognize the importance of the subject. The energy saving interventions are considered as more convenient with respect to others industrial investment, but compressed air related measures have low rates of adoption for organizational and cultural reasons; this are mainly three for the authors:

1. Lack of a specific cost item for compressed air, that makes invisible to the eyes of top management the share of compressed air consumption over the total amount;
2. Lack of awareness on the available savings because the top management is usually not aware of the possible saving in compressed air systems, despite the investment decisions are in charge of him;
3. The complex management structure, or the lack of enough fit for a decision to be taken on optimization measures, even though this problem can be reconducted to the first one, because of the responsibilities that are not clear for a low-priority item as compressed air.

Summarizing, the fact that the compressed air is usually a low interest utility, not being part of the production process, influence a lot the behavior towards its efficiency potential, further lowered by the lack of a specific cost item for compressed air services. The fact that some firms have no idea of the impact of the utility over the total energy expenditure, is a clear synthesis of how much attention is revealed to this item.

1.5 Objective of the research study

Since the importance of the energy use and consumption in industrial sector, the compressed air systems are a major source of potential efficiency, attractive for the high potential with relative low effort. The low adoption rate of efficiency measures spread all over the industrial sector for this utility is mainly attributable to the three characteristics mentioned in 1.4. The problem that arises at this point is related to the reason why the interventions are not implemented, and how, through literature and empirical research, is possible to cope with this problem, creating an ad-hoc tool.

The solution is a thorough analysis of intervention with respect to contextual and industrial characteristics, to see how they work; this implies:

- Analysis of singular efficiency measures (Chapter 3);
- Giving a relationship with all the possible outcomes in an industrial system and implications on and of the surrounding environment, with the creation of a framework, useful to approach easily the adoption of compressed air related efficiency measures.

To obtain this final result, all this information is brought together in a synthesis tool, able to shed the light to all the factors to take into account when a decision for the enhancement of efficiency in the CAS is going to be implemented. This tool will be able to make the awareness rise on possible criticalities and primary elements that are consequences of the implementation, as well as to trade-off the informative gap with technology suppliers or external experts in charge of installation of efficiency measures.

System description in Chapter 2, explains how and why the components of a compressed air system are present, to understand how they are interrelated and connected to each other. The following chapter is about the analysis of the single efficiency measures and how they affect the system once implemented. The fourth chapter explain the reasons behind the building-up of the model and the framework characteristics, with a brief introduction on decision-making process, followed by the literature review to understand how the reasons behind the factors choice and the complete description of the framework. The last two chapters are oriented towards the explanation of the research methodology and the validation/application of the model. The theoretical validation of the model is performed thanks to the industrial literature, the empirical part of the research study is addressed thanks to the case-study methodology, with personal and phones interviews. The discussion of findings outlines all the emerging aspects and final results of the research, both with a theoretical and the on-field validation.

CHAPTER 2
Compressed air system: technology overview

Thinking on compressed air, it's very difficult to find a product or task, for which has not been involved at some stage; some typical application in industries (manufacturing) are the supplying semi-finished raw materials, both for heavy products and light products, approaching the side of industries for end-user products, as well as in the packaging and processing of consumer goods (19).

Being the air freely available and due to its easy procurement, is usually treated as cost-free. Despite this belief, usually, most of energy costs in an industrial environment comes from the compressed air systems. This widespread misconception about inexpensiveness, most of times is translated to a poor focus on the efficiency practices and on the optimization of compressed air systems i.e. energy savings aspects are seldom considered in the design phase.

One typical situation concerning problems with the optimization, is showed up immediately in a decision for the purchase of a compressed air system[7]. In the design phase, one should look for the best compressors to install depending on the actual capacity of a system, nor more, neither less. This seems quite obvious, but most of the time, one firm can install a higher capacity with respect to the one required by the actual demand needs, just as a proactive measure from the possible future expanding capacity of the firm itself. Unless the expansion in not already designed and truly planned, this lead to a present part-load utilization of the machines, that has the consequence of higher energy consumption. Energy consumption is indeed of utmost importance in this kind of system, classified as "energy intensive", because of the high power required for the output provided. In these processes, the major cost of the system along its lifetime is the energy use (73% of the total cost during the mean lifetime) (20).

The widespread diffusion of the technology is brought by a series of factors: the ease of handling, the great safety, being sometimes preferred to hazardous environments for their low flammability, and the relative ease maintenance procedures.

[7] Acronyms CAS

As indicated from data available in industry facilities (21), such systems should be used only if there are some additional benefits, such as safety enhancements, productivity gains or reduction of labor due to high energy delivery cost.
The costs from air compressors but also dryers and support equipment, can represent up to the 90% of the total electric bill (in process industries, the percentage are significantly smaller in companies in which compressed air is solely used as service).

2.1 Generation of compressed air

Compressors are the principal components of the system. They are operating machines; this means they receive a mechanical work from the crankshaft and they provide a positive work on the fluid inside a compression ambient (can be a chamber or a different path). This work is needed to pump up the pressure level from the inlet value to the outlet one.

Two different types of fluid compressors exist: dynamic and positive displacement.

The compression is dynamic when the air is introduced on an impeller of the compressor for its acceleration, and then is performed the energy transformation from kinetic to pressure through the diffusor component. These systems are known as axial or radial turboblowers, depending on the pattern of the fluid inside the chambers. Positive displacement compressors include different types of compressors, whose utilization is for different field of applications; they usually are used for service in industrial sectors. The air is initially drawn in one compression chamber (single chamber compressor), which is insulated from the inlet through the aid of a valve. The volume of the closed chamber is then decreased (the method for compression determines the type of compressor) and the air is compressed. The pressure must overcome a limit to permit the triggering of the outlet valve, ejecting the compressed fluid thanks to the reduction of the chamber's volume.

The key characteristic of a general compressor is the pressure ratio, defined as the quantity that relates the absolute pressure on the inlet and outlet side. Commonly, the air aspiration occurs at atmospheric pressure (1 bar), so the pressure ratio is basically the outlet pressure itself[8].

2.1.1 *Dynamic compressors*

These compressors generally are in the radial or axial configuration. The latter, in reality, can be classified as a sort of mix of them: the air arrives axially and then the flow within the compressor is radial. Axial compressor has more stages in series; on the other hand, the radial and centrifugal can be mono-stage. These types of compressors are treated for the sake of completeness, but notice that no any application for services entail this configuration, used for process industries and in general high-power applications.

2.1.1.1 **Axial**

This compressor works thanks to the air passage along the compressor shaft through a sequence of rotating and static vanes. The internal rotor is longitudinally extended depending on the number of stages, with decreasing dimensions in the horizontal direction thanks to the higher air density in the internal stages. The axial stress is counterbalanced thanks to a cylindric part that equilibrate the stress distributing it.

With respect to their centrifugal counterpart, these compressors are generally more compact in dimensions and lightweight, and their rotational speed is much higher. The volumetric flow rates are large but constant, but the pressure ratio is maintained to a quite low level e.g. in ventilation plants. Since the rotational speed is that high, they are usually combined with gas turbines for the generation of electric energy or as propellers of aircrafts. Typical values for the flow rate go from some m^3/sec up to 600 m^3/sec. The number if stages can be very high, reaching a total compression ratio of 16/18 (22).

2.1.1.2 **Centrifugal**

The air is accelerated by stages of impellors; more stages are required to work at the right operating pressures. Despite the low installation costs, they are expensive for the tight tolerances required in the mechanics.

[8] This is simply a rule of thumb; in reality, the intake pressure depends on the drops by the passage through the intake filters, and on the altitude.

These compressors generally have a lower stage pressure ratio (no more than 3) for the maintenance of a quite high stage efficiency that otherwise will drop dramatically; for this reason, in high-pressure appliances there is the presence of more radial stages or, more commonly, multiple single-stage compressors set in series. In this compressor, is advisable a very high rotating speed of the shaft compared with the one of other types of compressors, up to more than 100.000 rpm.

This lead to very high axial dynamic forces, that are balanced mounting two different impellors at the sides of the shaft, whose rotation is allowed with plain oil bearings (or air film is they are oil-free).

Application example: single stage application for the centrifugal is the one in the wastewater treatment plants. Multi-stage applications of the same compressor allow the possibility of inter-cooling to reduce the power requirements from the crankshaft. Single stage compressors in series are present in the oil and gas process industry.

2.1.2 *Positive displacement*

Different types of positive displacement air systems exist, and their characteristics influence the energy consumption, the efficiency of the compressed air and the potential global efficiency of interconnected systems.
Analyzing the types of compressors, we will focus on the piston compressors (reciprocating ones), one single rotor and one double rotor, and one type of dynamic compressor.

2.1.2.1 **Reciprocating (piston compressor)**

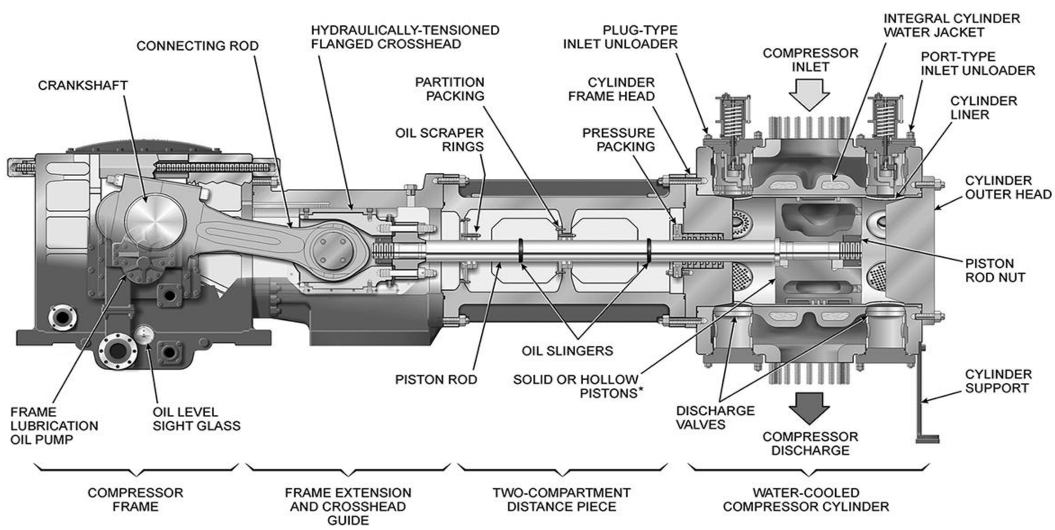

Figure 7: Reciprocating compressor components

This compressor is the most common as well as oldest compressor commercially available. Generally, the configuration can be single-acting or double-acting depending on the active strokes of the piston. The V configuration is the most common although not the unique configuration for small compressors. The large double-acting compressors have an L-configuration design. Oil-lubrication might be present, and the valves on the compressor are usually self-acting i.e. they activate automatically when the valve ends feel different pressures.

By means of an electric motor, there is the movement of a crankshaft, leading the piston stroke of the reciprocating compressor. They are used for general purposes and they're commercially available in a range if powers from 0,7 to more than 22 kW (1-30 HP). They are not so used in industrial sectors with the exception of automation systems and large reciprocating compressors in specialized processes such as high-pressure application. The major use of this type of compressor is for the supplying of air to the building control.

2.1.2.2 Screw

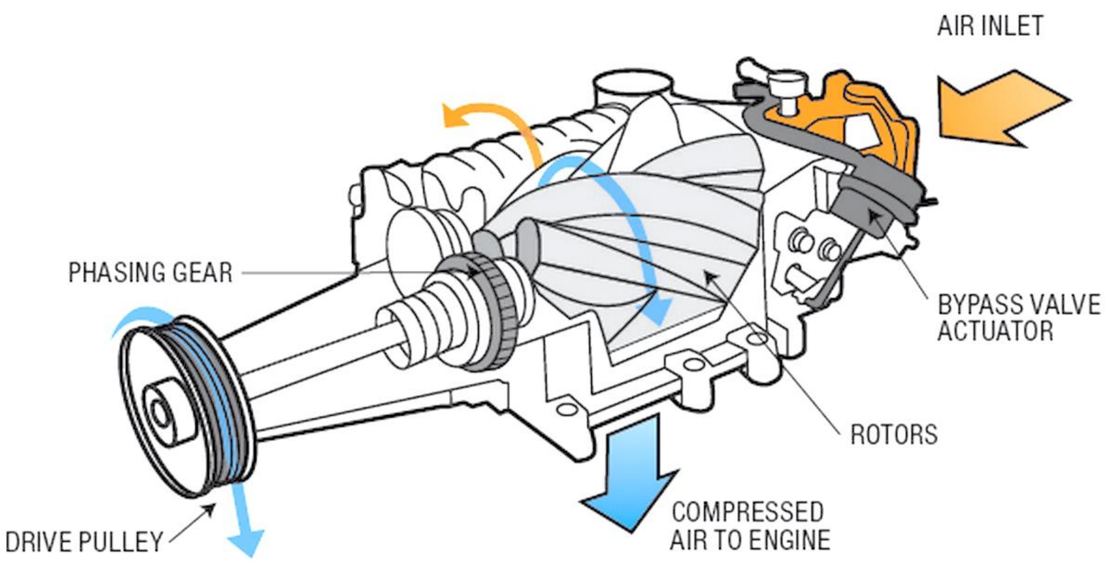

Figure 8: Screw compressor components

They are the main alternative of reciprocating compressors, having gained from the 80's a gradually increasing popularity. Nowadays are the leader compressors in the industrial market.

The first screw compressor was designed in 30's, when there was the requirement of high flow rate and stable outlet flow under different pressure conditions. Their main use is the industrial sector (general purposes), since their compactness and the steady-state running, that in general involves little vibrations, avoiding the use of one or more spring suspensions.

Basically, there are two parallel counter-rotating rotors, a male and a female one, that are independent from the point of view of the build-in pressure ratio (depends on the shape, length and discharge gate). Of course, from an efficiency perspective the required working pressure should be maintained in the discharge of the compressor. No any valve is present, and the only support force is needed by the bearings in axial direction.

Depending on the characteristic rotational speed, the higher frequencies vibrations are absorbed by rubber mounts. The size of the system ranges from 280 l/min up to several dozens of thousands l/min. The flow rates involved are the compromise between the reciprocating compressors and the centrifugal ones.
The most common type is the helical twin, screw compressor, where the two parallel rotors turn the helical screws, trapping the air in a decreasing size channel, enhancing the fluid pressure. Depending on the requirements of the final use in terms of air clearance, this type of compressor is available as lubricated or oil free type.

Lubricant injected rotary screw: This type of rotary screw compressor is the most used in industrial applications because of the compactness and versatility.

The main purposes of the fluid injection are basically two: the sealing of the compression chamber to the rotating parts and the provision of a sink for the cooling of the flowing fluid. The lubricating fluid is separated from the discharge stream, then cooled, filtered and recycled along a fixed guide. Most of the separation of lubricant and air are directional and speed changes, the remaining part are dropped out thanks to the coalescer or filter vessel that permits the separation from the gas (oil absorbs non-polar particulates of the gas). Despite not perfect, the mechanism permits the reduction of lubricant presence in the compressed air to few ppm[9]. Despite the lion's share is composed by oil-lubricated compressors, there is also the presence of water or polymers.
Since the sealing and cooling are increased, this permits high compression ratio from this type of compressors: a single stage can withstand to 14/17 bars in most extreme situations (at the expenses of the efficiency), but 8 or 10 bars are not infrequent.

Dry Type Rotary Screw: in this case the oil is not present at all within the mechanism. The main drawback here, is the possibility of handling lower maximum discharge pressures. On

[9] Parts per million

the other hand, there is the possibility of putting a series of compressors, giving as result the so called "multi-stage oil-free compressors", where the pressure reaches 10,13 bars (10 atm) and a maximum output flow rate that can reach 57 m^3/min. The main usage of this type of systems are atmosphere where is not permitted at all the air contamination (manufacturing of semiconductors or medical field). In any case some filters are present as well, due to the presence of contaminants in the environmental air itself.

2.1.2.3 **Vane**

This compressor is composed by a stator and a rotor, where the latter has an eccentric housing. The vanes are mobile and thrust the air all around the space within the mobile and fixed parts, forcing it to be compressed. When the distance between the rotor and stator is increased, air is drawn into the volume and then captured different compression chambers created from alternating moving vanes. The rotation makes air to be compressed until the way out is reached.
This type of compressor has not a very high air quality[10] but anyway better than the screw compressor. The major problem associated here is the limited range of capacity, so the compressor is not indicated for fluctuating air demand.

2.2 Control and regulation modes

Air requirements are quite variable during the time and for this reason there is the necessity to operate not always at full load, in order to vary compressed air production depending on needs. The efficiency of the system is determined on the quantity of air saved when not needed and on the promptness of changing of load over time i.e. an efficient control flow at part-load is required.

Based on the system took in place and on the control selection we can deeply affect the overall system performances, and the energy efficiency as direct consequence.
The strategies for the control of flow are plenty, depending on the compressor type, acceptable pressure variations, air consumption variation and acceptable energy losses.
The most common types of control follow.

[10] Air quality standards are defined by the ISO 8573-1: 2010

2.2.1 *Start/stop*

This is the simplest way of control for compressors. This method cannot be applied on vane compressors. Basically, the electric motor driving the compressor is turned on or off in response to the downstream pressure (discharge pressure) of the machine. For large compressors, problems in managing the pressure fluctuations may arise. Moreover, if the starts and stops are too frequent and repeated, the motor tends to overheat; this lead to issues as well, but above all the stricter maintenance need on components. For this reason, the method requires a large receiver or large pressure difference between threshold limits, for the minimization of the heat load on the electric motor. Due to transient problem for the running up period, the compressors involved usually range between 5-10 kW.

2.2.2 *Online/offline*

Often known also load/unload, keeps the motor running, but unloads the compressor only when the discharge pressure is high enough; this result in a discontinuous pattern in the pressure within the compressor. They consume in the range between 15 and 35 % of their full power load, while producing no useful compressed air output. The storage of the associated receivers should have a capacity high enough to permit an efficient part-load operation.

Pressure variations depend on the number of load/unload allowed, but in most of cases they address a range between 0,3 and 1 bar.

2.2.3 *Modulating control*

Modulating control is a variation of the output to meet the flow rate requirements by adjusting the position of the inlet valve, resulting in air restrictions to the compressor. The drawback with this type of control is that the full modulation leads to high consumption even for zero flow conditions. To reduce the amount of energy, the control can be activated or not.

This control is allowable uniquely for oil-lubricated screw compressors, and is the least efficient way to control compressors, for this reason is today out of use.

2.2.4 *Variable displacement*

Variates the output capacity thanks to valves, acting with their displacement in the variation of control volume. These valves are called spiral valves and are acted on the rotary, oil-lubricated, screw compressor. In this case is not necessary a variation of load or the starting/stopping of the compressor and the efficiency is high over the 60% load. Below this value a proper unloading control can reduce significantly the power consumption.

2.2.5 *Variable Speed Drive*

This control method responds to changes in air demand with the speed variation of the electric motor (read compressor shaft), changing, as consequence, the flow rate.

A normal AC electric motor works with a fixed speed, obtained from the frequency of supplied energy. The VSD technology addresses the conversion from fixed voltage, fixed frequency AC in variable voltage, variable frequency AC. The converter, filter and inverter boxes operate this transformation, with very little energy losses; the efficiency is in the 92-95%.

The integration of the VSD with an existing motor has revealed to be a very important recent evolution of the technology, with more affordable installation costs and elimination of problems connected to electromagnetic interferences.

Is usually implemented in packaged rotary screw machines, allowing the perfect matching of variation by demand side. When the air load drops out to a minimum value that will require a too low speed, other types of control such as load/unload or start/stop activate. This control mode is usually the most efficient way of reacting to a change in demand, despite the high purchasing price (of the overall equipment). A strategy to cope with a highly varying demand is to use multiple compressors, where one or more fixed speed supplies the base load, and a VSD will help in matching the variations in time. The energy consumption of this device is usually directly proportional to the speed of the compressor itself; this means more energy savings for partial load situations. The only drawback in terms of energy consumption is on full load situations, with a slight higher consumption with respect to the traditional fixed speed drives.

2.3 Air treatment units

A lot of auxiliary equipment is needed for such systems, constraining the application in situations where there are no space problems. Indeed, we have the presence of compressor aftercoolers, filters, separators, dryers, heat recovery equipment, lubricators, pressure regulators, air receivers and drains.

2.3.1 *Dryers*

Downstream the compressor, the air is normally at higher temperature with respect to the ambient, and the after-cooler gives a very high relative humidity. If such air enters in the distribution pipes, likely, will happen the condensation throughout the line with related problems of corrosion and contamination at the point-of-use. To avoid this annoying situation, the presence of an air dryer is the minimum requirement for every compressed air system.
The temperature and the degree of humidity of air depend on operating conditions, as consequence different dryers have different characteristics.
For instance, operating in a very cold environment, we need the dew point of air being lower than the ambient conditions to avoid any ice formation. In a warm environment (higher than air flowing away the aftercooler) since the dew point increase, we have not such issues. Throughout the dryer we have a pressure drop from 0,2 to 0,35 atm and higher drying degree entail a higher pressure drop, so from an energy efficiency perspective the ability to drying up and no more than the required dew point is necessary.

2.3.1.1 **Refrigerant**

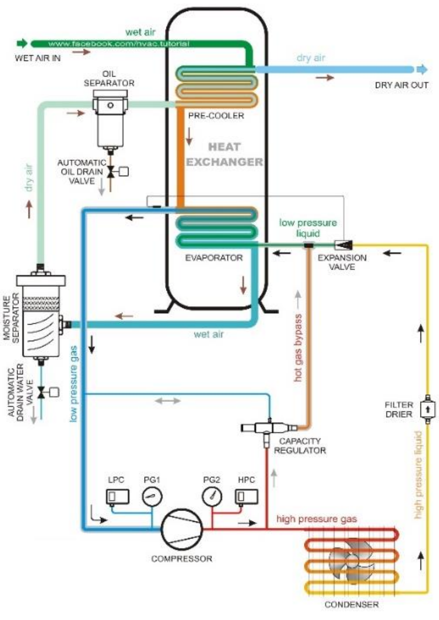

Figure 9: Schematic of the refrigerant dryer

The goal of the dryer is to reach a low humidity in the air stream. To do this, the air is cooled down by a closed-circuit refrigerant. Basically, the energy required for the cycle working principle is that of a compressor driving the fluid. The air can be pre-cooled eventually with the outlet of the dryer air, that is cooler; this gives two different benefits: the amount of cooling power by refrigerant is less and the outlet air is increased to room temperature, avoiding risk of condensate formation outside the tubes of the end-use-point. Refrigerant coolers are of different types: as an example, there is the glycol-water mix that own some advantage with respect to the use of pure water as a coolant. Indeed, the mix is able to cool down its temperature to 0°C without freezing, but we have a tradeoff because the thermal capacity is lower than the water-cooled; for this reason, the thermal capacity of the mix is lowered. Variable speed refrigerant dryers use electronic devices to adjust the drying capacity on the system demand; this entail a good part load efficiency.

2.3.1.2 **Desiccant (adsorption)**

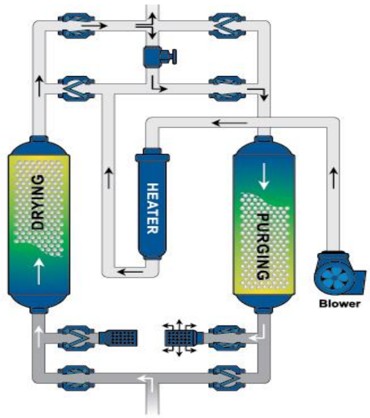

Figure 10: schematic of an exhaust purge desiccant dryer

This type of dyers uses a porous material to dry the air. Once this material is saturated, it must be regenerated; depending on the type of material it can be used different types of regeneration. The desiccant needs to be regenerated regularly to regain the drying capacity. There are more type of dryers depending on regeneration strategy:

- Heatless: use the dried compressed air to regenerate the desiccant material, this air is called "purged air". The ongoing use of the 15-20% of the nameplate rating, is an additional cost (3-4 kW per 100cfm); for this reason, this drying method is not used for high flow rates.
- Exhaust purge: this uses a lower amount of dried air for the membrane regeneration, because of the passage through an electric heater (2.25 kW per 100 cfm). This limit the purge flow of something like the 8%, guaranteeing a 25% less energy than the heatless.
- Blower purge: a blower that blows ambient air is used instead of the compressed air, so the entire output is available for the system (2.5 kW per 100 cfm). The energy consumption as consequence is pretty lower than the heatless dryers.

- Heat of compression dryers (HOC dryers): the desiccant is regenerated thanks to the heat of compression generated during the compressor's work. Instead of heading the air to the after-cooler, in this case the air is used to regenerate the desiccant. This dryer can be used only with oil-free compressors since the lubricated one has no so high temperature to guarantee the regeneration.

2.3.1.3 Absorption

Also known as deliquescent-type dryers, these devices use the drying medium that changes its physical state, passing from solid to liquid, and as consequence, cannot be regenerated. Despite nowadays this technology is in disuse, there are a lot of chemicals that can be used for drying, the most common are: sodium, potassium, calcium and those with a urea base.

2.3.2 *Filters*

2.3.2.1 Intake filters

Inlet filters are of paramount importance as shield from airborne atmospheric particles, insects and other impurities. Should be replaced periodically. One may ensure the pressure differential to be low, for the efficiency of the air compressor as well as its output capacity.

2.3.2.2 After filters

These filters are placed downstream the compressor and their primary scope is to drop out the excess lubricant in lubricant-injected air compressors. Different filter types exist, depending on cleanliness of air required. Thin filters have the higher pressure drop on its edges; the one that ensure a minor pressure differential is the particulate filter; take care of the fact that pressure drop downstream the compressor should be avoided, because this mean the loss of part of compression work made by the unit.
Pressure losses reduction are proportional to the double of increasing capacity of the filter. When pressure differential causes an excessive energy consumption, one may think on maintenance and replacement at the right time, applying some gauge for an ongoing system performances monitoring.

2.4 Heat reduction units

2.4.1 *Pre-cooler and inter-cooler*

The coolers unit can be placed at the intake of the compressor, between stages or immediately before the dryers. Intercooling effects have the same of the intake compressor position since they place before the next step of compression; the place of the intake cooler lowers the air temperature entering the compressor, increasing the efficiency since the air density is higher at lower temperatures, permitting more air particles entering the compressor for each rotation of the rotor. The need for other types of compressor is, thus, lowered.

2.4.2 *After-cooler*

The downstream cooling by after-cooler instead has the final objective of decreasing the content of moisture in the air, allowing the dryers to work at them best. The aim is to decrease the dry bulb temperature (wet) to condense water vapor, which must be separated and drained from the system. At this point the air has an optimal value of T, and despite the specific humidity is lowered, the relative one is nearly to the maximum value. The need for a dryer after the after-cooler is necessary to have a low relative humidity of the air. IT should be located in the vicinity of the compression unit and can be water or air driven; in both cases should own an automatic drainer. The drain water is almost all (from 80 to 90%) cached in a water separator. Compressed air Temperature outside the after-cooler is highly variable but is generally in the range of 10°C over the refrigerator temperature. Most of compressors have an after cooler included in the packaged units.

2.4.3 *Heat recovery on compressors*

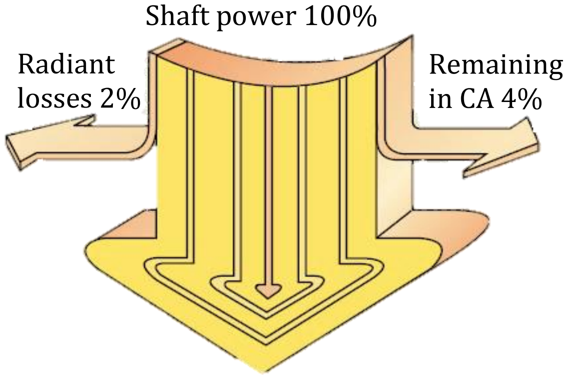

Figure 11: compressed air energy flows

From an energy efficiency point of view, defined as the output delivered on the total amount of energy consumed, the compressed air system has basically a very low ratio. In the figure is shown the strict dependence of air being compressed and the contemporary conversion of the supplied energy by the shaft of the electric motor in heat. Moreover, the system has end point applications that on average requires quite low pressure, making calculation of

the overall efficiency even lower (23). As suggested again by the figure, the energy is free of being recovered, usually in the form of hot air or water for the auxiliary services. In this situation problems arises when the point of use of compressed air, that is the same of the potential energy recovery, is far away from the possible point-of-use of the heated fluid. So, an alternative, is to sell the amount of energy produced as a consequence of the compression process to some energy supplier, when possible.
Basically there can be the presence of the air-cooled compressor system, with the hot air flow distributed by a fan and headed to a pre-heating battery or for building heating. The alternative is a water-cooled system to give a help as supplement for an existing hot water system.

From an economic perspective, the energy recovery in the compressed air installations are real and the ROI is as short as 1 to 3 years (24). Moreover, the use of energy recovery practices by means of a closed cooling system, enhances the compressor operating conditions, reliability and service life because of the lower rise of temperature inside the compressor rooms and high cooling water quality (24). A higher quality means higher temperature for the heating from the water. Depending on the enthalpic level, the air can be used for various purposes, from the heating of boiler return (60°-80°) to the hot tap water (40°-60°).

2.5 Ancillary equipment: receivers and separators

A capacity storage is required for maintaining the system stability over time, but also to maintain the required efficiency and the highest possible quality of air. Here a classification is operated between the primary or secondary type, depending on the task performed. Please, notice that the size is not unique and depends over the compression capacity, regulation system and consumer's air requirement.

2.5.1 *Primary receiver*

this acts as a general system storage of air, and its location is close to the main compressor in case of multiple compressors layout, but the exact location depends on the need upstream or downstream the clean-up equipment.

Major tasks of this components are:

1. Give a location for free water and lubricant to settle from compressed air stream;

2. Supplying peak demands from stored air without need for an extra compressor;
3. Reducing the cycle frequencies of control means to help **screw compressor** running in a more efficient way (an upper threshold is present for such motors that limit the turning on/off of the equipment to 6 times per hour;
4. Damping the pulsation caused by **reciprocating compressors**.

If the primary receiver is located upstream the air dryer, the combined flow of receiver and compressor have to flow throughout the dryer. This can cause flows that exceed the maximum capacity of the dryer.
Putting the receiver downstream the dryer, is a wise choice for the aforementioned problem; moreover, if there is a demand peak it will be ready for the use.

2.5.2 *Secondary receiver*

Secondary receivers are located in the distribution system of the facility or at the end use points, and have the protection task for pressure dips or large transient users. Moreover, it can supply the adequate stability wherever the piping is undersized for the current demand. This receiver is dimensioned according to the maximum air output. In more extreme cases, a higher-pressure compressor is used with a large receiver to meet high volume short-term air requirements.

2.5.3 *Separators*

These devices have the task of separating liquids entrained in the air. Usually should be installed after each intercooler or aftercooler to remove the moisture that is condensed.

2.6 Distribution network

Distribution network has a strategic importance in a compressed air system. It gives to the air the possibility of moving from the generation point, to the point where one should use it. The distribution system is composed at most, by piping. The piping is connected with others by mean of fittings for the directional changes or to cope for the length of the entire line.
The network path, design and dimensioning are important both for system efficiency, reliability and production costs.

2.6.1 *Piping*

Piping systems are the main volume receiver of air during the passage from the generation to the use side. They are made by different materials, depending on the application and needs. The pipe has to be strong enough to withstand the pressure. A good system design prescribes a falling pressure of no more than 0,1 bar from the generation to the point where the pipe ends (this do not consider the fitting and hoses losses). Moreover, the best solution of fixed compressed air distribution network prescribes the ring configuration; from the main distribution ring depart secondary lines directed to the many end-use points. This ensures firstly, a uniform air distribution, even in presence of strong utilization points, and secondly, that the various points are fed from two different sides, ensuring the continuity of service.
Sectioning valves are usually present along the path to insulate part of the plant, both for maintenance that for safety reasons.

The pipe dimension is revealed to be a major problem of inefficiency, since the increasing of the compressed air capacity in time, shall require an increased pipe dimension for an efficient air transportation.

Headers should also have a slight slope to allow drainage of condensate and drop legs from the bottom of the header to allow the collection. The direction of the slope should be away from the compressor.

2.6.2 *Fittings & Hoses*

Along with generation, treatment and distribution, the fittings for the connection of different parts are of utmost importance. They are revealed to be one of the major sources of localized pressure drops and leaks in the compressed air system, together with hoses. To ensure the lower drop rates the prescribed materials are stainless steel (e.g. AISI 316), that withstand to high pressure at whatever temperature below 50°C. Galvanized steel, copper aluminum and PVC are alternatives, with decreasing mechanical characteristics (tensile strength and elastic limit).

2.7 Point-of-use equipment

2.7.1 *Pneumatics*

Cylinders own the biggest share of actuator devices, and they exist in different configuration and for different extents. The two major groups of pneumatic cylinders are the simple and double effect ones. The single-effect cylinders have a regulating spring that contrast the effect of compressed air. The compressed air can move forward or backward the rod which the cylinder is connected, but not both of them. Double-effects cylinder, on the other way, can be controlled in both directions by the compressed air action.

Pneumatic valves are metallic compact regulating devices, that are able to control the direction or the pressure of compressed air; they are usually divided on their main purpose:

- Control valves, if the element act on the fluid directed to other valves units; they are classified on the number of inlet and outlet ways for the fluid. At least should be present an inlet way, directly connected to the distribution system, an outlet connected to a discharge unit (called tank) and one or more ways that provide the connection with the actuators;
- Power valves, that gives the air necessary to the actuators to move;
- Solenoid valves are pneumatic devices actuated by an electric signal; they are further divided in direct acting units and indirect ones: the second are the most common in industrial context and are composed by a power unit which command is given to two direct acting units.

2.7.2 *Motors*

Rotative motors are nothing but compressed air driven actuators that act to move pneumatic tools as drills, screwers and other portable tools. Vanes motors have the advantage of being compact despite the high power for mass unit: powers range from 7 to 100 kW and rotational speed reach up to 20k rpm. The working principle is quite similar to the vane compression unit, but reversed: the vanes movement, driven by the centrifugal force of the air i.e. the pressure, expands in the chambers and determine the birth of a moment in the crank. The more are the vanes, the more is distributed the moment among them, implying lower stresses; a further advantage with the increasing vane's number is the leaks reduction.

2.7.3 *Uses of compressed air*

The compressed air is used in a very huge number of ways within the industrial context; (25) summarize all the general uses of compressed air divided by sectors, specifying also that the electric-driven units counterpart of pneumatic tools, are much more convenient to use from an energetic point of view. Compressed air usage is thus suggested only when strictly required

Industry	Example Compressed Air Uses
Apparel	Conveying, clamping, tool powering, controls and actuators, automated equipment
Automotive	Tool powering, stamping, control and actuators, forming, conveying
Chemicals	Conveying, controls and actuators
Food	Dehydration, bottling, controls and actuators, conveying, spraying coatings, cleaning, vacuum packing
Furniture	Air piston powering, tool powering, clamping, spraying, controls and actuators
General Manufacturing	Clamping, stamping, tool powering and cleaning, control and actuators
Lumber and Wood	Sawing, hoisting, clamping, pressure treatment, controls and actuators
Metals Fabrication	Assembly station powering, tool powering, controls and actuators, injection molding, spraying
Petroleum	Process gas compressing, controls and actuators
Primary Metals	Vacuum melting, controls and actuators, hoisting
Pulp and Paper	Conveying, controls and actuators
Rubber and Plastics	Tool powering, clamping, controls and actuators, forming, mold press powering, injection molding
Stone, Clay, and Glass	Conveying, blending, mixing, controls and actuators, glass blowing and molding, cooling
Textiles	Agitating liquids, clamping, conveying, automated equipment, controls and actuators, loom jet weaving, spinning, texturizing

Table 1: sectorial uses of compressed air

CHAPTER 3
Analyzing the efficiency measures in compressed air systems: an overview

3.1 Efficiency measure definition

Efficiency measures are actions that imply the adoption of specific technologies or operative procedures, with the objective of lowering needs, but more in general of increasing the input-output ratio.

EEMs are defined as "technologies or behavioral changes that reduce the specific energy consumption of a particular process" (26) .

The efficiency measures, in the energetic field, are of utmost importance when the energy consumption is high and/or the cost of energy is not that cheap. In last decades, the attention to efficiency and sustainability issues has been increased a lot, but, on the efficiency side, not enough to create a sound knowledge background inside firms on the awareness of coping the energy efficiency gap. Or, at least, this is true for some type of systems, as the compressed air one.

The values behind the energy efficiency are the optimization of heat and power consumption, to gain greater energy-driven productivity. The revenues are tangible reduced energy bills as a primary and direct consequence, but other benefits are advisable when an energy measure is installed: greater capacity utilization, reduced scrap rates, more effective emissions and safety compliance, and enhanced risk management (27).

These and other impacts are a sound basis for the following chapters. To characterize at best the efficiency measures, means to have a complete picture how the measure influences and is influenced by a series of factors that determines how approach it.

From an energy management point of view, the facilities' situation is different from one case to another, and highly depends on the organizational characteristics. The programs on energy management may involve different actors and overlapping of different teams; moreover, programs are not unique and straightforward and can be performed in many ways.
The simplest way to handle energy features is to identify a central facility manager as decision-maker (27), especially when in not present a unique figure in charge of energetic issues (for instance the energy manager[11]). On the other hand, in structured facilities a more complex network can be present with different information fluxes coming from management and detailed reporting metrics.

3.2 Efficiency measures in compressed air systems

The introduction of compressed air systems, and efficiency measures on this topic, lies firstly in the high availability of technologies and ways to cope for the low efficiency and secondly, in the high cost of energy during the entire lifetime of the systems. The consumption of compressed air has a lion's share in the total electric bill (21) (28) and decisions on the adoption of efficiency measures should be consequence of the overall expected life costs rather than on the investment cost. In fact, the operating costs of compressed air, can overcome the threshold of 70% of the total.

Different type of CAS, involve different energy efficiency measures because the working way is quite different among each other; as an example, screw use in general more energy with respect to reciprocating compressors, and this is truer if they are oversized for the load. Efficiency measures for compressed air systems are both demand-side and supply-side depending on what entails the system's modification and where the impacts are more visible (29); (25).

Since the compressed air system is made of many components, the "system approach" is referred to the attention shifted from the assessment of single component performances to

[11] This figure is in charge of all the energetic mansions inside the plant, and requires both technical and managerial skills.

a total systemic view. The following bullets explain the actions to perform for a system approach to be applied (25):

- Establishing the current conditions and operating parameters;
- Determining present and future process production needs;
- Gathering and analyzing operating data and developing load duty cycles;
- Analyzing alternative system designs and improvements;
- Determining the most technically and economically sound options, taking into consideration all the sub-systems;
- Implementing those options;
- Analyzing operations and energy consumption and analyzing economics (performances validation);
- Monitoring and optimizing system;
- Operate and maintain the system to peak performances.

Is clear how the efficiency measures in compressed air systems need all the data on demand and supply to have an overview of the actual conditions to understand what are the possible actions to be taken.

The performances of the system can be addressed both for systemic efficiency measures that at component level. Please notice that component level does not mean that only a component is influenced by the measure, as will be outlined in the next chapter.

Despite all the efficiency opportunities can be clear once an external audit has been performed, some of them are available with low metering and engineering design projects.

The characteristics of each of the main efficiency measures for the compressed air system is an important starting point for the development of the work, since it clarifies and analyze the typical features to understand the impacts of the measure and operational and technological implications or constrains and gives an important basis for the assessment of the framework elements to be considered (Chapter 4).

3.3 Overview of the measures in compressed air systems

Since the compressed air system is quite complex and composed of different elements from which efficiency depends, there are many ways to increase the output-input ratio, each with its own characteristics. They are not only referred to particular pieces of hardware, but may involve also operations actions extended to the whole system. The description of the compressed air measure that are going to be analyzed are taken from the Industrial Assessment Center database.

3.3.1 *ARC database*

A very useful instrument for the analysis of the single efficiency measures has been developed from the U.S.A. Department Of Energy, with the Industrial Technology Program (acronyms ITP), related to the energy management topic. In fact, the recommendations cover also other type of interventions as the waste minimization (or pollution prevention) and direct productivity enhancements, that go beyond the scope of interest for this study. In the next paragraph, the taxonomy pertaining EEMs will be explained.

3.3.2 *Approaching the compressed air systems*

From the assessment performed by the IAC centers, whose identification codes are provided for each of them, the result was the listing of all the recommendations for the firm under study. The use of a code for the identification of the intervention to be undertake have been revealed a winning strategy for the easiness of data analysis, as well as for figuring out statistical result from the database. The coding scheme is comprehensive of most of the system present in whatever plant facility. The organization we are intended to analyze is of course related to the compressed air system, and here follows the complete list of interventions. The categorization was performed thanks to a coding system, called the Assessment Recommendation Code (acronyms ARC).

Please notice that under the Compressed air entry in the database (code 2,42XX) there are only hardware and operations related interventions, to which add some other interventions that are classified as waste heat recovery strategies (code 2,24XX) and in particular the ones specifically related to the system of interest.

3.3.3 *Install compressor air intakes in coolest location*

3.3.3.1 **Intervention information:**

The intervention is based on the compressor installation in a cool location for the thermodynamically benefits offered by new air conditions. The lower the inlet temperature, the more air can enter the compression unit. Indeed, the "cool" location refers to the intake temperature, that influence the compression capacity. Compressed air booklets (20), stress the point on the energy savings that come from this measure, identifying the values, exponentially increasing with inlet temperature decrease:

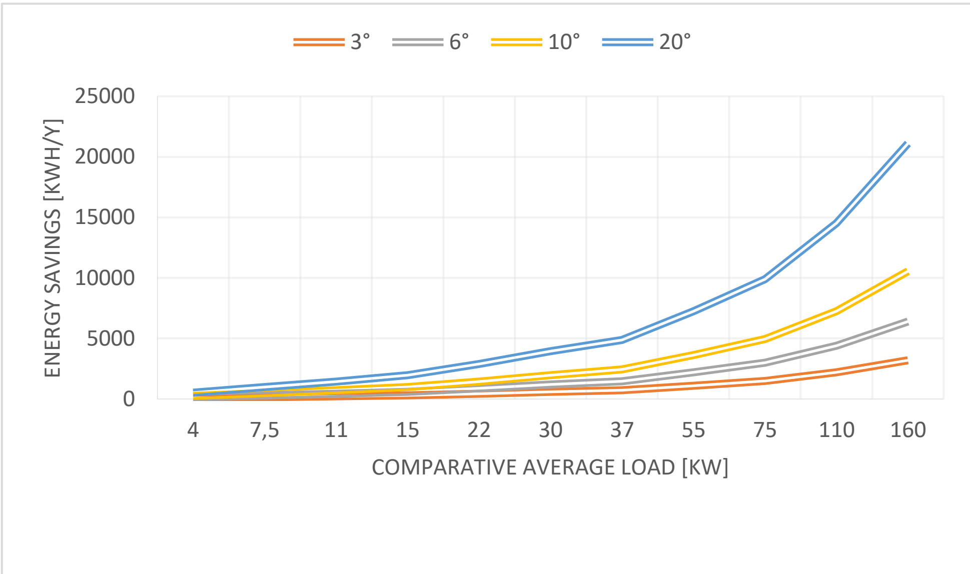

Figure 12: Annual energy savings with reduced compressor inlet temperature

From this simple chart, seems obvious that the adoption worth the installation effort because of the high energy-efficiency potential. The cooler the air, the denser is, increasing the mass flow and pressure capability. Technology experts (30) and experimental investigation (31) showed that a deeper knowledge on the compressors technology and individual controls installed have a huge impact on the decision. In fact, the real impact on energy is quite different due to the more power required by the compressor to run more air into the chambers.

3.3.3.2 **Operations and technology:**

the set of attributes that affects this intervention are mostly connected to the Temperature reduction, environmental implications and consequences of the increasing pressure gap inside the compressor.

Basically, the operational effort, as always, thoroughly lies on the context; the identified location distance from compressor unit with respect to the actual can influence the decision on the installation (remember that length means losses). Moreover, the installation in an external shaded area, can have an impact in term of average difference in power consumption with a 10 % increase in summer months (32), and requires higher filtration units, with primary external dust removal via a damper and external filter. The replacement time for inlet filter should not be underestimated, since the loss in efficiency by the pressure rise can reach high costs $327-980 with a $0.05/kWh and 16/5[12] utilization (33).

The intake air filter variation can be a major cause for the decision of moving the compressor inlet toward external ambient, because of the prevention in pressure drop and mass flow reduction (33). The installation can be performed both toward the external ambient, or to another location in-site. In any of the two cases, if the air was taken from the compressor room, this can entail a pressure reduction under the atmospheric conditions, translating in a lower compressor efficiency owing to the decrease in static pressure influences the compressor ratio (34).

For the in-site installation, the area should be ventilated enough to give potential for a substantial decrease of temperature. If the air is drawn from a remote area location, the inlet pipe size should be increased to prevent pressure drop and reduction of mass flow (33). As previously highlighted, the intervention effectiveness depends over the type of compressor and control unit.

Centrifugal compressors:

[12] Hours per day and days per week

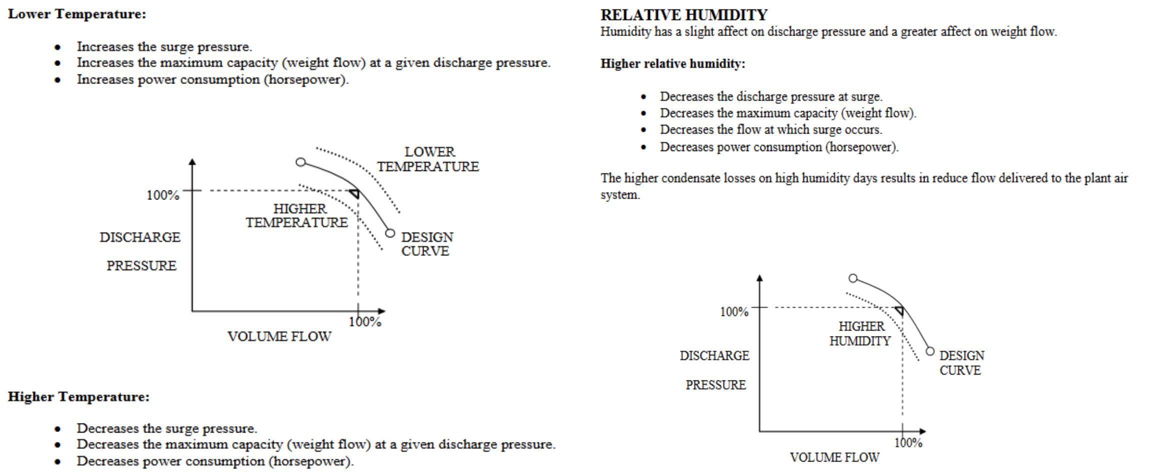

Figure 13: effects of lower temperature and relative humidity on centrifugal compressor performances

- Power increases with inlet mass about the same as the flow increases. The compressor motor current needs to be controlled at a maximum amp level to keep it from overloading in cool intake scenarios.

- This type of compressor is very inlet temperature sensitive. Power increases and flow increases, more here than in an oil-free screw. However, power and flow change by about the same amount.

Screw compressors:

The Installation in screw compressors depend on the regulation mode, and is to avoid in load-unload compressors, because the decrease of the inlet temperature acts as the increase in the velocity, this will increase the idle time of compressor, reducing system efficiency. The VSD installation gives advantage of the lower T for the reduced load, even though in the oil-free screw configuration (where the compression is more like an adiabatic) this does not give high potential for specific efficiency in sfcm/kW (30).

The oil-free screw compressor is temperature sensitive: the low inlet temperature has a benefit on the lowering of outlet temperature (preventing from shutdowns), on the other hand the dropping of first stage T, require a tight control temperature of outlet to avoid moisture after the first stage.

In oiled screw compressor, the inlet T does not influence the volume, but increase the delivered flow (5,5°C decrease in inlet temperature lead to 1,9% increase in mass flow). The compression can be referred to an isothermal so dependent on pressure ratio and speed. Their required power goes up of a small amount with lower inlet T.

Reciprocating compressors:

Variable displacement compressors of this type can have the sort of same impact about the lowering of the intake air. In the PV curve of the compression cycle, decreasing of the Temperature with all the other parameters unchanged, increase the need for power in the cycle because high air amount is being compressed, giving no or very poor energy efficiency benefits on the application.

3.3.3.3 Database information:

From the IAC center data, the assessment can be filtered out by a couple of criteria and factors that can be influencing or not. Since the implementation rate basically do depend on the intake position and accessibility, is not expected a big difference in the implementation

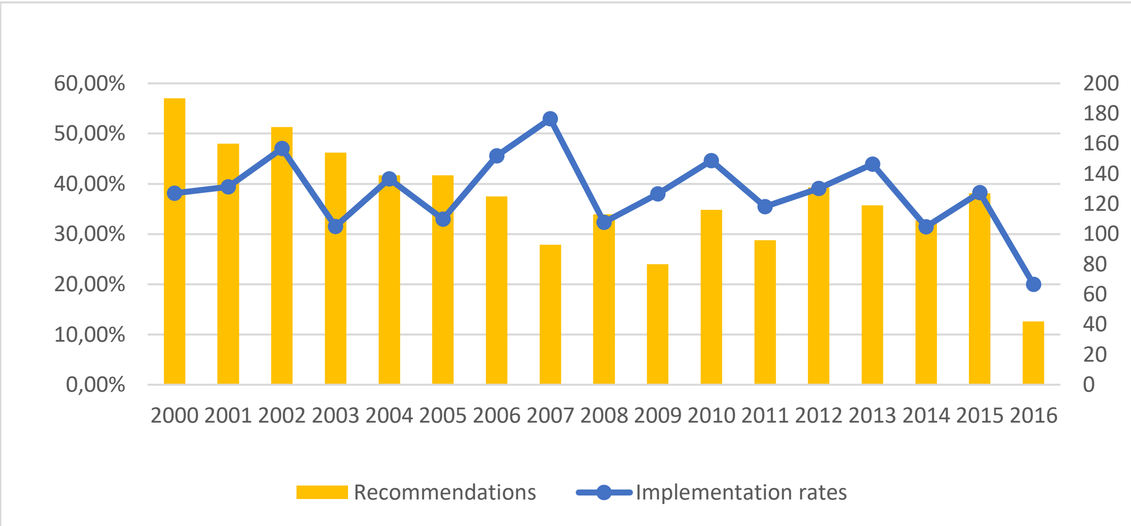

Figure 14: trend for the adoption of "Install compressor air intakes in coolest location" EEM

rates by dimensions and sector. The rates, as expected, are 46,89% for the SME's and 46,61% for the overall sample. The total amount of implementation from the 2000 in SME's is 561. The filter on the year, reduce the implementation rates to the 39,12%, meaning that in general better procedures in the design phase require less intervention of this type. The implementation rates per sector are different, because of the low number of recommendations for each of them. On the most recommended metal and plastic have the lion's share covering the 44 % of the total: 424 for the metal manufacturing with 42% of positive outcomes, 212 for the plastic (37,26% implemented).

3.3.3.4 **Final review**

The differences pointed out in 3.3.3.2, influences a lot the adoption rate, depending on the location of the compressor inlet.

The focus on the factors of influence, in parallel with the literature review (33), shed the light on the fact that if the new location is very difficult to access (roof location or difficult accessibility in winter months, etc.) the difficulty maintenance procedures may have a huge impact on the effective energetic gains of the measure, even more than the difficult prediction of the ambient conditions.

The external installation has some difficulty to take into account, that can require higher engineering, owing to the necessity of monitoring the average ambient air condition in time. Additional filters are required for the dust collection and dirt of the outlet filter have an impact on maintenance procedures and routine for the cleaning/change of devices. The air quality improvements, on its own, can be a cause and not a consequence of the intervention.

3.3.4 *Install adequate dryers on air lines to eliminate blowdown (35)*

3.3.4.1 **Intervention information:**

The dryers are part of the air treatment equipment in compressed air systems; they fulfill one of the most important tasks: separate air from moisture particles in order to maintain air dry enough, depending on the application and wear requirements of components.

Selecting the right compressed air dryer will have a big impact on energy savings and efficiencies; if the dryer unit use energy in proportion to the demand requirements, additional benefits of enhanced lifetime of equipment occur.

3.3.4.2 **Operations and technology:**

The different technologies involved in the compressed air systems are already been treated in Chapter 2.

Refrigerated type of dryers are the most economical to purchase and maintain and work well for most of the general manufacturing applications. The pressure dew point is in the 3°C÷10 °C temperature range. The temperature reduction owing to the heat exchange with a cold medium, saturate the inlet air and condenses the moisture as the temperature falls, drying air. Moisture separator unit is needed to remove the water content inside the dryer unit.

From an energy efficiency perspective, the cycling dryer units have the advantage of storing cold energy until is required, with the twofold benefit of using energy in proportion to the demand (they use a water-glycol mixture) and the additional capability of drying only the amount of air loaded inside the dryer. Moreover, the maintenance requirement are generally low owing to the refrigerant not being exposed to atmosphere.

Electrical cost for refrigerated dryers are mainly three (or two, depending on the cooling fluid):

- Refrigeration compressor;
- Controls if present;
- Condenser fans (only for air-cooled units).

Despite the non-cycling units have a lower purchase cost, the operating costs of the cycling units are far less. During the lifecycle, is very likely than the overall cost of the first will exceed the second.

Desiccant dryers are use the porous desiccant beads to adsorb moisture particles from humid air. Their composition usually involves two different towers that alternate their functions to provide very dry air. They have much lower pressure dew points with respect to refrigerated dryers, in the -74°C ÷ -40°C temperature range, so that their use is suggested where outdoor piping is subjected to freezing risk, or for particular food/pharmaceutical applications.
Heatless desiccant dryers use 15% of compressed air to dry the remining quantity, the others need an additional heater in the regeneration circuit of the dryer. These dryers require frequent valve-switching and, as consequence, frequent service and valve maintenance (also entails downtime for equipment).

The operating costs of the dryers requiring additional compressed air are usually far higher. The blower purged type is often the most efficient for this reason. Some of the manufacturers, to further increase efficiency, install the control to regulate switching of dryers

3.3.4.3 Database information:

In the last 17 years only 81 recommendations are suggested; of these, lower than half are implemented, mainly due to the high cost. The SME's in the last 16 years have implemented 25 out of 47 recommendations, and their simple payback is slightly higher than one year

(1,26 y on average). Metal manufacturing is the only sector with more than 3 recommendations (13) throughout years.

3.3.4.4 **Final review**

The type of dryer highly depends on need of the final user. The refrigerated ype is the most common and the one to install unless particular drying requirements are asked by the system. Thus, for manufacturing processes in general the refrigerated dryers will be sufficient.

General advises to check for the installation are:

- Space availability;
- Distribution system temperature conditions;
- Point-of-use desiccant driers may be used in case of needs for unique end-lines;
- Different maintenance procedures are required for different dryers;
- Adaptability to discontinuous demand is a cause for the decision of the drier to apply and the eventual switching control to be installed.

3.3.5 *Upgrade controls on compressors*

3.3.5.1 **Intervention information:**

As seen in the description of components of a compressed air system, takes a primary role the baselining of control measures to ensure efficient system operations as well as high performance, with the purpose of lower input power.

In typical manufacturing plant with compressed air system, is likely the presence of more units; the degree of complexity of the system determines the complexity needed for the control, that usually can be done for each **single compressor** as well with an intelligent **centralized control**.

Both for singular and system control, the system operations are addressed through:

1. Delivering of sufficient variable flow to achieve stable pressure at the end-use point;
2. Efficient working conditions, to ensure the lowest energy consumption;
3. Tracking and transmit information about current operative data.

The control methods to apply on compressors are useful to match the supplied compressed air to meet the demand; the task of the compressor control is to command the system to match the current demand in any time supplying the right power, ensuring the minimum required pressure is maintained for the proper functioning of all end-use equipment.

3.3.5.2 Operations and technology:

Since compressed air delivery is critical in many facilities i.e. there is no production with the interruption of the compressed air system, is highly recommended that control is applied in each single compressor, with eventual backup units preventing for unplanned downtime. Here some O&M advantage/problem is highlighted, because take in mind that, on one hand a good control application helps a lot for efficiency and other benefits, but a bad application lead to higher cost, increased maintenance and operation problems.

Start/stop: this regulation method is used on small scale compressors, from 5 to 10 kW usually (24). The demand should be flat enough to avoid frequent activation of the motor, otherwise this can translate to overheating of equipment, with a detrimental effect for the compressor’s life, increasing the maintenance cost. The setting of receiver capacity is determined by the control application i.e. the times the compressor is not running, it charges the air receiver so that it supply enough compressed air the compressor start again after a stop (20).

Load/unload: is the most common regulation method in the medium scale compressors (24). Check for the load profile of the system, because the 15-35% of full load power during the unload may be a high source of inefficiency in the system. Prevent the system to pressure relief after the unload of the compressor.

Throttling: variation of the amount of air entering the compressor, this implies an expansion before of the intake air, as consequence to be effective i.e. to have the same outlet pressure, the power requirement for compression are higher.

Inlet guide vanes: typical of centrifugal compressor is not so different from the principle of throttling the inlet, but here the control is more energy efficient, because the vanes give to the air the possibility of rotating smoothly, with some losses reduction. The regulation interval is higher (50 to 70% of the rated capacity). Moreover, a slight increase with respect to the rated capacity and pressure can be achieved rotating the vanes to the opposite side. This last method implies an efficiency reduction.

VSD, an opportunity to exploit: Variable frequency speed drives are a great source of savings in that compressor types (see paragraph … on compressors' control) able to handle the speed change. The application on rotary screw compressor is a constant torque load, if P is the power required, C the torque and w the rotational speed of the rotor:

$$P = C \cdot \omega$$

For a constant torque load the result is a proportionality between the angular speed change and the lowering of the required power (36); this is not perfectly true, since the performances lower more than expected for high loads. A rough data set on efficiencies here follows (36):

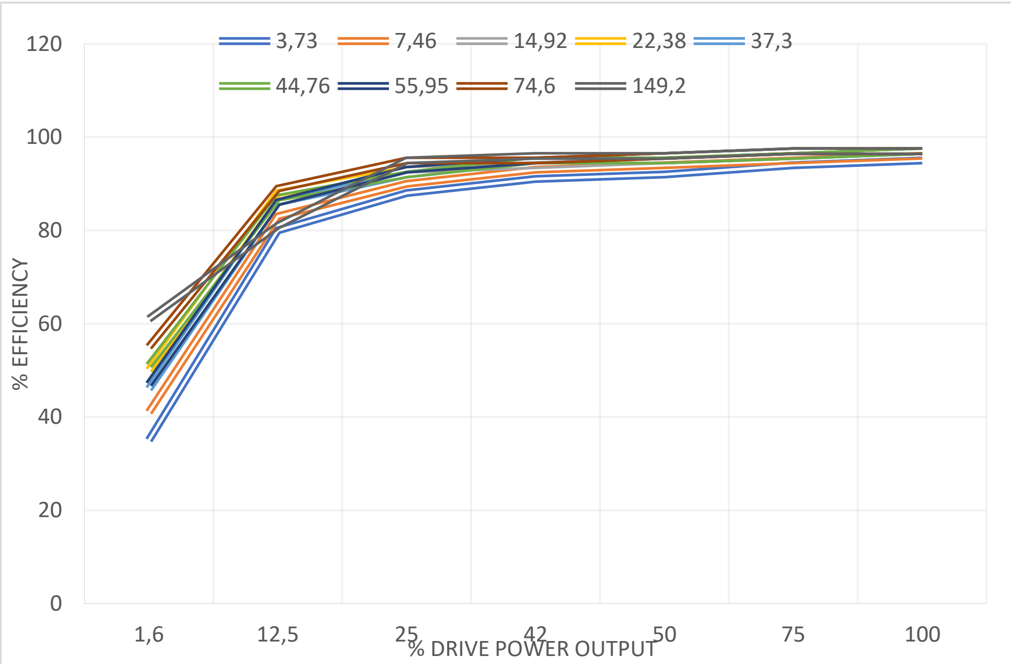

Figure 15: Part load efficiencies for different powers of compressors

VSD regulation pros are the high efficiency at part load that is reported in the upper picture, but the cons are the high investment for the initial purchase and the slightly lower efficiency at full load with respect to other control methods.

One typical installation of a VSD at variable frequency, is the matching of demand by an air dryer with the supply by one or more compressors running with load/no-load control; the mismatch of the two (bad design of the system or degrading performances of some equipment in time), entails a much lower control band with respect to the one set up in design phase, leading to short cycles and very low efficiency issues.

In some specific case, the installation of VSD is completely to avoid because of the thermal stress which the equipment is subjected (electronics and variable frequency devices will not last long), leading to break down of the system. In hot forging plant, temperature conditions require to consider this aspect before the initial design.

Other from control units: this intervention is one of the highly dependent on the other compressed air system equipment operating conditions and one of the most expensive, but this ensure high energetic return potential. The high cost can be one of the principal reasons for the decision about the adoption, especially in low budget enterprises.

With a bottom up approach one can assess the compressed air "food chain" built from the equipment installations that do not influence any others, e.g. pneumatics or single end-uses, to the more influencing and cost effective. The compressors control units are on the top both for the largest influence on other equipment units and as consequence, the need to be optimized as last. Their fit with the system is to deliver best performances after the optimization of the other system's component.

reducing and controlling the system pressure downstream of the primary receiver can reduce energy consumption up to 10% to 12%.

Singular control units are generally not time expensive for the installation, installation time do not vary a lot with different control modes, and being the compressor type always the same, is not required training inside the firm.

Because of the automatic regulation of the master control, the need for maintenance are highly reduced due to the self-adjusting feature. Moreover, the master provides an ongoing baseline of the system operating performances, giving advice for any sensing difference in the key parameters throughout the entire system. In fact, the double effect feature of the master control installation is the adjusting the supply to the demand and the continuous monitoring effect.

Another important aspect to consider is noteworthy: the control setting makes the lower operating hours compressor the major partner for an increasing demand requirement, with the possible indirect effect of lowering unplanned downtime (in the synoptic table this reduces the maintenance).

An important drawback for such installation can be a compatibility issue. Bus connection allow compressor control network to talk with different compressors but different brands or outdated compressors can be isolated from the rest.

Noise reduction is possible under certain conditions. If some machine is noisy, the central control can be set to make them work on the low crowdy hours i.e. in a multi-shift industry, the noisy units can be controlled to operate during night/weekend.

3.3.5.3 Database information:

The overall implementation rate is 289/644. With a slightly lower percentage 44,87%, the SME's filter gives 171/379 for a total of 45,12%, demonstrating that this intervention has not sensible difference depending on the firm's size; this percentage slightly decrease considering only the last 16 years (43,04%). Influence on the sector are not advisable since the low number of recommendations.

3.3.5.4 Final review:

There are many types of compressor and control modes for each of them, but from an energy efficiency perspective the way of acting for installation and upgrading of controls does not implies difference in the operation, even though the technology is different.

From different literature sources and case studies from the specialized sites gathering these information, differences are outlined between the control upgrading: notice that considering possible measures to implement in compressed air system, the master and singular control are at a different level of priority. The right procedure prescribes the sizing of each control on its compressor, and after this work is done for each unit, the implementation or upgrading of the master to avoid fighting.

Singular compressor units' control: The incorrect matching of current demand and not efficient part load conditions are the prime movers for implementation of this measure; different singular control types affect different compressors, refer to the paragraph on chapter 2 on control for further details. When upgrading one control unit, consider the possibility of affecting other parallel units and look for control gap problems.

VSD: The retrofit of existing machines can give good benefit at a lower cost that the purchase of a new compressor but in rotary screw and reciprocating compressors one may consider that correct levels of lubrications are maintained, vibration problems are not present and cooling is enough. The more stages lubricant free compressors are usually not allowed or suggested to have a retrofit with such solution. Specialist installer are required, also because the third party retrofit invalidate the warranty (37).

Centrifugal machines cannot be run in another speed from the design, so the installation is not suggested

Master control system: High number of compressor turns the regulation and optimum efficiency of single compressors to be a nightmare. Moreover, different controlled compressors with their singular setting have revealed that there is some chance for the fighting of their singular control units. Smart central system control can manage multiple compressors of different sizes, allowing the reduction of energy consumption in different ways:

1. Reducing compressor run and idling time. Only the strictly necessary units will handle the current demand, avoiding also frequent start/stop for that singular compressor control;
2. Improved pressure performances. Changing in pressure are ensured by a tight monitoring connected to the MCS, avoiding eventual cascading control efficiency problems when high demands are required;
3. Reduction of overall pressure but ensuring the minimal pressure requirements for good equipment and utilities functioning;
4. Effective load sharing, without conflicting for any capacity requirement.
5. If a monitoring system is installed with the central control system, other than energy efficiency, gains in maintenance cost and minimized unscheduled time are a further consequence of the installation.

The cost of a central control system depends on the intelligence of the system and on the number of compressor that can be managed, on the installation cost and on the capability to be integrated in plant process control system (38).

The decision on the groups to create for the intervention are basically three, the modulating and on-off load control are very different from the technology to be used, but here the focus is not on the technology but on what the installation implies, the VSD is treated as a separated unit because the installation is directly on the motor and not on the compressor unit:

	Pros	Cons
Single control units on the compressor	When air is required, a signal is directed to an electro-valve to command the opening of the compressor inlet (modulating, on-line/off-line) or directly the motor (shutoff)	When upgrading one single control, predict how it is affecting the others and, as consequence, the overall system
VSD	Part-load best efficiency, generally under 75 % with respect to single speed machines	Do not install it in low power compressor and when overheating harm is present
	Installation directly on the motor	High purchase cost
	Flattening of pressure profile reduce the pressure generation up to 0,5 bars (37)	Slight lower efficiency at full load capacity
		Specialist for the installation is required
Master control system	Load sharing of compressors	Additional equipment required (installation of flow controllers and possibly a different air receiver)
	Easier monitoring of the entire system	High purchase cost
		Specialist required for the installation

Table 2: recap on pros and cons of the major controls of compressors

The factor that differentiates the efficiency measure in sub-system is at the higher level the effect on the system: the system control optimizes the transition between the running, idling and stopped states of compressors (18). Their installation is especially hindered by an external expert required for the installation; moreover, sometimes the combination of the control system with other equipment is suggested (for instance flow controllers and storage systems) (39). The plant personnel in any case should be trained enough to handle the situational changes in the system requirements and adapt the control system. Another main difference is the investment cost that changes because of both the additional equipment eventually required and barriers are quite different from the single control installation and from the literature some of the manuals, slit the energy efficiency intervention (CIBSE).

Variable speed drives cannot fit on all types of compressors (generally not for centrifugal, unless designed before installation), their cost is higher with respect to the other regulation methods, and the required expertise for the installation is higher as well, affecting both economics (investment cost) and competences related (the vendor has to be consulted for the installation and adaptability to the system). All the three facets in which the intervention can be divided, have the necessity of measurement and record of current system performances, so this increase the complexity and adaptability to the existing system.

3.3.6 *Install common header on compressors*

3.3.6.1 **Intervention information:**

From the room where the compressed air is generated, it passes into the distribution system, characterized by pipes, tubes and fittings. The best layout for the distribution system is the closed loop configuration, as will be highlighted throughout the following description. The connection of the main header with the secondary lines is made thanks to sphere or flow valves, to supply air to end-use points.

The closed design ensures the air to be supplied from one of the two sides of the line, and for supplying the largest possible area. This ensures a constant compressed air source, increasing the promptness to air changing demand. This system should be used with the exception to some end-use points where supply requirements are particularly high and/or the plant distance is too far from the point of use.

3.3.6.2 **Operation and technology:**

The main purpose of installing a common header is to have the compressors working together in the same line, ensuring the demand from each of the point of use is always supplied correctly. Load sharing is one of the most advantage a compressed air system can benefit (refer to master system control in intervention 3.3.5 for more information).

In the **first** part, there is an analysis of changing the pipes for the CA system, in the **second** the attention is moved toward to the installation of a different layout for the distribution system.

Firstly, sizing the ring mains the choice should fall on slightly higher than the actual perfect size for the current demand, because in energy efficiency terms the under-sizing effect are very significant.

The design requirements of the main CA line prescribe low pressure decay for unit length, the materials of the pipes prevent from rust and dirt stacking and the whole system is usually monitored to prevent from excess of pressure drop along the system or intermittent load of the lines. The crucial part with the piping systems lies in the installation, and as outlined by Seslija, Ignjatovic Dudic (40) the installation should be made by experts in compressed air technology and not by companies that perform other fluid related installation works. Other than installation problems, if one or more compressor is independent from the main connection, absence of single lines monitoring systems can translate easily in service problems, but for sure in excessive cost of equipment: the cost of designing the line and the equipment of the distribution line itself (the expenses for service piping is not an additional cost since had be borne in any case).

Efficient operations, in fact, prescribes the lowest pressure differential and not the lower investment cost. Designers and installation team is usually oriented toward the lower investment cost, but the harm of the lowest piping diameter is always not considered properly. Higher velocities in a better and lighter material pipe sounds awesome from both the promptness in demand services and for installation purposes, but the main problem is the pressure drop on the fittings, that can lower too much the savings, until no energy efficiency gains are available.

The larger the bore, the less are the pressure drops along the line:

$$\Delta P = 450 \frac{q_c^{1,85} l}{d^5 p}$$

Where:

$$\Delta P = pressure\ drop\ [bar]$$
$$q_c \ = airflow\ (FAD)\left[{}^{l}/_{s}\right]$$
$$d = bore[mm]$$
$$l = pipe\ length\ [m]$$
$$p = initial\ pressure\ [bar(a)]$$

The lifetime of the header depends over the material, but is very high, making the investment pay for themselves many times over the life of the system. Materials general in use are:

- black iron. Is a type of steel, withstanding to over 400 psi, but high rust generation and rough internal bore, harmful for the contaminants present, can reduce the airflow;
- Galvanized steel. Similar to the first one but enhanced corrosion protection, unless for the joints in which higher problems can be advised;
- Copper: corrosion resistance ensures high air quality. However, it requires soldering or brazing during installation, so the installation is to avoid in ATEX environments.
- Plastic: very easy to install, is inexpensive, lightweight and corrosion resistant. On the other hand, the T dependence is quite low. Hazard are present if PVC because contact with other substances can corrode the inlet bore. Moreover, the mechanical characteristics are highly influenced by T, that can lead to brittleness;

- Aluminum: with polymer fittings, the most modern and cost-effective installation is on aluminum and polymer fittings, matching the lightweight and ease of installation with potentially lower cost. Maximum pressure range is 200 psig. The metal fittings have the additional advantage of maintaining strength over time. Installation is easier with respect to other metal pipes for the lightweight (41).
- Stainless steel. Corrosion resistance and high-pressure ratings are the strength points, despite the high weight are bad from installation purposes.

In this **second** part, the light is shed on the intervention characteristics: the purpose is the elimination of a line, lines or the overall piping system, for a more efficient distribution system, with the great advantage of load sharing. If the actual configuration does not imply the ring distribution system, the structural change to undergo is quite huge and the downtime of air lines, shutdown time for the installation, commissioning and start-up of equipment, other than the capital cost, can discourage the site manager from the implementation. On the other hand, benefits of such a configuration (42) are:

- The velocity to any point is reduced, since air can converge from two different directions, reducing the pressure drop along the system;
- If automatic zone valves are fitted, can isolate areas operating different working patterns;
- Alteration or future expansion is much easier with this configuration;
- Larger piping is installed in case of common header. This ensure better performances and facilitates future additions to the system at little extra cost (Compressed air safety manual), giving more flexibility.

Another objective for the main header is to transport the maximum anticipated flow to the production area and provide an acceptable supply volume for drops or feeder lines; this is a further benefit for the entire system, since this acts as an additional capacity to maintain the demand pressure if the compressor is unloaded.

For the flow monitoring the flowmeters should be substituted since they are usually located in correspondence of shut-off valves and should record correctly both the flow directions.

3.3.6.3 Bad practices on compressed air distribution systems:

Sometime the plant has two different lines for compressed air, one called instrument air line and the other is the plant air. In the former generally is given more attention in the cleanness as well as the dryness, the second one is not so important for the production process and this can lead to underestimation of maintenance or problems with that line. A good design prescribes the same air quality for all the plant, unless for very specific application requirements, the initial major cost is almost always recovered from the high quality of air and less operating problems coming from the "normal plant air".

3.3.6.4 Database information:

This is the case observed from the analysis of the IAC database, with the intervention being the fourth of the worst implemented in term of total percentage, 37.04% overall score. Please note also that the first three in order have the common root of waste heat recovery, so after the "waste heat recovery intervention" on average, the installation of common headers ranks second.

In any case is to notice that the total number of recommendations along the years is only 54, meaning that the higher portion of the firms does not face this type of inefficiency.

Anyway, here there is some additional information: the recommendations are far less for the Large enterprises (21) with respect to the SME (35). In the last 16 years the trend is 11 implemented out of 26 total recommendations for SME's, with an average payback of 1,96 years.

3.3.6.5 Final review

Investment cost is revealed to be a very influencing factor hindering the adoption of the measure if not enough economic resources are available. Design problems affect the complexity of the measure, since the planning should be performed carefully to ensure proper operations (43) and the fluid velocity and piping material influence the identification of pressure drops (41).

Shutdown of equipment is a consequence of installation requirements and may influence the timing of installation to low production periods or planned downtime.

Moreover, the accessibility of the piping towards the distribution lines can be a problem for the installation. This is less true for the packaged compressor units for which a factory-connected piping is present to increase manageability

3.3.7 *Use or purchase optimum sized compressors*

3.3.7.1 **Intervention information:**

This efficiency measure refers to the capability of a compressor unit to follow and handle the demand of the system in any time with efficient operation. Oversizing or installing a wrong number of units are two of the major problems in the supply side of compressed air systems; whenever a change in the demand or number of units is in place, the re-evaluation of system requirements in term of operating condition is compulsory, for a better use of units i.e. of energy. The intervention is harder with respect to what it seems to be, because, to make the compressor run efficiently, it should work properly and in synergy with the system in which is embedded. The installation of a new compressor in an old system can change the way the system act, and for this reason is fundamental a phase of commissioning, for which is wrong to consider the savings only from the single energy saved from the new compressor unit, but the system's overall performances. In this sense, the installation and commissioning of the entire system requires a very high involvement from regulation/control experts.

The general rule when substituting a compressor unit is to look for the specific efficiency, in kW/100 cfm, for ranges of capacities (from full load to fractions of it) and see the suitable unit, considering dimensions, ease of handling, monitoring and maintenance requirements e.g. when installing a diesel engine for problems of handling the electric line, remember the oil change may be frequent, so maintenance cost will rise.

3.3.7.2 **Operations and technology:**

For the design of an optimum compressor, to determine the type and size, one may have a clear idea about the operating conditions of the air, in term of capacity, pressure and temperature. Here follows some important tips schematic of the considerations to evaluate every time is required a new design of the system (44):

Fluid properties:

- Since the high strength materials of the compressor case, no problems with corrosiveness of the fluid;
- Presence of water inside the compressor should be avoided for the harmful damage possibilities inside the case. The pressure gap and final T of the gas determines the final

pressure and as consequence the pressure dew point at which moisture condensation happens;

- Inlet Pressure should not go under a minimum, the inlet filtration and losses in inlet hood and piping should be considered to guarantee performances. Pressure drop may arise also with the throttling inlet of some compressor types, just consider it as well;
- Discharge pressure on the nameplate is locates: downstream of the flange for centrifugal compressors, downstream of pulsation suppression device for the reciprocating, and downstream the silencing device for the rotary;
- Inlet Temperature: refer to 3.3.3;
- Discharge temperature: is affected by the last three bullets and efficiency of compression. Is quite important for determining the design of more stages (intercooled), after cooler design and the mechanical design of the compressor.

Mechanical design of compressor:

- Maximum allowable pressure (MAWP) is the requirement together with the max temperature, to manufacture the casting and cylinder to withstand stresses:
    - For centrifugal compressor is calculated adding the MAWP to the maximum differential which can be subjected the compression unit;
    - For variable displacement compressors casing MAWP exceed the rated discharge pressure by the 10% or by 1,72 bar (the bigger of the two);
- Maximum allowable temperature is calculated considering a margin of at least 28°C over the max speed and flow conditions (centrifugal compressors) or the exceeding of the same amount with respect the rated discharge temperature (variable displacement);
- Design specification sheet must also contain lubricating oil supply, shaft and piston rod sealing (variable displacement compressors) together;
- Dimensions increase with pipes size and flange ratings.

Process compression stages: compressor stages increase the efficiency of the process, because of the lower temperatures from intercoolers that set the thermodynamic transformation to be more like an isothermal (that requires lower work) and increase the safety, or just allowing the pressure to reach the desired value (cannot be reached in one stage, especially in low pressure ratio technologies, as the centrifugal singular stages).

Baseline of current system conditions (45)**:** the first step in baselining the system requirement for the sizing of equipment, is determined by the pressure and flows that with any probability will enter in the system. The pressure considerations can be found in the paragraph on reduction of pressure to the minimum required (3.3.9); flow considerations are important to be outlined in this sheet, because they determine the optimal sizing of compressor units.

Each end use has one average demand, and the peak one, depending on the application. The high variability, as usual, is source of uncertainty about the current demand, calculated as the sum of all the demands of single users. Of course, the sum of the peaks is not the correct way for dimensioning and is handled with air storage units; the utilization factor of each end-use, on the other hand, is of utmost importance since different flows comes from the same utility with different working times.

The consumption to calculate, suggested by manuals is given by the full load consumption (q_{Ni}) multiplied for the working coefficient (f_i), that accounts for the duty cycle of each tool:

$$Q_{NB} = (q_{N1} f_1 + q_{N2} f_2 + \cdots + q_{Nn} f_n) \cdot j$$

Where:

Q_{NB} is the total consumption of n tools;
j is a synchronism coefficient of tools, that varies depending on their amount in the lines;

The value should be increased by the nozzles and pneumatic cylinders' applications $Q_{Nm} = Q_{NB} + Q_{ND}$ to be monitored and changed in case of plant modifications. The flow required by the compressor unit, should ultimately consider the cycle time for the compressor (t_C) as a fraction of the total time (t_t):

$$Q_{NC} = \frac{Q_{Nm} \cdot H}{t_C / t_t} \qquad\qquad t_t = t_C + t_0$$

H accounts for the leaks, but in general one should always add a safety factor. The supply air time and zero load time of the compressor cycle will depend on the sizing of the air receiver.

Different features are outlined on the <u>intermittent use</u> of very high flows, as for example the baghouses, commonly used in steel or concrete mill, and for the incinerator plants. In this case a storage tank will be designed with metered recovery (limiting the capital cost at the expenses of a large unit for the storage), to avoid high fluctuations of pressure. The use of a needle valve ensures, once the pressure is dropped down after the emptying of the tank, that the recovery is slow enough to avoid an imbalance in the ring configuration (19).

The peak demand has to be calculated as well, to size the total compressor capacity (46).

Moreover, the base load requirements should be calculated, to ensure that the demand can be met efficiently (46). Peak, mean demand and base load are advisable in the following figure:

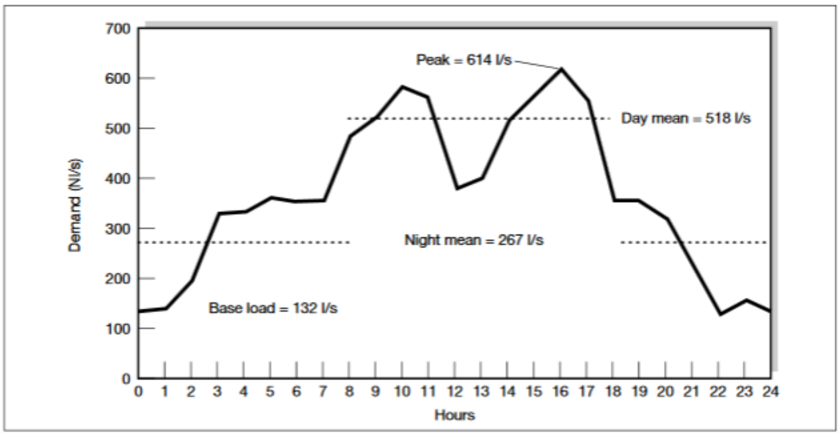

Figure 16: demand load variations; base load, peak load and mean loads can be easily identified

For different production areas, CAGI offers a rough table for examples of compressor capacity required for single utilities (19):

Constituents of Demand		Required Flow (cfm)			Intermittent Use Time	
Production Area	Required Pressure (psig)	Constant	Average	Max at load	Time on (min)	Time off (min)
Assembly	80	250	250	250	-	-
Drying/Blowing	90	100	100	100	-	-
Air Wands (blowing)	90	-	75	150	0.2	0.2
Pneumatic Cylinders	80	50	50	100	-	-
Overhead air winches	80	-	32	400	6	35
Venturi Vaccuum	90	100	100	100	-	-
Electrical Cabinet coolers	80	80	80	80	-	-
Paint Spray Booth	80	-	150	200	-	-
Other users for production	80		150	250	-	-
Waste/Leaks	90	250	250	250	-	-
TOTAL	-	830	1237	1880	-	-

Figure 17: Capacity of the most common compressed air end-uses

Additional information for the installation (47) (25):

- If a different cooling method is expected, account for the possibility of supplying the fluid in open circuit configuration, or account for space requirements of the cooling system around the compressor area;
- If the sizes are quite different, or units are a different amount, account for the space required for the motor-compressor coupling (and eventual transmission) and maneuvers for installation and maintenance procedure;
- Other than considering the efficiency of the compression, the prime movers' efficiency gives information about the delivered mechanical power to the crankshaft over the electrical power input. Electric motors are the most used, but also diesel and natural gas engines are available. When purchasing a new electrical motor, the choice is between a standard unit and a premium efficient one remember that incremental cost of the second is usually recovered in a low time span, thanks to the energetic savings.
- If the firm handled only one compressor type over the production years, this may hinder the adoption of a new technology. This happens because of the unit working principle, control methods, maintenance procedures may change a lot between types of compressors, requiring new training activities for the employees.

3.3.7.3 **Database information (48):**

The cost of intervention can range from the simple purchase of the compressor to the installation, commissioning and turnkey start-up of the principal unit and further equipment required. The new compressor installation can require adjustments on pipes or ancillaries: this is one of the reason why the decision is outclassed.

The average implementation cost, as consequence, is high, averaging 29.500 € with a simple payback of 1,62 years. The savings are high as well, with a value of 20.800 €. If some other measure is going to be implemented along with this, the budget for retrofit can be lower lowering the installation likelihood, especially if the compressed air system is not feeding the process line, but only the instrument side one.

The average implementation rate is 42,88%, rates over year are represented in the figure below and do not shows any pattern:

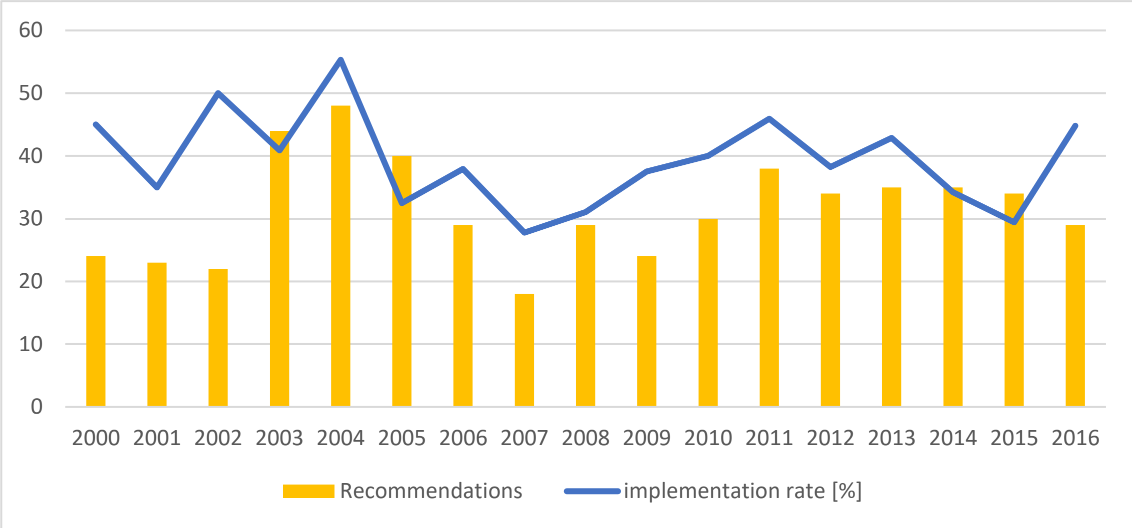

Figure 18: trend for the adoption of "Use/purchase optimum sized compressors" EEM

The filter on SME's in the last 16 years gives 41,84% as percentage of implementation rates, and an average payback of 1,61 years. No enough information about the sector can be inferred because of the few recommendations for each of them.

3.3.7.4 **Final review**

Here are outlined the major pros and cons:

	Pros	**Cons**
Use/purchase optimum sized compressor	Major source of energy savings, leading to low payback Evaluate the possibility of obtaining rebates from manufacturer More performing and new units can reduce space requirements for themselves or for cooling units Possible noise reduction Replacing single-stage compressors with two stage compressors typically provides a payback of 2 years or less (49)	High dependence on current conditions, look for regulation modes to adapt on changing High purchasing cost Different technologies require different technology experts Different compressors require different setting of other system's components Baselining of current condition and commissioning phase are of paramount importance If future expansions are planned, the need for more capacity should be considered Other than the physical space occupied by compressor, enough space for maneuver, installation of components and piping, and maintenance procedures are required.

Table 3: Recap on pros and cons of the measure installation

3.3.8 *Use compressor air filters*

3.3.8.1 **Intervention information:**

This measure pertains the utilization of one of the simplest hardware part to install and maintain, pointing out all the benefits this entails for the compressed air system and on overall performances: the intake filter before the compressor inlet. These types of filters are not the only present in the system (others can be found in the piping, before some of the application requiring a certain cleaning level for air), but are the ones that should be compulsory for every good design of the generation side of the CAS.

Other than less efficiency for the presence of airborne particles, the lack of filters cause compressor equipment worn, added to the possible quality loss of lubricating oil in lubricated units.

3.3.8.2 **Operations and technology:**

All the types of compressor require an inlet filter (50). Inspect and replace air inlet filters on a regular basis (about every 2000 h). This timing reduces component contamination and air-end wear, which improves operating efficiency. An inlet filter with an increase of pressure drop of 1% reduces compressor capacity by 1%. Oil filters should be changed and strainers cleaned about every 1000 hr. The maintenance time can be done at the same time of the cleaning of compressor and intercoolers from foul and dirt (51). Intake filters they are mainly of three types: dry, oil wet and oil drawn.

Good procedures require the use of a primary housing unit, which host the filter (plastic made). Is of paramount importance for the filter life and to avoid low air quality to leave close and fitted this unit, since most of the dust is removed by the cyclone action inside the housing (52).

The filters applications aim to the delivery of compressed air quality to the lower required energy cost. This energy cost is measured in the filters looking at the differential pressure, with the rule of thumb of 2 psi increased differential, requiring 1 more HP by the compressors.

The replacing of the filters is recommended after a pre-determined time span, because of possible rupture of the filter media that won't give a correlation between the delta-p (unchanged) and the filtering effect of the device (lowered or null); the recommendation is of changing compressor filters every 12 months (53).

Filters selection

Look for the ratings of filter when selecting it (52):

- Extraction efficiency: is the % of dust removed from the air with the related size;
- Flow rate: bigger flows require bigger air filters;
- Dust capacity: pressure drop along the filter increase with the dust accumulation, seek for the reduction of performances with the pressure drop;
- Comparing filters remember that small changes in extraction efficiency change a lot the situation, since the rates of reduction are very high i.e. a 99,8% filter will pass the double of the dust particles of a 99,9% one.
- Compare filters on the saturated pressure drop and not initial pressure drop (53)

Maintenance

The maintenance procedure is quite starightforward (54):

1. Remove the filter element and clean it with a jet of hot water or steam, or plunge it into a strong solution of salt soda;
2. The filter body should be drained and replaced;
3. If the filter is the oil-wetted type, one should dip it in clean, medium-grade oil. Moreover, one may allow it to drain thoroughly before replacing the filter in the intake.

The maintenance problems are not a lot; from a study on 222 firms on compressed air systems have reported the problem of frequent fouling of compressed air intake filter in the 11% of cases, but in the maintenance schedule almost the 60% of firms have the cleaning/replacing of air filters, ranking as the second most implemented (55).

The maintenance procedure can be performed in each of the compressors separately and is quite easy and straightforward.

Benefits

The cost of purchasing the filter, replace of the filters and the unavoidable pressure drop by the filter presence, are traded off by hidden benefits that the user cannot see unless they stop to apply filters:

- Noise reduction;
- Contaminants inside the compressor house can worn the compressor inlet walls, reducing their life-time;
- Save the compressor oil, oil separator and oil filters;
- Save from unplanned maintenance (mainly over-heating and clogged coolers).

3.3.8.3 **Database information:**

The number of implementations is very low; when the filter on SME's is applied in the last 16 years, the trend shows only 20 recommendations with 11 implemented. The average simple payback is lower than one year.

3.3.8.4 **Final review**

There are not difficult features in the installation of the component: the procedures to follow are quite easy and straightforward. Apart from the pressure drop across the filter in the intake, that does not influence at all the compressor performances (if the filtering element is maintained clean), there is not any difficulty.

3.3.9 *Reduce the pressure of compressed air to the minimum required*

3.3.9.1 **Intervention information:**

The pressure is one key parameter for delivering air at optimal conditions. In any case the pressure of the system is set on the minimum for the requirements by end-users. Starting from the point of use one can go upstream, determining what is the pressure required by compressor unit, taking into account all the losses along the system. The good design of the system should prescribe losses lower than 10% (without pressure reducers) (56) (25) from the production to the delivery of compressed air. All the equipment built in the compressed air line, account for the current pressure requirements. It's not only a matter of the compressor but a high involvement from all the components: piping, valves, dryers, filters and the design of the line.

With an electrical system similitude, the hoses and piping lines are affected by some resistance, represented by low fitting of fluid or friction along the pipe walls. This characterize the pressure losses that, as consequence can be minimized with the choice of the right material and the higher diameter associated with lowest length possible; the leaks are another major source for pressure drop across the lines.

As a rule of thumb by many manufacturers and technicians, for every 2-psi increase in the discharge pressure, the energy required by the compressor goes up by 1 percent.

3.3.9.2 **Operations and technology:**

Distribution, demand side and usual compressed air system equipment are possible source of pressure drops.

In the supply side equipment, main items where pressure drop are localized are air/oil separator, moisture separator, dryers, filters and others (25). If the compressor is packaged, pressure signals are located at the discharge of the package; when more compressors are in parallel and the signal is moved downstream the air treatment equipment, one may lose information about localized pressure drops on that units. The pressure drops upstream the compressor requires a higher compression work to achieve the set discharge pressure.

About the distribution system, the main header pressure prescribes the possible end point-of-use conditions. Main header should be sized to not overcome the 20 ft/sec velocity to minimize pressure drops and to account for possible future expansions (45). The trade-off on the piping dimension is about the pressure losses, increasing with the turbulence inside the pipe, and the higher flow rate achievements with a constant pipe diameter and more promptness to fluctuating demand.

On the demand side, there is the possibility of applying some gauge exactly before the point-of-use, to gather information on the current demand requirements. Information about the effective state of the fluid is of utmost importance, as well as delivering fluid with at right pressure levels, to ensure the minimization of artificial demand (25).

Please note that the reduction of artificial demand is highly related to the pressure reduction along the compressed air lines

Bad maintenance of filters, as well as the under sizing of the piping system are two of the major causes for pressure drop, leaded to low attention from design and maintenance phase[13]. A higher initial expense on pressure measurement devices at different points can

[13] For filters refer to 3.3.8. The maintenance is quite the same for every filter, expanding the applicability to all the filters in the line (other than the intake ones).

help the detection of the problem for a lower pressure in some point-of-use (25) e.g. installing female Pete's plug in the lines.

Reducing system operating pressure can entail heavy modifications of other system parts, as matching performances with controls, compressed air storage devices, capacity and location. In load/unload compressors the setting pressures may require adjustment if the lowering of the system pressure lead to a lower of the discharge pressure of the compressor. An additional consideration is that a higher flow rate translates immediately in higher pressure drops and leakages.

Solutions and benefits: the reduction of the pressure gives additional benefits as the reduction of the total flow (57), in some case this can lead to lower number of compressors to run, but for sure a reduction in the power requirement is a direct consequence of this efficiency measure.

Manufacturer importance: check if manufacturers include pressure drops in filters, regulators, and hoses in P requirements for end-use equipment. Check also the compressor manufacturer for performance specification at different discharge pressures. Check for exercise P drops instead of new equipment P drops: the pressure drop under stress conditions is much more important that the nameplate drop with ideal condition flow (see 3.3.8 on filters). For this procedure is of utmost importance the information by the manufacturers of components.

Additional units for localized uses of high pressures: as highlighted in many case study, and by literature review, the compressed air system design is on the minimum required pressure by the system, but no further clarifications are present on this point. The fact to outline, is that usually the minimum pressure required is NOT the maximum pressure of the end-uses (increased by the forecasts on artificial demand), but lower. This depend on the flows along the line. If, for instance, a single end-user requires more pressure, rather than increasing the overall system pressure is energy efficient to feed the machine with a separated unit; if it's not convenient (high energy consumption by the machine), the alternative may lie in a power booster (57) that takes already pressurized air from the main line, and further increase the P to the requirements of the utility. In general, the cost of the singular improvement probably will be insignificant compared to the energy savings by operating the system at a lower pressure (25).

3.3.9.3 **Database information:**

The overall implementation rate is 2216/4470= 49,57% and the recommendation for almost the 70% is suggested on SME's. This influence on the firm dimensions for the recommendations can be explained with the lack of management procedures for handling a big problem as the pressure drop, and secondly an overall lack of monitoring systems on individuation the pressure drops. The problem is so wide, that if one has no idea on how the system works, is impossible to act in a coherent manner to eliminate it. This is expected in all the intervention that are not concentrated in a piece of hardware but the cause can be anywhere. No big differences in the implementation rates on different dimensions are shown; the big ones have 46,14% versus the 50,99% of the Small Medium. On this, since the average cost is much higher for high systems, this should have influenced a lot the higher rates of the second group.

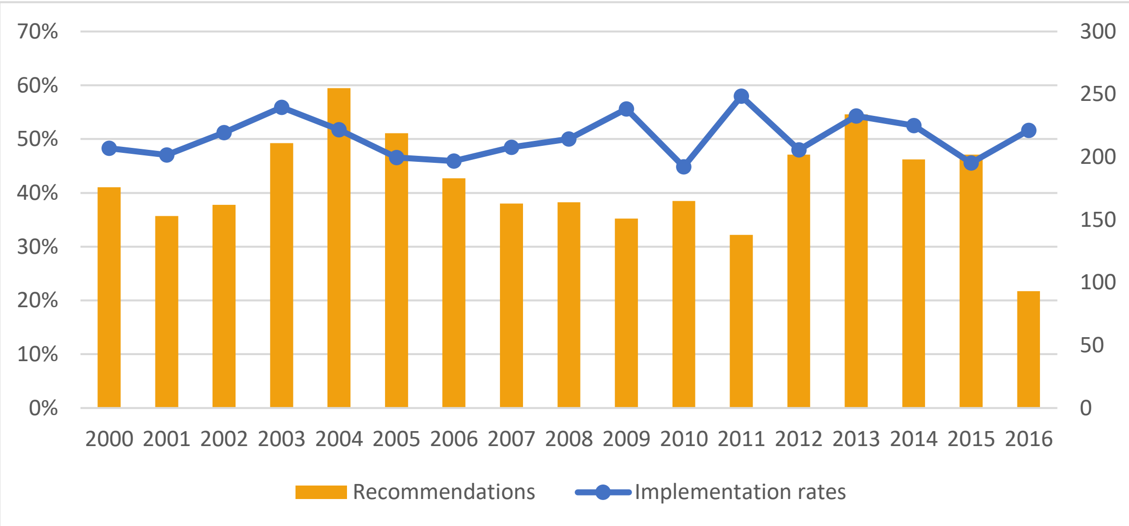

Figure 19: trend for the adoption of "Reduce the pressure of compressed air to the minimum required" EEM

The cost is highly influenced by the dimension, and the sector highlight big difference in the cost for motor and vehicles firms, with an average cost that is very high, around 14.000 €, but that can lead to higher savings opportunities (maybe the decoupled demand side applications have some bad design, and since the pneumatic tools used in this type of firms are a lot, the implementation cost of the measure is function of the points of use amount). The literature reference on the consumption of compressed air systems (55), in which the industry is given as "transportation equipment", outline as this is the third source for shares of compressed air consumption on the total electric use (14%). Moreover, with respect to the others, is using compressed air exclusively to power plantwide systems and not directly to the production process[14]. The suggestions on the industry sector, is that, as expected, very high savings potential is possible in that industries that have not compressed air usage in the production process. The filter on the SME's in the last 16 years, gives a higher implementation rate of 51,76 % and an average payback of 7 months. Highest implementation rates are present in the textile industry (56,57%) and the lowest, that anyway is not that low in absolute terms, in the wood and furniture sector (45,5%).

3.3.9.4 **Final review:**

Since the pressure losses can be located anywhere throughout the system, and most of the equipment change their performances working to a different pressure level, the measure is not independent from the system components' performances. Solution and benefits are the following:

- Correctly size the line for a maximum drop of 1-2% and consider impact of future expansions on pressure reduction;
- A sound air treatment equipment should reduce corrosive fluid parts, that increase the pipes wearing, with a direct effect on pressure drops;
- Economically speaking, the increase in the generated pressure by the compressor in order to have a higher pressure in the end-use side, is the worst choice. It's not sure at all that this action leads to higher pressure at the demand side: losses and leaks are amplified by higher pressure and the demand side could be not see the consequences of the higher supply side pressure (24) (58);
- The utilization of modern regulation equipment can reduce the drop up to 0,5 bar;
- Specify size of components on actual flow rate and not average flow rate;
- Specify homogenous points of gauge for pressure for all compressor units i.e. after common dryers and filters in the main header line; usually the gauge predefined are located downstream the compressor discharge;
- Check from the manufactures of system components real pressure requirements;

[14] The energy estimates on compressed air consumption are not able to disaggregate the compressed air used for processes versus the plantwide systems (cross-cutting technology)

- Consider the possibility of installing single equipment for low flow-rates high-pressure applications, rather than increasing the overall pressure of the system;
- If the firm has more end-uses, should contact different manufacturers for the optimal conditions under some pressure drops;
- Air receiver can be a shield, so that, the pressure control can be upstream (at the discharge of the compressor, to change this pressure is required advice to the compressor's manufacturer) or downstream on the demand side, not affected by changing in working pressure on compressors. The control of system pressure downstream the air receiver can affect as much as 10% of energy consumption.

3.3.10 *Eliminate or reduce compressed air used for cooling, agitating liquids, moving product or drying; Eliminate permanently the use of compressed air*

3.3.10.1 **Intervention information:**

This intervention cluster two of the efficiency measures in compressed air systems because they have a common matrix. Both entail the dismission of a compressed air line, but the second have no substitution with other technologies: one may think the first as an extension of the second. A further consideration is the low number of recommendation of the second measure with only 286 suggestions in the IAC database.

Here the point to outline is the wrong use of the technologies that can substituted by a much more efficient equipment units. The alternatives for the use of compressed air are a lot, and cover a wide range of applications that are going to be listed (most of them, for which literature data were available) in the next section, since the difference is going to cover different technologies.

3.3.10.2 **Operations and technology:**

The effort of the cutting-off compressed air system, is quite the same in terms of skill of the operator involved, despite the workforce load depends on the line extension and involvement in the processes inside the firm. Technologies can be replaced with new ones, much more energy efficient; the most relevant (in terms of spread of end-uses) are grouped here.

An alternative in compressed air is found to be the blower technology, basically providing very low pressures with a high volume of air being compressed. The Free air delivery can go up to more than 7 thousand cfm and the typical pressures arrive up to 1.4 bar. The installation procedure is very easy in case of integration with existing compressed air network[15] as outlined by some new technology blower supplier.
In general, the blowers are required when operating pressures does not overcome 2 bars (a typical use as substitution is found in the dense-phase transport air).
Sometimes, with blower applications, rises up the problem of the electric service requirements needed at the point of use. Despite this, the operating costs of blowers are far less, so where can be installed (59), for example in agitating tanks, is always an opportunity to exploit. If the requirements are intermittent the blowers can consume more energy, since they are typically constant running systems, and moreover if the application is not so large, the lower power requirements of the blowers became marginal with respect to the compressed air one (60).
Reliability of the blower-systems are in general lower, so the importance of spare parts is fundamental for the application, especially if critical (60).

For dense phase transport in the article literature are investigated the pressure drops across the lines (61), but not the energetic impact of using a metered storage aside the regulated plant air supply, rather than using the current supply as the storage. The problem of this system is the high volume required in short time. The consequence is that, even if the pressure requirements are not too high, the preference is to produce higher pressure air and then reduce the pressure supplying more. This lead to the production of air at 80-90 psig, that is used to feed parts of the system requiring much lower pressures, 60 or 70 for the booster nozzles, 35-40 psig for the transport air (25).
The most efficient units of blowers can save up to 80% of the energy spent by an air compressed system.

The vacuum generators are another typical inefficient use of the compressed air: they are very easy to implement, the size is quite small, lightweight, no electricity is required in the end-use point and their low capital cost and promptness of availability (62) may render this application attractive; moreover, if they have load coefficient lower than 0,3 their operative

[15] Variable speed direct drive centrifugal air blowers, Atlas Copco catalogue

cost is lower than a centralized system. In all other cases, except for uses in a very wide area or for safety reasons, their use is strongly to avoid because of high operative costs. The motor-driven dedicated vacuum pump is a valid alternative for the low dimensions and ease of installation, the central unit has the disadvantage of a high initial cost as well as the design of the system. The conditions for which use of vacuum generators (25) (compressed air driven) is convenient, are:

1. Low duty cycle (high peak load applications[16]);
2. Different vacuum levels required.

The main problem with this type of adoption, is to have a clear view of what are the capital and operative cost for the different technologies. Expertise in the field is required for the right choice, because as outlined by Pascoe (62), is very common that the vacuum worked before will be used again, so a better knowledge on the technology can break down barriers for ignorance and difficulty in exploiting opportunities for savings.

Concerning to blow-off applications (63) (64), the latest innovation in new technologies can be exploited, but the suggestion is always to see if benefits with lower costs can be achieved, weighting the costs over the benefits. In bottles industry, a good low-cost option is found to be the blending of compressed air with ambient air associated with high performance nozzles (Venturi type or engineered nozzles), for which the volume air requirement is reduced a lot. This example belongs to the "partial wrong use of compressed air" or more correctly to the "use of engineered nozzles". The lower operating costs is due to the lower amount of air.
The aforementioned option can be a low-cost alternative to the more expensive passage to blowers, although of course not that effective from an energetic point of view. In this case one saves on the new blower technology with the simple installation of high performance nozzles.
General comments are that the investment is worth but the BEST investment does not exist,

[16] Note that if the peak load requires a second compressor to be started for the peak volume, this may lower the benefits obtained by the compressed air application. The process engineer has to evaluate the life-cycle costs of the system to make a sound choice about the right technology to adopt.

since the option should be tailored to the specific lines composing the compressed air network, as well as the capability of the firm on sustaining the installation costs.

Electrical fans are a valid alternative for aerating areas where no much power is required but a constant air movement is needed. Is the most implemented solution for personal cooling substitution. Electrical fans are another technology with respect to compressed air. The start-up phase is of utmost importance and inspections are user's responsibility so that a quite high consciousness has to be present for that technology. Eventually, one may delegate to external experts the installation, but in any case, the initial inspection can be time consuming and affect also economically the installation of such measure; the source of problems can be very hard to diagnose, so that the knowledge and inquisitiveness required render it an "art" more than a "science" (65).

Diaphragm pumps suffer from the lack of specific equipment for their control and regulation. The over regulation, with a pressure higher than necessary, leads to an increase of demand of compressed air; the other problem of this device is the amount of flow to provide, since it should be brought to the minimum required. The cause of these problem is the loss of this devices in the standard package of the pump. Where isn't in place, one may think on substituting it with an electric pump, with the advantage of lower wear and maintenance costs (25).

Pneumatic actuators are used for their safety and precision characteristics, but many times the lower energy consumption of the electric actuators is to consider as an alternative to not underestimate, as well as the pneumatic motors have a power ratio of 6-7 times the equivalent direct drive electric source; if not light weight or sparkles explosions are required, consider the high savings potential of the substitution.

3.3.10.3 Database information:

On the first of the two efficiency measures, that is the most diffused, the SME's in the '00s and '10s have a total implementation rate of 42,69 % with an average payback of less than 9 months. The permanent elimination of compressed air line has a much lower implementation rate in SME's with 26 out of 73 recommended (35,62%), despite the payback is slightly more than 1 year.

3.3.10.4 **Final review:**

The technologies to use in place of compressed air are very different. The hypothesis for the adoption is that the installation is profitable from a technological point of view (the blowers have a high enough cycle time that justify the installation, the vacuum pumps have low load coefficients, etc...):

- the lack of diffusion of knowledge about the new technologies to adopt one of the major factors that can inhibit the investment;
- the spread number of configurations depends on the different technology and the specific application and this lead to the lack of performances on the true energy benefits;
- the electrical service availability close to the installation can be another factor hindering the installation procedure. The compressed air, on the other hand, can easily access some of the points that are difficult to reach for the electrical lines.

3.3.11 *Abandoned equipment*

3.3.11.1 **Intervention information:**

The cut-off of the abandoned equipment refers to some change that occurred over time in the layout or operating process, or some malfunctioning leading to the line replacement. The air flow should be stopped, but the need should be underestimated if it impacts only one of the end-uses (25) (66). Reasonably, one can think that more the air waste is relevant in terms of equipment involved, more the attention is keep high on that side; on the other hand, if only one end use branch is affected, the personnel can think that disconnecting the equipment time/effort may not be worth enough. Best practices prescribe to operate as soon as possible the disconnection, that can have some other positive benefits such as noise reduction from the equipment and saving the space occupied by the equipment itself.

3.3.11.2 **Database information:**

For the inappropriate uses of compressed air there is about the 45% of the implementation rates. The recommendations are 1452, of which 994 are for small and medium enterprises, highlighting that the compressed air is used for other purposes in the SM realities. This is expected, because different technologies from compressed air have a lower number of applications, and the savings may be not as high as expected leading to misuse of compressed air rather than adopting new technologies. The amount of savings is 8746 dollars on average and the payback is almost one year. The firm dimension seem to have not a big influence on the implementation rate, with the 46,4 % for the SMEs. The abandoned equipment on the other hand have 52 implemented out of the 80 with a payback slightly lower than 9 months

For the intervention on personnel cooling, it was recommended for the first time in 1995, but is unknown if the reason is that was considered embedded in 3.3.10 or was not find in any of the assessment sites. In any case the implementation rates are slightly higher with 17 over 28 implemented: 60,7 %. The reason can be find in the higher attention payed by plant in security issues, that can act as a driver for the implementation of the intervention.

3.3.11.3 **Final review:**

For Seslija, Ignjatovic Dudic (67) the lack of valves for interrupting the supply to certain parts no longer in use (or not operated if more than one shift is present) are one of the major problems for bad working conditions of the distribution network.

Competences and awareness of the energetic waste can be major problems:

- The major problem with this installation of the measure lays in the accessibility of the piping and easiness of maneuver for the disconnection of the air supply to the equipment, leading to high hidden costs for the plant. The low accessibility can have an impact also on the measure of the real wasted air;
- The factors on the low interest in the energetic problem, or on the EEMs for cross cutting technologies can discourage the investment decision. In this case the awareness on the benefits are lacking.

When the lines are idle for a lot of during the production cycle, it is suggested the installation of shut-off valves, activated after a certain amount of time. The success of the installation is guaranteed by the high potential savings (68).

3.3.12 *Cool compressor air intake with heat exchanger*

3.3.12.1 **Intervention information:**

As introduced in the intervention on the cooler intake air (3.3.3), the low temperature air, has the potential of increasing the air density, giving more volume capacity at the compressor output, and maximizing the efficiency of compression because of the more air compressed per time unit.

The lowering of the inlet temperature, have different effects, depending on the compressor types: the screw, centrifugal and positive displacement have particular features to be outlined.

3.3.12.2 Operation and technology:

Oil-injected screw: the compression in this device is the more like an isothermal transformation for the presence of the lubricant acting continuously as a cooler inside the compression chamber (space through the screws):

- the volume is constant with inlet temperature;
- the delivered flow is proportional to the inlet temperature. A decrease of 5 °C results in a 1,9% increase in mass flow;
- the required power in an isothermal compression depends only on pressure ratio and speed of compression; since the device diverts from ideal conditions, the power go slightly up with the lowering of inlet Temperature.

The overall efficiency of the compressor is higher in scfm/kW, because the mass flow increases more than the decrease of power.

On the other hand, depending on the control method used, the increased flow can lead to an equal or even lower efficiency. Let's consider two different compressors, one running and one controlled. In a **modulating** system, the increasing pressure for the higher mass flow rate leads to a higher power and a higher modulation, which decrease the overall efficiency; if the regulation of the trim compressor is **load-unload** the unload condition are more frequent and the idle time increase, decreasing the efficiency; in the **VSD** compressor, it reduces the speed increasing the efficiency, because of reduced load. In this last case, the overall efficiency will increase.

Oil-free screw: usually this application is for higher air quality performances, where strict and clean ambient conditions are required and no oil presence is allowed in air stream. The mechanical of the rotors is slightly different from the lubricated counterpart, because the parts of the rotors are not in contact due to the lubricant absence. For this reason, leaks are usually higher and the synchronization is maintained from an external gearbox. The speeds in place are usually lower because of the higher temperatures due to the internal cooling absence. The increased temperature per stage is the highest of the analyzed compressors; moreover:

- the inlet volume is constant with inlet temperature;
- again, a 5°C increase in inlet temperature, gives an increase of 1,9% in mass flow;
- high inlet temperature can cause outlet temperature to rise uncontrolled, with the risk of shutdown of equipment;
- low inlet temperature causes the temperature of the intercooler/aftercooler to be in control of possible high moisture condensation.

The compression is more like an adiabatic, so the high pressures lead to a volumetric efficiency drop and, as consequence, no efficiency in terms of increasing of scfm per kW. Being in a condition of controlled intercooler, the cooler the inlet, the safer from shutdown of the system. Control types of this units are usually the load-unload and the VSD. The **load-unload** regulation unloads the compressor for more time, with an energetic offset in the reduction load of the trim compressor, by the increased energy of the base compressor, with the further drawback of increasing the idling time. The **VSD** regulation method has the same energetic principle of the load-unload regulation, without the second drawback, giving potential for the same efficiency.

Centrifugal compressor: the multi-stage centrifugal compressors, are increasing their share in the last years for increased efficiency and capability of delivering a high capacity of flows. The flows entering the compressor varies with the point of use in the efficiency diagram. Moreover:

- inlet pressure depends on the fluid density. The higher density increases the pressure and the compressor is going to work on a different efficiency point, as well as an increasing of speed;
- the IGV control, if present is tending to push back the pressure rise to have a higher efficiency in a better end-use point;
- the regulation range increases because of the increased distance from surge point when the curve goes up;
- inlet mass increase with lower temperature, gives the higher power and the risk of overload should be considered with a control on maximum current;
- is more sensitive to inlet temperature change with respect to an oil free-compressor. The power and flow ranges change more or less of the same amount.

Efficiency is fairly constant with inlet temperature. The protection against surge is increased, motor load can increase and delivery of air increase as well, saying that from an energy efficiency point of view is not worth the implementation of such measure.

3.3.12.3 **Database information:**

The recommendations are quite low with a total of 50. The implementation rate is 44%, but the average implementation cost is quite high, with more than 7000 dollars. In the last years (from 2000) the SME have implemented only 10 on a total of 26 recommended (38,46%) but the payback is quite high respect to other installations on compressed air systems, with 1year and 8months on average.

3.3.12.4 **Final review:**

Calculations about the real amount of saved energy is vital for a sound implementation; the payback can be increased a lot by the real impact on the efficiency, because the control on compressors are influenced by the actual fluid condition. Moreover, the intake air lower temperature can lead to an increase of the maximum flow rate in the line; the decision-maker should take into account all these concepts before the final choice. Maybe, in some cases, the reason for this adoption can go beyond the energetic savings: one can increase the regulation range (centrifugal unit) or can use the lower temperature as a preventive means against shutdowns. The measure has revealed to be energy-efficient on the oil-lubricated screw compressors system with variable frequency controls.

The implications of this measure are in part overlapped with the measure of installing the intake on the coolest place possible, at least for the implications about temperature. The installation of a heat exchanger is easier, requiring only enough space around the compressor.

3.3.13 ***Eliminate leaks in inert gas and compressed air lines/valves***

3.3.13.1 **Intervention information:**

Leaks are the major source for cost savings in the compressed air system. The leakage of a small hole in the system, can have a high impact on the final consumption, depending on the leak size and the pressure in place. Additional indirect drawbacks are present, such as the lower pressure by the system due to leaks, that for long time can lead to malfunctioning of control on compressors (that adapt their load to the new pressure established). The pressure drop, of course determines an artificial demand that make the equipment run for more time than required, or at a higher pressure, both determining a lower lifetime of the equipment (25).

Maintenance is of paramount importance to prevent leaks occurrence, but in any case, leaks are always present, because the non-perfect fittings, coupling units, valves connection, thread sealing etc... A good leak management program (proactive detection and repair) ensures that leaks does not overcome 5-10% of the total compressed air production; more in general the leakage rate should be at an economically acceptable level.

Since two types of leaks exist, here there is a focus on the unplanned leaks, since the planned ones are usually made for the production processes (blow-off or particular applications), or to fix problems inside the system (basically in a wrong way). In this last case, please note and redirect to the previously treated problems with wrong uses of compressed air, such as leaks for cooling purposes (3.3.10).

The unplanned leakages, most of times, can be prevented by different operational good practices such as: avoid the wrong tightening of assembling parts, the incorrect handling of the components, the wear of the components and stressful operating condition for wrong material in place (69). Rectifying leakages should be done as soon as possible, once the leak is identified, because of the immediate benefits outlined before, but the management procedures are different for different leakages; just think that the 20% of the leak in existing system, usually account for the 80% of the extra energy cost.

The dimension and position of the leak, should act as a measure of the promptness needed to rectify the problem, so a well-structured program is the way to cope with the leak issues. Leak management programs have been developed along the years and implies the seeking, repair and the follow-up adjusting of equipment for increasing efficiency, compressors and overall compressed air system reliability. The fundamental passage to understand is that, although the key elements of the procedure are always the same, the potential of leak repair program is very dependent on the correct baseline of the actual compressed air usage and on the real potential for savings through the calculation of leaks/pressure in place.

This efficiency measure refers to the energy savings opportunity from leak repair; this means that theoretically the total amount of leakage has been estimated. But the assumption, here, is that only the total amount is roughly estimated, and the recommendation is suggested over a certain % of leakage with respect to the total compressed air production, meaning that the detection and location of leaks is part of the efficiency measure to be implemented.

Rough calculations for the estimate of leaks amount depends on the compressor technology (25):

$$Leakage\ (\%) = [(Tx100)/(T+t)]$$

T=on-load time (min);
t=off-load time (min);

$$Leakage^{17} = V\ x\ (P_1 - P_2)/(Tx14.7)\ x\ 1{,}25$$

V=Volume in cubic feet;
P= pressure in psig;
T=time in minutes.

3.3.13.2 The implementation problem: bad estimates and disappointing results

A very interesting document by Hank Van Ormer (70), outlines the problems with the implementation of such measure of energy efficiency. He, more than focusing on the leak estimate and calculating the potential for savings with straightforward methods found in manuals and sourcebooks, points out the heart of the matter under a different perspective, trying to understand why this energy saving operation has not yet optimal implementation rates. The database of the IAC suggest that the leak procedure gives an average implementation of more than 80%, that is more than satisfying compared to the others.

But here a deeper focus on the problem is worthwhile: this measure, unlike all the others, independently on the size, number of employees, production process, type of compressors and control used throughout the system, is a measure that if recommended should be always put in place, because the potential of savings are always positive. The payback is one of the lower with on average 5 months and the expenditure are only for the detection of all the leaks, despite one may think of overcome this expense focusing only on visible leaks.

Van Ormer points out that the reason for disappointing project of this type, lie in two basic issues:

[17] Cfm of free air

- the major, is the inexperienced personnel tending to overestimate the actual volume of leaks, leading to potential savings that will never be reached; the well-known orifice/cfm savings table in fact, consider only perfect regular holes with increasing diameter, and the pressure of the leak equal to the one of the mains;
- true recoverable value recovered with leaks elimination is varying respect to estimates because the values of saving in scfm/input power are at full load, so that the changes given by the part load operation (depending on controls) can overstate the savings. Even the post-project consequences can vary the calculated savings i.e. if the saving permit the shutoff of one unit, the savings may be understated.

The passages for a sound leak management projects are:

- Baselining the current state of the system;
- Estimation of leaks all along the site, with one of the leak load tests, when the demand side applications are turned off:
    - Monitored compressor operation in case of start/stop or load/unload controls, and measuring the average time to load and unload the compressor. The load/unload cycles are given by pressure drop of the leaks so the number of leaks can be determined as % of compressor capacity losses;
    - Bleed down test is useful in case of other compressor controls: after the system is pumped up to full pressure the units are shut-off and the time to reach half of the peak pressure is calculated. Note that for this procedure the exact volume of the system volume has to be used, including pipes capacity and any secondary air receiver downstream.
- Leak detection: consider that the detection always requires labor cost and equipment. The method provides for an ultrasonic acoustic detector and its auxiliary equipment or in a simpler, but more time expensive way, with water soap to apply with a brush for painting; other methods can be the addition of pigment and gases to make the leak visible. The first method is for sure the more reliable and versatile, moreover they require a minimum training (15 minutes can be enough) and the test works even with working equipment. Some machines may be, not accessible during production time and in this case the potential energy savings are understated.
- Leak documentation: to have a log about location, size, reading and brief explanation about useful both for the prioritization of repair areas/specific leaks and also to act as feedback for projects in future;

- Once the major/all problem are fixed a post-project is fundamental for the efficient operation in new system conditions i.e. regulating again the controls on single compressors and setting the new pressure range in the mains as the operational ones.

The detection of leaks, can be done by automatic equipment installed on each of the machines, that reports on a daily basis the amount wasted by each unit. This provide a continuous monitoring, and the devices are easily adaptable on the current PLC control. The decision maker, on the basis of current leaks rate and baseline of the system, can decide if this installation is worthwhile.

Leak surveys (i.e. detection) are suggested on an annual or biannual basis. One of the practices to exploit when a survey is being made, found to be convenient in petrochemical plants, is to have a local employer of local contractor (pipefitter or operator) that is able to fix on the spot the worst leaks in terms of compressed air lost, and easiness of handling: this procedure can save moneys and compressed air immediately creating a payback from the moment of the survey itself (71).

Leaks can be reduced as well not acting directly on them, but by simple operational accuracy. In this case the leakage prevention and maintenance program is not implemented but there is some reference with measures explained in other paragraphs:

Reduction of plant operating pressure gives an overall leak rate to reduce, because of the less thrust on the escaping point. Pressure regulation on demand side can be figured out by applying a pressure value lower than the one present on the header, reducing leak rates in that part of the system. Moreover, applying an automatic valve that idles the compressor when the end-side is turned off by the operator, gives the opportunity to avoid compressors to supply pressure on leaks (see also 3.3.9 for pressure reduction operative solutions). The automatic electric valves are useful even in case of not worthy investment: if there is the presence of pneumatic circuits, the compressed air is for sure not used for most of the time. For this reason, a central PLC controller can manage the cycle of the pneumatic cylinders turning off the air supply for the most of time. Imagine a project plant having a huge number of cylinders and which for an investment on pneumatic circuits have a forecast of years' payback (72).

3.3.13.3 **Database information:**

The overall implementation rate is the highest of the efficiency measures, as well as the recommendations. This means adopters are aware of the potential given by leaks elimination or reduction, but they do not adopt preventive solutions to eliminate the risk.

On adoption by SME's, the implementation rate in the last 16 years is 79,34%, in line with the overall sample.

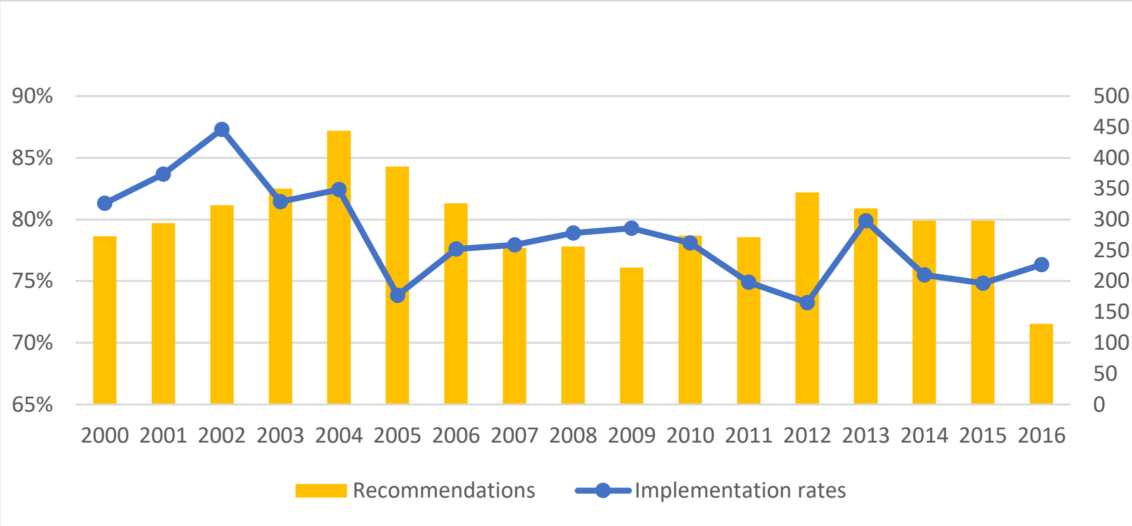

Figure 20: trend for the adoption of "eliminate leaks in inert gas and compressed air lines/valves" EEM

3.3.13.4 **Final review:**

Since the different detection program influences a lot the system operational state, training and need for personnel, purchasing of different equipment, at this point there will be the focus on the influencing factors on the measure to implement, and how these influence different barriers for the energy efficiency.

Leak detection through noise is the easiest method to be implemented and has the lowest investment cost. Despite this, can result in any case the worst economically speaking:

- Cost for the **shutdown of the equipment** is to take into account, highly influencing the cost of lost production.
- The **accessibility of the piping** system can hinder the adoption because of the resources are not able to manage comfortably the leak location point; moreover, the accessibility can influence negatively rate of adoption of this method because certain background conditions are present (noisy environment);

Leak detection through detection spray:

- The high time for inspection mean that high costs for the measure implementation are needed;
- The **accessibility of the piping** system can hinder the adoption because of the resources are not able to manage comfortably the leak location point; moreover, the accessibility can influence negatively rate of adoption of this method because certain background conditions are present (noisy environment).

The ultrasonic leak detection has revealed to be the best way (and as consequence also the most suggested by suppliers), but despite the objective advantages, the cons are quite different with respect to the others; this means that different barriers are in place for the decision:

- Skills needed for operators inspecting the detection is higher with respect to other cases: they need to have enough training and information about the ultrasonic technology;
- The tools for the detection are all but economics, the alternative is the outsourcing of the service (for instance Auditech is a service supplier) but the maintenance of the leak program prescribes a set time to perform the assessment.

Despite the leak control has a primary importance in maintaining efficient a compressed air system, the influences of the measure on the overall system cannot be avoided for a complete picture of how the decision is going to be take. Efforts required to actuate a preventive maintenance program for the leak detection is oversaw the maintenance personnel, but for this purpose the installation of monitoring devices can help a lot. The effort required is high in terms of time, but the difficulty is varying depending on the technology used. The impacts of the measure, referred as the one-time reduction of leaks, may lead to significant changes in the utilization of equipment, because of the higher flow rate available.

On additional benefits are advisable the pressure reduction as consequence of higher flow rates in the piping system and as direct consequence the reduction of artificial demand. The leaks make the fluid flowing at a higher pressure, with a negative effect on the pressure delivery at the end-use point.

3.3.14 *Substitute compressed air cooling with water or air cooling*

3.3.14.1 **Intervention information:**

The cooling of the compressor is revealed to be one of the greatest source of energy savings for the compression units. The lower temperatures ensure a higher amount of air in the compressors, and moreover, the air in the compressor outlet should be reduced in temperature for (i) the blowdown collection and (ii) to avoid heat exchanges once the air is in the point of use. The compressed air cooling can be a source for decision makers to reduce some cost, but the first step is to understand the alternative types of coolers available for the current system.

The decision on the cooling system to adopt is given by the nameplate horsepower of the compressor, and number of compressors. The second step identifies the power available in the site and particular conditions of upstream air required for some of the equipment (dryers). The step forward is to determine the maximum heat load, and for this data is figured out by the maximum BHP of the compressor. A security margin is introduced to take into account dirt, inefficiencies and condensation, so that the max heat load is increased by some percent.

The temperature approach on the compressor data sheet gives information about the cooling fluid temperature, and as consequence, the more appropriate cooling method to use in the application (73). If data are not available, instruments need to be installed to measure flows, temperatures in play, and pressure requirement.

Closed loop cooling methods, prevent from the continuous use of air and water supply from the external ambient and treatment of water/air to ensure an efficient heat exchange; they require much more reliable system to prevent from inefficiencies given by coolant issues inside the piping, though.

The advantage of using a vortex technology compressed air cooling unit is the fact that no moving parts are in place, and the simple installation and little maintenance (74). For whatever assessment, except for operational cost, is seems to be great. The problem is that, this “except for” can be a huge cost in the electrical bill, depending on operational hours of the plant. Considering an average specific power of 22 kW/100 cfm with a consumption of 20 cfm and a high electricity cost 10 cents/kWh, the annual consumption for 8h/dd is 1285 $/y. The consumption is doubled of triplicate for more shifts per day, increasing the gap with a more energetic efficient solution. In this case the refrigerant dryer can be the appropriate solution, with the only drawback of increasing in maintenance expenses due to dust collected in the grid. The other solution if the cooling requirements are not so high can be a forced convection cooling system. The refrigerant coolers can be equipped with a control unit, increasing the total cost but going down with operational cost, with peaks reaching more than the 90%. The solution is to consider if the energy cost is quite high (Italy) and/or if is possible to exploit some aid come from incentives.

Additional benefits of this retrofit can be the lower noise caused by the coolers, maintaining a lower acoustic pollution in the workplace. And the safety requirements for the use of appropriate coolers.

3.3.14.2 **Operations and technology:**

The cooling performances have to be taken always into account because the air operating parameters (in term of pressure and temperature) at the outlet of the compressor unit and aftercooler determines the rated capacity of the air dryer i.e. higher temperatures increase the moisture quantity per flow rate unit, reducing the dryer capabilities of the drying units.

To have a more comprehensive view, where some "good" cooling system is present, a retrofit of the same can be identified as a great source of energy saving. In case of water cooled units, the high quantity of water consumption can be a great expense for the facilities; moreover, problems may rise for the water treatment cost. The decision makers can focus on the switch to air cooled compressors (or dryers) or on less consuming water cooling systems (75). Whatever possible the air-cooled units have some constrains to overcome, as the room ventilation, ambient temperature (even though the modern units withdraw to much highest temperatures than in the past), giving always a look on the performance capability of equipment that just follow the coolers' systems.

The retrofit of air cooled compressor is performed to increase the efficiency through the enhancement of air cooling potential; drawbacks of the retrofit are always to consider, and can have a bad influence on future energy savings operations decision by the energy manager (o who oversees energetic issues). One simple example is the pre-cleaning of air from dust and air-borne particles with a bag filter. This influence the volume of air flowing into the cooling area, and as consequence the compressor room air is far higher than the requirements, losing any benefit from the new installation.

Once the compressed air system is installed, the manufacturer should give better specifications on the cooling medium required (76), despite the water-cooled compressor have usually a slightly lower specific power in kW/100 cfm with respect to the air ones i.e. they are more efficient.

The recommendations are very low, the SME's in the last 16 years have a 56% of implementations but the recommendations are only 18, one each year on average. The payback is 9 months but the average cost is quite high.

3.3.14.3 **Final review**

- In documents by industrial literature, the major suggestion is on contacting manufacturers for the installation of the right cooling method because the best available technology in absolute terms does not exist;
- the fact that the compressed air is used as a cooling method, shed the light on ignorance: the possibility of important energy saving is not considered because the decision-maker did not pay enough attention on the expenditure of compressed air as heat exchange fluid. The cause of the ignorance may be also some supplier, that did not give advices on exploiting suitable cooling methods;
- space requirement for the installation and eventual simulation runs to choose the right cooling method can have a positive impact on the decision, but a negative one on the cost;
- the additional energy requirement for pumping (water cooled) or moving (air-cooled) the medium, lowers the advantage of having lower T for the compressed air i.e. an efficient system;
- availability of sources (lakes, existing cooling towers in the plant) may diminish the investment cost required for the installation;
- working environment enhancements are to consider since working with compressed air is more dangerous and noisy;
- this activity can be synergized with the heat recovery activities, since the air/water used for cooling can be used to heat or pre-heat other plant equipment (77).

3.3.15 ***Heat recovery in compressor and other equipment***

3.3.15.1 **Intervention information:**

The energy entering in the compressed air via electric power, is transferred through the increasing of the pressure and temperature of the fluid. The energy converted into increasing of the pressure is the aim of compressor unit, the temperature rise, on the other hand, is the side effect that cannot be avoided. The energy flux diagram in compressed air is awful thinking that the head generated is being lost because is not useful. The amount of heat that can be recovered is more than 90%, and therefore is a great opportunity to exploit in some cases.

The heat flux recoverable is not located in one single area or piece of equipment but, referring to the most common type of compressor (screw) in industrial application, the 5% remains in the drive motor, the 75% can be recovered to the fluid cooler units, and the remaining part by the aftercooler.

The fluid injected screw compressor and the oil-free screw compressors. They are quite different from a thermodynamic point of view since the difference in temperatures inside the chambers, and as direct consequences the T from which heat can be recovered, so that a distinction is here underlined on the different types of compressors for recovering issues.

3.3.15.2 Operations and technology:

Heat recovery opportunities in different screw compressors:

- water cooled fluid-injected: The 96% of energy is available, the water temperature is in the 70°C range. The space heating requires an extra stage of heat exchange, for fluids recovery (water and coolant oil) with the air required, so that the available temperature is lowered. This application is more suitable for hot water production, despite a double wall heat exchanger is recommended when the heat is extracted from coolant, for tube failure problems. Uses can be heating of non-potable or potable water, central heating and boiler systems;
- air cooled fluid-injected: the amount of energy is lowered since the air have less thermal capacity, 76%, but the temperature range is the same of the water-cooled fluid-injected. As a rule of thumb each 100 cfm of capacity (at full load) corresponds to 14,5 kWh of energy. The air temperature is 17-22°C higher than the cooling air inlet temperature. The energy recovery of this type may not give the right amount of heat when required and maybe not in the right time; this translates in additional energy to the ordinary system, rather than substituting it;
- water-cooled oil-free: The 96% of energy is available, the water temperature range is 90°C. This entails much more opportunities for heat recovery, from the compression elements (stages) to the coolers (intercooler, aftercooler, oil cooler). Built-in solution

for recovery can be present from the manufacturers of packaged compressors for recovery on this compressor type.

Equipment options: the fluid to fluid heat exchangers for heat recovery are of different types, but the most common are the plate-type, that can be installed externally and have quite low investment cost, and the shell and tube one, especially for water-cooled systems; this last unit separates the cooling fluid from the process fluid and is available also in the fail-safe configuration to monitor for leaks in the fluid and starting an alarm signal if needed. In case the supplier of packaged compressor offers such a solution, very low on-site engineering is required.

Plate type

Shell and tube

Fail-safe

Notice that the heat recovery process is highly influenced by the part load working of compressor, so that the trim units have much lower amount of heat recoverable, that is lowers as the part load working time is higher. If not consistent amount of heat can be recovered, the installation can result as not worth; since if not planned before, this requires high engineering, space requirements for eventual ducting, additional heat exchanger and also space vent the source where the hot air/water is required, this suggests to pay attention on the real savings achievable.

In fact, a good planning (78) (25) prescribes the data collection to realize the potential, before the installation, gathering above all: the fluid medium thermal capacity, temperature levels and differentials, volume flow rates, specific heat capacity of the media, hours of operations, continuity of the heat source and structural conditions. As second step, the heat recovered can be used for many purposes, but careful attention should be payed first of installation to look for the right application in your facility, if exist. Possibly is one of the following:

- Industrial process heating;

- Preheating boiling water;
- Make-up air heating;
- space heating;
- Heat-driven chillers;
- Heating food and beverage products.

Than one might determine the heat available energy, looking at compressor parameters and running hours, as well as loading time and the cost of heating energy. At last one may match the heat source with heat use or storage, analyzing the local conditions, period of time when the heat is available etc.

The important point when deciding from such installation are two: the thermal match between the produced hot air/water and the one required in the plant; the other is the time match, the producing hours i.e. hours in which the compressor is running preferably at full load, with the required hours of hot stream.

The real energy savings: to calculate operational total energy savings (34), one should compare the recovered heat amount with the current source of energy for that will be replaced, calculating the efficiency of heat recovery, that is rated at full capacity. Thus, remember to adjust the formula for trim or controlled compressors with the average load, and as consequence the average efficiency in heat recovery:

$$Annual\ energy\ savings\ \left({}^{BTU}/_{yr}\right) = E_{rec} * BHP * 2{,}545 * H$$

Where:

$E_{rec} = recovererable\ energy\ (\%)$
$BHP = Power\ of\ the\ compressor\ in\ horse\ power$
$H = oprating\ hours\ per\ year$
$2{,}454 = conversion\ factor\ ({}^{BTU}/_{BHP - hour})$

$Cost\ savings\ \left({}^{€}/_{year}\right) = AES * C_{fuel}/Eff$

Where:

$AES = annual\ energy\ savings$
$C_{fuel} = cost\ of\ substituting\ fuel\ source$

$Eff = efficiency\ of\ the\ source$

Fans and eventually different ducts for the delivering of heat where required, are not taken into account in this calculation, and should be considered before the installation.

By literature (79), there is a sensible difference in the time recovery of the investment depending on the final utilization. The warm air can be paid back in one year, the water systems are closer to two years. Of course, the time depends over the water and space heating demand by the plant.

Influence on the decision making for the energy savings through heat recovery are a lot, here there is a synthesis of some procedures and routine to check before to undertake the investment, highlighting the factors that influence barriers for the EEM (80):

- little knowledge in thermodynamics laws can lower the efficiency of the compressor where hot air recovered is taken from the compressor room and ducted outside (the direct consequence is the under pressure of the inlet ambient, that acts like a throttled inlet of the compressor);
- Identify opportunity for savings is not that easy since are needed both a thermal match (enthalpic levels) and a time match, leading to the following:

  Heat availability ≠ Economical to recover (34)
- Modification to existing equipment are hidden costs, accrued during the service life;
- For potential investment expenses, consider also the working h/y of compressors, installed electrical power, compressor room location, local temperature range; required specifications are:
  - The distance between the compressor and the point-of use of the hot fluid influence the piping cost and the workforce for the connection; in the easiest case, a little tank and a recirculating pump are sufficient, in the worst situation the plant cost grows up over the threshold for a good investment;
  - A continuous service is much more convenient for the heat recovery, as well as a service optimum yield conditions;
  - The annual working time should be at least of 2000 h/year;
  - Electric power usually should be over 30/45 kW;

3.3.15.3 Database information:

208 of 696 implementations on the last 16 years by SME's are implemented on compressors; the payback is less than one year. The refrigeration condensers heat recovery is much less convenient with an average payback of 2 and a half year, and the implementation rate is 27,58%. There are only 5 recommendations on the heat recovery from dryers.

3.3.15.4 Final review:

From these bullets, good practices standard on the heat recovery and good thermodynamics knowledge, the identified possible implications of the efficiency measures are:

- accessibility to compressor room: modifies a lot the approach to the implementation of the measure, since it can be source of hidden cost for (i) the eventual modification of the equipment to access the room and (ii) the pre-investment to check the capability of the system to deliver the heated fluid to the needed points;
- technological constrains: the technology, despite useful and potentially installable to the current system, cannot be applied in the current condition because the hot fluid is not supplied continuously, and thus will not help as required, leading to low energy benefits;
- technology can be not adequate also in terms of thermal requirements, because many times the heat is available at a temperature far lower than useful. This is particularly true if an additional heat exchanger is needed for the heat delivery throughout the system (i.e. heated water requirements for an air-cooled compressor or air requirements for a water-cooled compressor);
- effort in maintenance is increased because the activity type is a new installation, so both piping and fittings for fluid delivery have higher requirements;
- the air quality is improved when the heat exchange between the aftercooler and lubricant cooler with the air to warm happens, extending air quality and lubricant life (81);
- the tight monitoring of Temperatures that comes from installation, has a positive effect on compressed air equipment life (81).

CHAPTER 4
Model for characterization of interventions in compressed air systems

The construction of the framework has been developed using a synthesis process starting from the major causes and consequences that can have an impact in the decision-making process dealing with the implementation of efficiency measures in compressed air systems. The efficiency measures have been fully described in many manuals and literature articles, with the major concern on cost and economical implication; for instance, some work focus on methods for the evaluation of the energy losses and benefits (21), (82). Poor attention is prescribed on the technological and organizational features of the cross-cutting technologies, for their distance to core processes and the lack of a specific voice accounting for energy-efficiency investments, and this is particularly true for the fourth utility, the compressed air. The scope of this work, is the synthesis of the major characteristics, implications and operative parameters to consider when a decision on compressed air efficiency measure is going to be installed. Mainly, the characteristics and the implications outcomes have been picked up with a bottom-up approach, starting from what are the technological or organizational features of the single efficiency measure and turned in broader attributes that can be applied and adapted to more measures. On the other hand, the categories are found from literature review on energy efficiency measures and innovations. In the first review, more general studies on the efficiency measures characteristics are present (83), and efforts were made to characterize also the cross-cutting technologies (84) through the barriers of influence, clearly distinguishing the intervention dependent barriers form the general ones. Here the focus is thoroughly oriented towards the more empirical side of the characteristics, trying to match the results obtained by the study of the single technology oriented efficiency measures with the ones of the general characteristics owned by each of the EEM. The result, is a tool to use from the decision-making when he/she should undertake such a difficult decision, considering the whole frame of what to expect from its adoption.

The objective of the chapter is to shed the light on all the factors that have some implication accrued in different phases of the efficiency measure's implementation, form the design, installation, or during the service life of the components. In appendix B, all the elements composing the framework are synthetized, in order to have a full-picture of the model.

4.1 Importance of the decision-making process

The decision-making process is the series of events dealing with the passage from the actual condition of the people in charge of the choice, to the achievement of a final result; in this subject, the decision goes from the status quo to the implementation or not of an efficiency measure. Note that the decision process starts with the recommended efficiency measure and ends with the implementation (or not) of the measure. The change to undertake is not straightforward and requires a set of skills so large, that in the vast majority of cases is not owned by a single person, leading to unavoidable problems. Capability of forecasting future energy prices, technology developments, adapting the recommended technology to the current system and organizing the economical and labor resources properly, are some of the required attitudes to consider for a sound decision. Moreover, the subjectivity naturally embedded by the person in charge of decision is influencing the weights to give to each of the terms considered as important.

The same individual will use many different types of strategies in making a decision, depending over a number of different factors, among which the complexity of the problem is of paramount importance as highlighted by Payne and Bettman (85). Their work is focused on decision from different alternatives. The different alternatives, here, are represented by the wide range of energy efficiency opportunities inside the production facility.

They give advice of the context effect, for which the value of an attribute assumes different values depending on the specific decision and is not associated to the structural characteristics of the decision problem (response mode, number of alternatives, time pressure, possible outcomes etc..). This problem will be outlined in this study, because of the implicit contextualization of the efficiency measures when applied to the industrial environment.

At the same level of an industrial process, where the raw materials are transformed by a series of activities and actions, the nature of this "process" i.e. the decision making, is indeed dynamic, since it entails a mental effort toward the implementation of a measure. For this reason, the present study is going to explain, through a series of attributes, called factors, the main characteristics of the single efficiency measures. The schematic view, as consequence, can be applied to a set efficiency measures belonging to the same field, since the major operative parameters, characteristics related to main attributes and other-than-energetic implications are considered. The values assumed from each attribute can be known with reasonable certainty or not, depending on the efficiency measure and how it adapts to working conditions.

On this last point, thoroughly revised in the next paragraphs, the light is shed on the broad set of operative consequences (implications) implementing and exploiting the EEM, to consider in parallel with the energetic-economic and technical outcomes. We believe that, the scope of the work can, at least partially, face the energy efficiency gap problem defined by Jaffe and Stavins (3), on a specific technology.
Other than financial profitability, the importance of considering aspects from different sources has been revealed a winning factor for the explanation of adoption of ATM technologies, in the study by Godwin and Ike (86).

As highlighted by Cagno, Trianni (87), the decision-maker is bounded in its decision by many limitations and attention on resources, because of the human capability of dealing only with a limited set of information. For this reason, based on the system and firm conditions, one may attention some problem and tend to hide some other aspect, creating an underestimation or overestimation of achievable savings[18]. Another study by decision making process corroborating this statement is the one performed by Tversky (88); he advises that a usual behavior when making a difficult decision among different alternatives, may orientate the choice on the attribute considered most important, tending to hide the others[19]. As consequence, the need for a comprehensive mean to deal with a decision on the implementation of efficiency measures in compressed air is quite important. Hasanbeigi et al. (89), in their framework, distinguish three crucial moments on the decision of efficiency measures to undertake: raising of awareness from staff and top management is the first, motivation is the second, action is the third. Experts interviewed in their study, notice the need for raising the awareness of top management and staff in companies on energy efficiency issues, but they had difficulties in finding a mean to cope with this problem.

The scope of this study is indeed twofold: other than giving more awareness, the study has the objective of affecting positively the human behavior, enhancing interests to the energy

[18] Since the focus is not merely on energetic aspects, "savings" is referred to both energetic and non-energetic results of the implementation and impacts of the EEM.

[19] This is called lexicographic choice rule.

efficiency and helping to prioritize the EEMs that the firms can face better i.e. the measures suitable for their organizational context.

The quantification of the different types of benefits that can occur from energy efficiency projects, is a step of paramount importance in the improvement of understanding the dynamics at work, and is worth to include these multiple benefits in the investment decisions (90).

The decision making is made of many interrelated processes, and this simple listing explains how the framework will help in this sense, as underlined in the work by Payne and James (85):

- Information acquisition: the pre-determined set of variables to consider is a preliminary mean to cope with the information gap on efficiency measures and all their implications;
- Evaluation of information: the part on the theoretical validation of the model will analyze in detail each of the values assigned to attributes for a specific measure, with some comment and the related reference from which information has been taken;
- Expression of a decision: this is the part when the person in charge of the final decision expresses his willingness to implement or not the measure. This consideration is in part addressed in the empirical part of the research, where the interviewee is asked about the how and why the complete set of factors influence his decision and the differences without the use of the model.

One further comment is that decision makers and people who have an active role in management of energy may not coincide. In general, the responsible of energy management inside the production facility has a more technical profile and need to tackle the problem of facing both decision-makers and other figures, which requires the capability to express easily the technical concepts behind the choices. Moreover, being the energy a horizontal feature[20], requires dialoguing with other corporate functions (91).

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[20] Encompasses the purchase of electricity and other fuels, equipment and machineries personnel, maintenance personnel, who is in charge of bidding for big projects and so on.

4.2 Working perspective

For a comprehensive analysis of what the work is going to explain and analyze, the scope of the work cannot be clear enough if the perspective is not clarified a priori. This means that from this point on, each consideration on the efficiency measures or what they are expected to influence, is implicitly shown from a specified perspective.

The different actors influenced by a market transformation for gaining efficiency in compressed air systems are, accordingly to Radgen and Blaustein (18):

- electric utilities, that as consequences decrease their sales;
- manufacturers of CAS equipment have to perform some adjustment in the products but can benefit from market expansion for better quality;
- engineering consultants and compressed air suppliers have a higher opportunity portfolio to make consultancy for final users;
- final users of compressed air systems that, along with the benefits from greater energy efficiency, should increase capital investments and maintenance costs, so that each investment should be carefully evaluated.

Different user typologies entail different adoption strategies, so that the perspective can result as different:

- Private users;
- Industrial final end-users.

Since our field of interest is the industrial one, the second perspective is the one under the scope of the work. For the industrial end-user, each energy efficiency investment is translated in cost terms, and the availability of implementations in terms of cost and opportunities has to be approved by the top management.

4.3 the literature reviews

Many articles, books, but literature documents more in general, highlight the possibility of having a mean to categorize efficiency measures through a series of attributes, or with a deeper basis, with the introduction of categories (composed of one or more levels) that are able to give a more structured view about the topic. The literature on efficiency measures characteristics is widespread, but scant when referred to single technologies.

As just pointed out the characteristics of efficiency measures is often regarded as neglected dimension (83), (87) for the adoption of the efficiency measures, and this has revealed to be particularly true for the cross-cutting technologies (5) (6) ,where, often, the lack of strategic value, hinders the interest towards the argument. As presented in the first chapter, the role of compressed air is indeed underestimated and the operative costs are the major share of the lifecycle costs, in some cases overcoming the 70% (21).

In the literature, many authors provide information on additional features of efficiency measures with the development of different list of characteristics or the built of comprehensive framework to address the feature that comes from the adoption of efficiency measure in different contexts.

4.3.1 *Mere list of attributes*

Pye and McKane (92) stress the point on the difficulties of estimating some incremental or hidden costs (for instance line shutdown) for industrial efficiency projects, because this may imply the possibility of giving wrong estimates of the financial opportunities in this type of investment. They provide a list of attributes that go beyond energy savings, focusing on the enhancements with respect to the actual operating conditions such as increased productivity, capacity utilization, reliability or quality of the product, reduced production or environmental compliance costs without any advice of why the choice was moved toward that and not to others (easier accessibility, reduced noise or air quality). Moreover, they notice that productivity gains motivate industry to take action, and suppose that without comprehensive data about non-energy benefits it is very difficult to make awareness rise.

In reality, each of the investment projects in energy efficiency entails a so broad amount of information, that there will be for sure some of them that are not easily quantifiable or for which is impossible to have a numerical estimate. Increased awareness, will be created when the complete picture of the implication that follow the installation are well understand and properly considered.

Mills and Rosenfield (93) use the perspective of the industrial end-user, despite their work do not only pertain the industrial world (but also a residential program is considered). For them, non-energy benefits are of primary importance to enhance the end-user adoption.

Even though they use categories of benefits, they have a sort of listing of single attributes for the composition of each of the categories. In any case, this will be treated in 4.3.2 .

Skumartz et al. (94) focus their work on several entities who receive some benefit from the adoption of efficiency projects and found: utility, ratepayer and shareholder perspective, the societal perspective and the customer or participant one. The theory is very interesting because it was developed in two different articles over a decade. Despite the first of the studies is a mere list of attributes, in the second, the people to which non-energy implications are accrued, are synthesized as the categories. The crossing of some of the attributes through different parts, means that the author's perspective is not oriented on the exclusivity of the factors.

4.3.2 *Categories of factors*

Throughout the literature studies, in recent years, the adoption of structured framework has revealed to be a strong tool to explain the different nature of factors related to efficiency measures i.e. these types of taxonomies consider as important the feature of the single attribute, which presents commonalities with the others under the same category. This approach ascertains that the factors have common roots, and, moreover, this represent a first validation about the completeness of the tool.

As pointed out by Worrell in his study about the quantification of other-than-energy benefits (95), the first passage to evaluate the productivity benefits is their *identification and description associated with a given measure.* They consider as noteworthy this description, since these improvements may change the cost of assessment of the technology and result in a more favorable evaluation. Other than specifying how an efficiency measure is influenced by what benefits, the implications should be described as more specifically as possible. In that case, the categories were taken directly from the suggestions of industrial case studies review, with the explicit specification of the categories: reduced waste, lower emissions, improved maintenance and operative cost, increased production and product quality.

Carrillo-Hermosilla and others, in their study on diversity of eco-innovations (96), explore the diversity based on different key dimensions on the perspective of the study.

Mills and Rosenfield (93), having adopted a unique perspective, focus on the working environment quality and operations related opportunities, identifying primary role of non-energy benefits in consumer decision-making since they increase the value of the implementation of an efficiency measure. This is especially true where the economic aspects give not high level of relative advantage, that in this case must be gained with other aspects. Even though at different levels, their attributes partially overlap with the ones in this work, among which are advisable improved indoor environment, comfort, health and safety, reduced noise, labor and time savings, improved process control, water savings and waste minimization and direct and indirect economic benefits from downsizing or eliminating equipment.

Lung et others (97) examine the importance of ancillary savings and production benefits in industrial facilities; they have information about 81 projects in industrial facilities and quantify all the ancillary benefits for the integration of results for a comprehensive economic evaluation. Their final results are obtained thanks to the weigh up of cost of conserved energy against the ones with included benefits. The conservation supply curves[21] are able to display the gap between the two, and show the underestimation of the effectiveness of energy efficiency measures adoption.

For Fleiter et al. the lists of attributes are grouped in three categories (83), defining also a selection criteria for the choice; the relative advantage, technical context and information context. This is maybe the most important contribution by the literature, because give a deep rationale behind the choice of grouping axes and decline the factors in discrete levels, assigning them to each of the efficiency measures. They also use a morphological box to identify if the efficiency measure is influenced positively or negatively by that factor. Moreover, they stress the point on some factor, that despite not being quantifiable[22], can be perceived as high or low in any case in the industrial context; if this is the case, that factor will influence the adoption of the efficiency measure and it is worth to include it in the framework.

4.3.3 *Compressed air literature*

Part of the compressed air literature give information about the system components and technical features, for which Chapters 2 and 3 are comprehensive; in this part, the focus is moved to articles and industrial literature that itemize features of compressed air that can

[21] Curves that display the cost of energy conservation.

[22] The quantifiability was instead a factor of paramount importance for Worrell, 2003

be useful for the development of the framework; it goes from technical parameters to check, to the description of CAS efficiency measures.

The focus on the specific technology, gives advice of what are the main operational parameters that are modified by the installation of the efficiency measure, but more in general when a change in the working conditions is shown. Saidur and Hassanuzman (21), pointed out the most important data needed for a compressed air analysis, through which emerge three direct factors that encompass for all the others, Pressure, temperature and air flow rate (and the variation of these parameters in time); moreover, the fact sheet drafted form the Berkley laboratory (25), gives information about what are the operative parameters needed to have a clearer picture of the current system conditions and highlight pressure, mass flow rate and their variation in time and air quality.

The document on improvements for the pulp and paper industry (98), does not focus parameters to check when an efficiency measure is being adopted, but on the factors for which monitoring is necessary to save significant energy and operating costs; pressure and temperature gauges, flow meters and kilowatt-hour meters as well as hours run meters are revealed to be the important ones.

Energy efficiency manuals for compressed air (21), (25), (20) face the efficiency issue itemizing all the possible aspects that influence a specific measure in the "fact-sheets". They are informative documents prepared for the most profitable efficiency measures, that serve as a guide to underline opportunities, both at components and system level. Implications for factors and categories towards a technology

4.3.4 *Critics*

As highlighted by Olsthoorn et others (99), some of the perceived characteristic of energy efficiency measures, are evaluated as too "ambiguous" criteria. Relative advantage, for example, is tuned into purely economic terms in some of the studies (83), or remains too general to be considered as a factor for the adoption, because of the high dependence of the relative advantage on the context (83): this intrinsic problem in developing theories about specific efficiency measures is found in their study under the name of "heterogeneity of EEMs".

The question of how the heterogeneity of the efficiency measure can affect the adoption is a crucial point for the study: Olsthoorn et al. point out how that is difficult to categorize EMs that are too general; the tradeoff in finding specific or general characteristics lies in the

description of efficiency measures. On one side, if the framework is too general, there are not real possibilities of understanding what an adoption of a technology-specific EEM implies. On the other hand, the reference to a single technology, under a single perspective, treating only one type of EEM (cross-cutting vs process), can result as too specific, and there will be the need of many of these tools to handle all the problems related to the implementation of EEMs.
The fact that this work has this specific orientation, may result in a series of justifications to the critics moved by Olsthoorn. First of all, the framework is oriented towards a cross-cutting technology, in order to be applied in a widespread set of different production facilities. Moreover, without the specification of a single technology, the work can lose the practical interest by industrial end-user (because too general to be applied for all the efficiency measures).

The perspective of the studies by Pye and McKane and Mills and Rosenfield results neither enough oriented to specific efficiency measures nor to a single end-user.

In another study, the terms introduced by Klein and Rogers (100), (101) (cited in almost all the literature studies that tried to give a characterization to EEMs), for the characteristics of innovations, seem to be too general to be applied to a specific efficiency measure i.e. they can refer to different aspects of the efficiency measures. For this reason, the complexity, compatibility and observability factors cannot be used as a specific characteristic of the EEMs; moreover, they have problems in quantifiability.
If the framework is technology-oriented, it results much more useful, to use these "characteristics" at a higher level, as clusters of characteristics, used as a basis for the development of the lower level, where specific technological and operational/organizational features are advised. As will be clarified in the next paragraph, the basis with this three "axes" seem to be complete, comprehensive and lacking in overlaps of the singular factors.

Food for thoughts are advised in the work by Fleiter and Worrell in 4.3.2, despite their work was oriented toward each type of efficiency measure and not on process or cross-cutting. This changes the way they approach with the final choice of factors and their work remain too generic to be applied experimentally in production facilities. The factors that they found, should be analyzed deeply when referred to a certain technology.

Some of the studies, critics the lack of quantifiability of some factor to explain EEMs characteristics (95). Cagno and Trianni highlight (6) the most important barriers hindering the adoption of measures for compressed air systems used as cross-cutting, and found in implementing of interventions, followed by awareness and investment cost. This means, that the gap in information about compressed air efficiency potential and actual status, should be prioritized, even if this happens at the expenses of quantifiability of factors.

Pertaining the efficiency measures analysis found in compressed air literature (4.3.3), is able to create more awareness for the adoption of measure, but there is the lack of a synthesis tool comprehensive, complete and exhaustive. This tool, should be also useful to shed the light on all the implication that depends on the context the EEM is embedded in.

4.3.5 *Needs*

The first evidence by the literature review, evidenced the more interesting perspective as the one of the industrial end-user. With respect to the work of Carrillo-Hermosilla (96), indeed, we choose one of the different dimensions (refer to 4.2) to categorize all the implications of an efficiency measure towards homogeneous actors in the industrial contest.

As some recent work underline (102), the implications of the efficiency measures in the industrial context, can be quantified as benefits or losses. The positive intrinsic nature of the factors for the characterization of EEMs, found in almost all the literature studies (see 4.3.1 and 4.3.2) has been overcome. The direction of the influence is dependent upon the fit of the specific factor with the efficiency measure analyzed. Moreover, in the third part of the same work, the analysis of the innovation characteristics has been thoroughly evaluated in a list of attributes translated in entries directly connected to the technology. This is a step forward with respect to the classification of innovations given by Tornetzky & Klein (100), or the diffusion of innovations by Rogers (101), since it takes into account how to evaluate more in detail the characteristics related to the technology in use.

Moreover, since the difficulties in implementing the intervention in compressed air systems (as in all the cross-cutting technologies) was revealed to be the major barrier in the study by Cagno and Trianni (6), and this is partially to ascribe to the lack of skilled personnel in SMEs, the compressed air systems service providers are needed for the implementation. Principal-agent relationship between compressed air service providers and adopters can be influenced positively if the second is more aware of the implications and additional features that comes from the adoption of a measure, and here comes the need for the framework that will be able to partially cope with this gap.

Selection criteria for the decision about factors to characterize energy efficiency measures are explicitly recognized from (83), but some of them are not useful for the purpose of our study; in particular the independence, specifying that "the characteristics should not depend on the adopting firm or the other contextual factors to increase the comparability among EEMs", is not in accordance with our scope, since the comparability is not so useful for this study. The gap that is intended to be reduced with this work, is the one on the contextual factors that are dependent on the operating conditions of the adopters. Adopters should be aware enough to understand how the factor influence the adoption of the EEM.

Efficiency measures adoption process is, in general, not straightforward. For this reason, not all the adopted EEM lead to expected profitability levels, with lower incomes or, in the worst case, to losses rather that positive energetic outcomes. This is linked to the risk related to the installation, usually in charge of the adopters[23]. Some of the measures are more inclined to perform negatively if the consequences of adoption are not properly evaluated before the installation and, in many cases, is the lack of specific actions or accuracy in determining all the implication can determine this condition. The need for a tool that is able to overcome this problem for specific technologies is evident.

The built-up of a model that comprehends all the specifications for a whatsoever measure should have some characteristics:

- independency of single factors characterizing the energy efficiency measures;
- completeness in explaining all the implications that are consequences of the adoption of the efficiency measure;
- utility, under the working perspective;
- clearness of all the factors, and how they apply to the single efficiency measures.

4.3.6 *Bottom-up Approach*

The peculiarity of this study, is its orientation toward a specific technology, and this, of course, have an important influence on the decision of factors to fully characterize an

[23] This risk can be avoided whether the intervention is realized by an ESCo with an EPC (energy performance contract), so that the performances are risk of the external company and no burden are in charge of the plant company.

efficiency measure in this type of systems. The consequence of this introductory concept, is that, despite for the characterization are fundamental the categories to which factors belong, this does not mean the factors are always found starting from a deep analysis of the three categories that are going to be explained in the next paragraph. In some cases, indeed, the decision upon the choice of one factor, comes from the technology revision of single efficiency measures in Chapter 3.
This is the reason why, some of the factors can be applied only to some types of efficiency measures and are not applicable to others. In this sense, the approach for that factors does not come from scientific literature on characteristics of efficiency measures, but from the bottom i.e. the technology.

In this direction, the work by Rogers (101) helped a lot, because the categories chosen to characterize the group of efficiency measures, are revealed to be applicable to both type of factors, without any exclusion.

The bottom-up approach refers thus, to this double side oriented nature of the framework for a specific technology, where some of the factors are derivable to the observation and analysis of efficiency measures referred to the technology and others from the thorough revision of scientific literature on characteristics of efficiency measures in general.

Moreover, since the framework characterize deeply the efficiency measures, some of the factors can have different findings when applied to different situations i.e. different firms. This "context dependency" is made clearer with an example, and should be understood to read properly all the factors' level on the table in the of theoretical validation (Chapter 6). As consequence, the dependent factors, have not one single level, but their grade may change on different plants with different organizational background.

In the theoretical validation, will be presented the details for which one measure has one specific level of the factor; notice that this may be also a feature of the measure and not of the context in which is applied. For example, using one of the possible compressor technologies or performing one operational activity in one way or another (leak detection through ultrasonic detection or chemical soap detection).

The assignment of a factor's level to a measure is the first step of validation of the framework. Indeed, the way the framework has been built, is a first prove of the completeness and exhaustivity of the tool to analyze the efficiency measures.

4.4 Framework introduction

The three different categories' typology that are going to be presented, is influenced by scientific and industrial literature on compressed air systems and, more in general, on efficiency measures and innovations. Starting from the characteristics of the singular efficiency measures, outlined in the previous chapter, is possible to have a structured view of how to make a complete evaluation of each of them, for compressed air equipment substitution or operative procedures.

As observed by the guide book on compressed air efficiency (28), the purchase and design decisions should be made on what is the expected overall cost of the equipment during its lifecycle. At the same way, the decision of undertaking an efficiency measure should be a consequence of the implementation and impacts on the existing systems, rather than on pre-determined calculations based on mere energy outcomes.

This does not mean that these preliminary data are not important, since studies of this type permit a focus on the economic viability or the energy range saved (21), (82) , but they should be always integrated by a comprehensive view of what are the consequences of the decision.

The types of macro-categories are basically three: the first ones are economic-energetical considerations, fundamental and widely recognized as paramount important for the adoption decision energy efficiency measure; the second ones, are more related to the operative industrial context in which the efficiency measure adopted will be embedded, that is the object of the research study. Categories and factors specifications should not make lose the sight of the final scope of the work: to have a practical tool that can help in decision about compressed air systems' efficiency measures. Is necessary this caveat, to consider practical factors easily manageable from the site management or from who is in charge of making the decision.

The first parameters are technological, and related to the fluid conditions: this primary feature gives advice on what implies the measure adoption from a technical point of view, as it consider temperature, pressure and flow rates information. Knowledge about operative parameters is of utmost importance, since usually the people in charge of adoption decision have not an elevated consciousness about their relation (103) and, as consequence, the implementation of a measure is not addressed properly.

When an analysis in compressed air system is performed, from the baseline of current energy consumption assessed through an energy audit to a simple check of performances, the data needed to assess the actual energy expenditures are generally a lot (21), (25) and are comprehensive of how technical parameters change in time other than on the three main operational parameters.

Each of the items that is going to be presented is able to highlight main issues, opportunities or, more in general, consequences of the adoption of an efficiency measure.

4.4.1 *Operational parameters*

From industrial literature, all the main features and the relationship among the operational parameters are known. This section provides information on what the efficiency measures act, and how they affect the main parameters, and their variation in time.

The needs for compressed air are defined by quantity and level of pressure required by end users in the plant (25), so that, the parameters considered as most important for the purpose of the study are pressure and air flow rate, to which is added the air temperature, because of the many options in which it has an important role. Please notice that the parameter chosen does not represent only that item, but is the starting point from which also the secondary parameters are considered.

To understand better this last point, we consider secondary parameters the ones that strictly depends on the primary, so that for the calculation of a secondary parameter the data on the primary are needed. The primary parameters, as consequence, are not the only ones to consider when calculation on energy savings are made, but the basis from which all the others are extrapolated.

Secondary parameters like heat and thermal capacity are directly linked to the temperature parameter; the pressure and flow rate related are power, work, but also volume, density and mass flow rate of the air.

4.4.2 *Economic and energetic parameters*

These parameters are the fundamental ones for each decision for an energy efficiency investment, but more in general for whatever type of investment. Since this type of parameters are thoroughly evaluated by each of the study on energy efficiency investment decisions, here we consider only the fundamental ones, usually used in an industrial context.

As highlighted in the study by Fleiter (83), profitability is the most important characteristic for the adoption of a technology, and to compare the profitability owned by EEMs, the internal rate of return is considered as the stronger determinant. On the other hand, he recognizes how firms, in the vast majority of cases, prefer to use payback period as a simple investment decision rule for EEMs. The payback is a poor indicator of profitability, because of its ineffectiveness in considering the lifetime of the measure, but we prefer to include it, since our tool should be supportive without losing in simplicity and the IRR is often not used inside firms, especially SME's.

The other prioritized factor for whatever type of investment is the initial cost (104), maybe the major barrier hindering the adoption when budgetary problems are present, and moreover in the realities where the economical aspect is a priority (87). Fleiter (83), pointed out that rather than the total expenditure, if it's required the passage from a technology or its efficient alternative, the initial expenditure should be substituted by the marginal cost.

The amount of energy saved is the first indicator of savings coming from the adoption of an efficient alternative to be applied to the existing system, and thus used as third item in this category. The source of energy saved, despite industrial compressors may be driven by other sources, is almost always the electric one; on the other hand, pertaining waste heat recovery, the savings are quantified as the reduced heat energy consumption to supply.

4.5 Characterization of EEMs, contextual parameters

Other than considering operative and economic-energetic parameters, the compressed air energy efficiency measures, can be characterized by a series of "contextual parameters", strongly dependent on the industrial context in which an efficiency measure will be embedded; we think that the influences of the context have a big impact on how efficiency measures are perceived and influences the adoption decision.

The literature review on innovations' characteristics by Rogers (101), is revealed to be very interesting, because the axes chosen from the taxonomy, are directly taken from the characteristics of innovations. Transferability of innovations' characteristics to efficiency measures characteristics (83), i.e. the applicability of a model born to encompass all the innovations' features to the energy efficiency area, is an allowable passage once the analogies between the two groups and how they act on the study subject are clarified.

Each of the items composing the Rogers model, will be thoroughly revised along the Chapter and adapted to the characteristics of the efficiency measures, explaining the rationale behind each choice; the factors composing each of the axis are then illustrated.

4.5.1 *Complexity*

Complexity is the degree of difficulty perceived when a measure is going to be adopted, and the increase of the complexity is generally negatively correlated with the adoption of an efficiency measure (101).

Along literature studies, the starting point is to understand in which case the efficiency measure is revealed to be complex in its adoption. The innovations' literature refers to the radicalness as an index of complexity because it refers to the degree of change (that is indeed difficult) required for the adopters (105), but the problems arises for the generality of defining the complexity issues (106), (83). For this reason, the complexity here is treated as a wide family that can be decomposed in its singular factors, which definitions are much more clear and easy to understand, for the comprehensive analysis of an efficiency measure.

The complexity factors considered in this work, can be related to information on competences required for the adoption, or on the type of activity expected when such measure is adopted. On the other hand, in this section are advised complexity with the accessibility of some system parts for operation or maintenance activities. The other important aspect to consider is that an efficiency measure can be not complex on its own, but the degree of impact that it has with the existing system or other processes influences a lot the complexity of its implementation; here a critic on the previous taxonomies of non-energy benefits arises. Some of them (see 4.5.1.4 for references), include the reduction in maintenance effort. In our perspective, the impact of the measure adoption on the maintenance processes or policy is not always quantifiable as an advantage, per se. The implications may be positive in some case, negative in some other.

Complexity has been revealed to be an important axis in the synthesis of efficiency measures characteristics. The technological complexity features are advisable in different documents (104), but are referred to the adoption of a technology for which the know-how is not gained. This feature is translated in terms of expertise required for the adoption, because the technological complexity entails different level of expertise.

4.5.1.1 Activity type (83), (84)

The type of activity explains what are the actions that are going to be taken after the measure adoption. This feature is strictly connected to the complexity of the measure, since as highlighted by Sandberg (add REF), the simple retrofit measures are easier to make with respect to new investment on equipment. For the authors, the new equipment purchase is perceived as heavier to face, and the companies first reaction is trying have some shortcut to avoid it, for instance at the expenses of increased maintenance procedures.

Retrofit refers to a process in which existing capacity is upgraded by implementing energy-efficient technologies or measures, but that does not entail a big technological change with respect to the actual situation (107); on the other hand, the same article stress the point on the stock turnover, but this is very situational, because, the applicability of this feature highly depends on the evolution of the state of the art and on the average lifetime of equipment; the both of them are not so dynamic to be considered for compressed air systems.

4.5.1.2 Expertise required

Since the efficiency measures to be installed in a plant are of different types, the skill range is so wide that in SMEs is quite difficult to find technology experts, especially if the only compressed air use is on the service processes (108).
If the level of expertise required is not in line with the actual capacity, this can lead different barriers to be showed up in different phases of the decision, but they are mainly related to competences; barriers act both before the knowledge of inefficiencies and opportunities for efficiency are known and after this phase, immediately before the energy efficiency measure is implemented (87). Once the investment assessment is made, internally or through service outsourcing, the problem is to gain enough experience for a sound installation. The problems can be related to the decommissioning of old equipment (if present) and the implementation phase, or on looking for an external service provider to perform the job. In this last case, the positive aspect is the unneeded gain of expertise or training required for the implementation, but the negative outcome may be having too low information to manage properly the part/system during its lifecycle.

4.5.1.3 Independency from other components/energy efficiency measures

One of the major problems with introducing a new technology or new procedures in a context, is the extent of influence of the measure on the existing system. This can entail low or wide modifications, that will influence the adoption of a measure. This feature is directly related to the complexity issue (as highlighted by Tornetzky and Klein (100)), or underlining the twofold nature of the impact: local or component (83), architectural or component (109). In our case, the possible consequences can impact at the equipment level but can influence directly compressed air, other systems or can generate cause-effect relationship with other efficiency measures. For Fleiter and Worrell (83), this is embedded in the technical category. It can be seen as a technological or operational problem, but, in any case, influences the complexity of the system.

The degree of influence on other systems, together with the other complexity factors, give a complete picture of what the measure implies; the influence on other equipment or operative conditions can be explained with the plug and play concept. The more the measure does not affect other system parts, the easier will be to understand the consequences of installation and predict the total savings.

In compressed air system, for instance, one major impact is given to the influences to the heating and cooling systems. Benefits of having different cooling requirements are displayed by Nehler and Rasmussen (110), that gives information of how reduced need for cooling or heating is relevant as a non-energy benefit.

4.5.1.4 Change in maintenance effort

This factor is related to the complexity issues because maintenance procedures from the adoption of an efficiency measure may imply difficulties embedding new/different maintenance procedures.

A comprehensive evaluation of maintenance procedures includes maintenance measures, aiming to improve cost-effectiveness of maintenance practices, and reduce to the minimum non-value adding activities.

The cost of maintenance is composed of different items (111), from material and labor cost, to the maintenance management and planning, administration, training, and allocated costs as external maintenance services.
The maintenance is the first step for gaining competitive advantage, so that a change in the maintenance influences a lot how the firm behaves. For all these reasons, the dynamic nature of maintenance relatively to single efficiency measures, is considered as an important discriminant factor that may influence the choice for the adoption (93), (95),

(97). Please note, that also a neutral outcome[24], can be considered as positive from a decision-maker point of view, since does not entail big efforts with respect to the current situation.

4.5.1.5 **Accessibility**

This is one of the factors whose scientific papers are not comprehensive. The nature of the factor is strictly related to the complexity issue, for which the space availability or effort for human and technological resources are a major concern to take into account in for the measure adoption. This is particularly true for the compressed air system, in which the distribution system is usually difficult to access, but the accessibility can refer to the space unavailability for maintenance procedures when technology add-on measures are installed.

The ways the measure is declined i.e. the levels, in reference to the single efficiency measures (see technical validation of the model in Chapter 6) clarify this last point, giving advice of what is the degree of accessibility of the measure or how the accessibility issues affect the measure itself.

4.5.2 *Compatibility*

The compatibility factor refers to a new technology to be applied in the existing compressed air system or to the new state of the system (because of the implementation of the EEM) that applies to already existent technologies. Tornatsky and Klein (100), gives attention to the compatibility issue but in a broader sense, referring to many articles where the compatibility is explained as an innovation's characteristic. Many of the studies, have not statistical inference about the compatibility of innovations with the user group, because of the objective difficulty in using this item since the poor quantifiability. The compatibility of an innovations defined by Rogers is divided in three different clusters: the compatibility with the values and beliefs in some innovation, which does not apply to this model on the energy efficiency characteristics because is more oriented on the cultural values that can hinder the adoption of a technology; the compatibility with the previously introduced ideas, that can be translated in previous adoptions towards some technology (technological compatibility), layout orientation or operating conditions that difficultly fits with new installation or retrofit in the system; and compatibility with need. In any case, the objective

[24] i.e. the efficiency measure does not affect at all maintenance activities.

influence of the compatibility is proven by several studies but the attributes of compatibility can difficultly pass from innovations to efficiency measures: the cultural values in an industrial context can be in fact seen as organizational values as well as the previously introduced (adopted) ideas are the part measures and the status quo.

Despite being relevant for the adoption, compatibility and possible derivate factors are not considered properly, because strongly dependent on the adopters' characteristics (83). The fact that this work shed the light on a specific technology permits to explain compatibility through peculiar conditions or status of the system or with other activities to perform with the adoption of the measure.

Talking about a specific technology, the focus here, is more oriented on the compatibility of the measure with an existing system i.e. the fitting of the technology to install on the current system to the system itself. Potential adoption availability and adopters' efforts in coordinating activities are how the compatibility is re-interpreted in the efficiency measures field. The compatibility axis explains to which degree the new measure to be adopted, can be adapted to existing system conditions, so how can be referred to the technological variability of the used equipment for the measure adoption.

Without any doubt, the factors of this kind are highly dependent on the context, since the conditions of the compressed air system determine the degree of technological fit of the EM (installed compressors, pressure dew point of the dryer, ecc…). The evaluation of the compatibility with existing system conditions is made by mean of the specific factors in which this category (axis) is declined as follows: high values of compatibility are translated in positive oriented levels of the factors composing this index. Where no problems of compatibility are advisable for a specific measure (or technology with which the measure is going to be implemented), this is showed in the theoretical validation table as a positive outcome.

4.5.2.1 Technological

Compatibility issues related to technology explain the technological constrains related to the efficiency measures and under which condition they are suggested or to avoid. For many of the potential measures installed, since they are hardware related, more technologies concur for the installation, but the best choice is context related.

The factor is important to understand to what extent the measure is suitable for the use and whether or not can emerge problems for the match of the chosen technology (or technologies embedded in the efficiency measure) with the existing system. Energy Trust Program have defined a set of characteristics to consider for the installation or optimization of new technologies and the technological "suitability" refers to the substitution potential as percentage of the baseline (112).

The risk potential of an installation with no technological compatibility is the lowering of performance during the service life of the EEM. 'A negative experience with one innovation can damn the adoption of future innovations'. Such innovation negativism (113) is an undesirable aspect of technological compatibility.

Innovation Negativism is the degree to which an innovation's failure conditions a potential adopter to reject future innovations. When one idea fails, potential adopters are conditioned to view all future innovations with apprehension' (101).

4.5.2.2 Presence of difference pressure loads[25]

The presence of different pressures at the end-use side, means that at least two pressure levels exist. This entails that some of the efficiency measures are suggested to save energy under this system conditions, and the positive or negative effects of installation of measures under this (common) situation are suggested in the comments of the theoretical validation table in Chapter 6.
As "Kaeser guide to design a compressed air system" prescribes, the different pressure levels can be source of high inefficiencies of the system. The main reasons for this are two. Firstly, this can be attributed to the widespread availability of pressure reducers, that can be fitted in most cases where a low-pressure use is required, but that are high inefficient because the pressure gap is basically a lost. On the opposite side, the generation of a high-pressure point is to recommend only when a considerable amount of air is required at that pressure i.e. the purchase of a new compressor should be justified with the operating cost of producing air at that lower pressure.
The influence of the implementation of some measure can be not negligible, and for this reason the table offer a guide on how to behave in some situation.

[25] This factor is not characterizing the efficiency measures as the others, but it refers to particular system conditions, under which the adoption of the measure (when a match between the two is present) may be influenced.

4.5.2.3 Adaptability to different conditions

Flexibility is acknowledged as one of the major benefit of compressed air systems (25) so that the degree of adaptability conferred to the compressed air through the technologies installed, became of primary importance.

The adaptability of the measure when a different demand or pressure requirement is needed, can be measured by this factor and this, clearly belongs to the third stream of compatibility cluster pointed out by Tornetzky and Klein and Rogers (100), (101) , so it involves the compatibility with needs from consumers. Read in this optic, this can be translated to a compatibility towards demand requirements that are the end-use points (the demand refer to air demand in the case of strictly compressed air efficiency measure, or the demand of heat for the waste heat recovery measures). Adaptability to different conditions in a specific case (EEM 2,4221) refers to the adaptability to the different ambient conditions, since this EEM is not influenced by changes in the flow rate demand, but on the air temperature and humidity entering the compression unit.

The measure that easily adapts to different conditions has a lower adaptability index; as consequence, the decision-maker that knows the fluctuation of the demand, or at least knows how it is expected to be, can be influenced by how the installed measure can be adapted to the existing system's conditions.

4.5.2.4 Synergy with other activities

In the implementation of the measure, the decision-maker may identify and exploit the possibility of coordinating the action with other activities that are of the same type, or imply the same contextual conditions of the measure that is going to be installed. The synergy is indeed considered as one of the features of the compatibility characteristics, accrued during the implementation phase of the EEM (102) or during the life of the EEM. Synergy may be referred also to the coordination of the implementation of the efficiency measures to others, that usually are suggested contemporarily.

The nature of synergies may be positive or negative, depending on how the implementation impacts other activities. Of course, the positive synergy is going to positively affect the implementation, the negative may influence the decision-maker about not moving from the status quo.

To better describe and assess the synergy of one activity with others, many different conditions can be met: the synergy with maintenance procedures, or the installation of the measure (if requires the stoppage of the process) since the downtime cost is not easy to predict but influences the global cost of major overhaul and equipment replacement (114).

4.5.2.5 **Distance to the electric service**[24]

The first factor linked with an ancillary service is the distance with the electric one, advisable when passing from the compressed air technology to others. The meaning of this factor and how it's applied to the CAS is straightforward, but is anyway considered as important, since for some of the measures it can represent the problem for which one technology is hindered in favor of the compressed air units. As the previous factor explains, the technology results as not adequate (giving a high endeavor for the change in technology), despite, from an energy efficiency point of view, they are profitable. This is highlighted in two different industrial literature documents about vacuum generation units and blowers (115); Blowers…).

4.5.2.6 **Presence of thermal loads**[24]

The quality level of the fluid delivered by the heat exchangers from heat recovery units are the major problems for the low diffusion of this technology throughout the CAS. Despite the measure can be theoretically installed in each of the compressors types (both packaged or not), the profitability of the measure depends over the fluid quantity and temperature.

The factor is to check in all the heat recovery measures and gives advice of what are the conditions of the fluid that can be recovered, depending on the compressor type. If the compressor load is highly variable, the variability has an impact on the heat of the fluid, delivering a discontinuous amount of heat in time. This is a serious factor to consider before the implementation, because the fact that the heat can be recovered is not a reason for the implementation per se, and this is the main reason for the low level of adoption of these measures.

4.5.3 *Observability.*

Observability represent how an efficiency measure, once implemented, can be perceived within the production context. The concept of observability of innovations is connected to the visibility and communicability to others (101), but in the narrower world of efficiency measures, the observability concept can be translated on what are the sensible changes detected in the working environment or to components, once the measure in implemented.

Adapting interventions in an operative context, means contextualize them to see what is their degree of impact; in accordance with the academic literature, the concept of "implications on the existing system" is quite similar to studies pertaining non-energy benefits, coming from adoption of EE interventions.

The impacts are usually described by literature as non-energy benefits, from the identification (116) to the effort to identify the quantifiability (95). Worrell in 2003, focus the point in the area inside the firm, where the productivity benefit is identified, giving the basis for the identification of different areas in which can be categorized. For the purpose of our study, more than talking about productivity (or non-energy benefits), the direction is neither oriented toward positive nor to negative levels. They indeed are characterized in the second step of the research, with the theoretical validation, but also when the firms are asked about the influence of the factor in the working contest.

Despite this precondition, some of the factors are, for their own nature, more oriented towards one side and as consequence, the characterization of the measure result easier.

The importance of non-energy benefits in compressed air system is highlighted by the U.S. DOE, with the proof that the 76% of the compressed air efficiency measures implementation experienced positive benefits other than EE. The energy savings can also result in improved reliability of the system and support for production (117).

To better describe the factors, the upstream classification is of utmost importance. The implications of the efficiency measure on the steps before the decision-making process can be traced back to the barriers to energy efficiency, but they are tuned on the basis of the described system. The implications and effects accrued during the service lifecycle, can be instead reconducted to the non-energy benefits. The explicit addition of non-energy benefits in a framework that may lead to higher adoption of EM was performed in the study on cross-cutting technologies by Trianni and Cagno (84).

4.5.3.1 Safety

Since handling compressed air is not easy for high fluid pressure and high speed of rotating parts, the safety requirements are tight. The compressed air safety manual (118) prescribes all the information to gain awareness on the harmful aspect of compressed air, but at the

same time helps to minimize the risk of occurrence of these dangerous situations. The measures are oriented to all the plant personnel that is going to treat compressed air and whose decisions make them responsible for the individuals' safety: designers, manufacturers, installers and users.
Moreover the enhancements of the working environment are one of the most stressed non-energy benefits in the literature, where safety is considered as the most important (94), (97).

4.5.3.2 Air quality

Pollution in indoor environment is one of the more underestimated problems inside a production facility, and the responsibilities of the bad ambient conditions are of designer and of who is in charge of the commission, before of being of the installer, end-user or maintenance responsible.

Many of the literature documents on non-energy benefits, stress the point about the impact of a higher air quality that affects the working environment. Here the reason for having a higher air quality is twofold: on one side, is exactly the same of the previous literature studies; on the other hand, the air quality provides better conditions of all the parts in contact with the fluid. The quality of the compressed air is classified according to the ISO 8573.1 depending on the level of solid and liquid contaminants. The idea is to prescribe a mean to ensure that the environment is safe and clean, that is a quantifiable item to enhance worker safety (97) (92).

The risks and cost determined by a poor level of air quality (110), can determine some choice about the implementation or not of an efficiency measure. For Skumartz and Gartner (94) these non-energy implications goes under the category of participant benefits.

4.5.3.3 Wear and tear

In many of the documents dealing with the productivity benefits, the reduction of the wear and tear on equipment, is almost always explicitly considered and positively evaluated (95). It may be also seen indirectly, as influencing the lifetime of equipment (92), (94). In compressed air systems, the reduction of the wear is usually a consequence of the lower stress by the fluid, attained with the reduction of pressure, or the lower use of equipment due to enhanced control capabilities. The levels of this factor are quite straightforward because the influence of the efficiency measure is identified as an increase, a decrease or a neutral effect.

4.5.3.4 **Noise**

Oscillations in acoustic pressure cause a hearable air movement known as noise. All compressed air equipment emits noise and vibrations that can be detected via some pressure-sensitive tool. The way the noise influences negatively the working environment is evident (24). Noise reduction is one of the most referenced non-energy benefits in literature (93) (95) (94). It is defined as an undesirable sound that influences negatively the performances of the workers. The profitability and positive aspects of the installation of devices that reduce noise are not easily quantifiable since are the reduced cost of absenteeism, accidents and employees who are unable to work at full capacity (119). Usually, the low implementation of measures that impy noise reduction is a direct consequence of the lack of awareness on the possible long-term diseases caused by the continuous exposure to high dB level.

Sometimes the noise level is lower with compressed air operated tools. For other systems, the noise reduction can be attained only adding some additional equipment, with the related additional cost.

Case study analysis consider noise reduction as one of the drive actions of non-energy benefits, that can exceed the value of energy savings. Of course, a reduction in the noise generation is more effective if the compressor room is embedded in the working environment; indeed, a noise reduction far from the working place is positive only for the employees operating and maintaining compressors.

4.5.3.5 **Artificial demand**

Constituent of demand will consume more flow at higher pressures, especially in applications in which the air is open blown to atmosphere, so that, the sizing of the system based on the maximum pressure of one or two pieces of equipment creates an over pressurization that minimize efficiency (19). The artificial demand is considered to be one of the major cause of inefficiencies in compressed air systems, at the same way of compressed air leaks, inappropriate uses of end pipes, etc., so its reduction should be an efficiency measure rather than a factor that infuences adoption.

The choice of artificial demand as a factor, origins from its causal relationship with the reduction of system pressure i.e. each time an efficiency measure entail a lowering of the pressure in the system, or the reduction of an unregulate use, this affect poitively the amount of air being delivered, but this is a consequence of another efficiency measure.

4.6 Identification in the time span

Several studies have pointed out the passages for the decision-making process for industrial implementation of efficiency measures; this lead to the distinction of different phases throughout which the decision is undertaken. This goes from the modification of the status quo, to the real implementation of the efficiency measure (87) (6).

Since the factors can act during different phases of the decision-making process, they can be accrued during the service phase or implementation of the measure. The observability factors, for their nature, are going to be shown during the service life, after that the measure is implemented, because their characteristics are related on how the results of the efficiency measures are visible to others. The complexity and compatibility factors are quite heterogeneous from this point of view, being observed both before the implementation or during the service, depending on to how and to what extent they act on the efficiency measure. For instance, change in maintenance effort impacts the during the service life; expertise required for installation is accounted in the pre-implementation and implementation phase; accessibility for operations can be both for the measure installation or during the maintenance activities (87).

CHAPTER 5
Research methodology

5.1 Research objective

The framework for the characterization of efficiency measures has been developed, but it needs both the validation and the application of the model. In this chapter, I detail the reasons for the adoption of the case study methodology, as well as the research questions and how the research design is composed. Then, I explain how data have been gathered, as well as the purpose and scope of each sample companies. Firstly, both a theoretical and an experimental validation are part of the study, since the extensive literature analysis on single efficiency measures pointed out the major aspects to consider when an efficiency measure is going to be adopted. This is true, despite many conclusions can not be generalized, since their high dependability on the context. Secondly, the experimental prove is necessary both for the reason just highlighted and to give a direct connection between the study research subject and the real industrial context, from the perspective of the industrial energy efficiency adopters.

On this last point, the needs are twofold: on one hand, the first objective is to have a feedback on the completeness and usefulness of the e framework and on the model used to represent the entire work; on the other hand, the single factors are analyzed to understand to what extent they are categorized in the right way, can be adapted to different efficiency measures and to discover common patterns of underestimated or overrated perceived factors.

5.2 Rationale for the case study methodology

The study performed by Yin (120), gives all the needed information for the development of the case study methodology. First of all, the multiple case study is going to be applied, since the differences on the businesses and environmental factors influences how is the status of compressed air and how they approach on energy efficiency topics. In this case, the aim of the analysis is not comparative among firms so each of the companies will be treated as a single case study. The development and validation of theories in operations management by mean of the case study methodology, has been thoroughly revised by Voss et al. (121).

For the application of the case-study methodology, three conditions should be met:

1. the scope of the research should be explanatory;
2. the extent of control over behaviors has to be very low;
3. the focus should be on contemporary events.

The conditions are all met, because; the nature of the research questions is explanatory, since they investigated how and why they are approaching in that way the adoption of efficiency measures. Secondly, the research is not carried out in an environment where the control over events is high, i.e. the context and the phenomenon under study are not distinguishable. Thirdly, the source of evidence is contemporary, since the interviewees were not prepared on the topics investigated.

Multiple case study research methodology is the most appropriate for the purpose of our study, because they are discrete experiments that serve as replications, contrasts and extension to the emerging theory (120), so that each of the case-studies give a contribution of the theory development (122)(or, more appropriately for this case, to the validation of the theoretically developed theory); more than being a confirmation of the first on-field validation, the multiple cases objective is to emphasize the rich real world context in which the phenomena will occur (122).

The research questions are the first step for the preparation of a good case study. Since the scientific community agrees on the need for a higher focus on the adoption of cross-cutting technologies energy efficiency measures, but moreover, some of the studies give a primary result on the major barriers affecting the compressed air systems, the research questions to be answered are as follows:

- What are the main factors to be considered for the adoption of an efficiency measure? Do they take into account all the implications that the adoption entails?
- How the postulated factors have an influence on the decision? How the importance of single factors varies considering different efficiency measures?

5.3 Research design

5.3.1 *Unit of analysis*

The way in which the companies sample is taken, has a high influence on the way the interviews are carried. Since the context and the phenomenon of study cannot be explicitly separated, the decision on the firms to interview is of utmost importance for the final success of the study. The companies investigated are Italian companies, but mainly located in the southern part of the country, except for one of them.

The second selection criterion, as explained in Chapter one, was oriented on the small and medium enterprises, because they are the big majority of industries in the national area (99,8%), encompassing the lion's share of employment (80%), but also the share with the biggest potential, since they usually do not see favorably the energy efficiency topics (123). According to the European Observatory, in the sampled Small Medium Enterprises across EU, more than the 65% do not have simple rules or devices for energy savings and the 25 % have never experienced efficiency measures.

The third selection criterion was on the sectors that is mainly oriented in the mechanical and electronic manufacturing, plastic and rubber production and food and beverage industry. The different sectors and industries have different use of compressed air inside their plants, some use it exclusively as service, but others use it also for the production process. The way compressed air is used may be very influential for the adoption rate of EEMs for this technology. Unfortunately, no specific information on compressed air consumption are present in annual reports for each sector, being its use usually embedded in data on electricity consumption (124) (125).

For this reason, to better understand which is the involvement of compressed air in the aforementioned manufacturing sectors, some utilization examples are suggested (16):

Food and beverage: where the products are in form of grains and powders, compressed air is the vehicle for pneumatic transportation throughout the line. Another typical use is for the final packaging of products. Moreover, high pressure compressed air applications are used for the thermoforming of PET bottles. Various applications that were found during our visits are for marking, filling of dense-phase products into bottles, sterilizing and cleaning activities.
Air compressors filled pads for pressing of grapes and olives, are respectively found in wine and olive-oil production.

Chemical: is widely used in agitating and mixing of composed products in paint manufacturing. The backpressure generated from compressed air is also used in the regeneration process of tires, to avoid any change in the shape during thermo-forming process.

Machine manufacturing: the compressed air use is mainly ascribed to actuate many of the processes of the CNC machines, from the actuating devices for the open/close of the doors, to the cleaning process of spindles, but is never directly involved in the production process.

Plastic products manufacturing: it is involved in the production process for the forming activities, with or without plug assist, in dependence of the product manufactured. High pressure compressed air applications are used for the thermoforming of PET bottles and glasses.

5.3.2 *Boundaries: theoretical and empirical*

The theoretical validation of the framework proceeds from the analysis of single efficiency measures supported by industrial literature, starting from the listing available from the IAC database information. In this case the boundaries of the unit of analysis is only dictated by the efficiency measures for which we have decided to perform the study: compressed air specific and waste heat recovery from compressed air equipment. Before defining the boundaries for investigation in the two different phases of the validation, it is noteworthy to define how the firms will be interviewed:

- five of them are interviewed to validate the framework structure and utilization, with on-field interviews;
- there will be 15 investigated efficiency measures, one or two for each of the sites. For simplicity of contacts, the firms for the validation of the first part were contacted again, via phone call (for problems of distance) or with a further visit to the plant.

The boundaries for the investigation of the phenomenon of interest are now defined. They assume a critical importance when referred to the on-field validation and application of the case-study methodology.

The type of interview performed is suggested by Bernard (126), with the form of semi-structured interview; the conditions for this type of event are: there will be not a second chance to interview someone and several interviews are conducted into the field to collect data.

The two conditions are met because the second chance to interview people were made only for some of the companies and for completely different scopes; moreover, the time constrains did not permit, in the first meeting, a deeper investigation of the topics that will be treated during the application phase. The second condition is met in most of the cases, since several (despite not all) the interviews are conducted on-field to collect data.

The semi-structured interview allows also to take part to inspections to very customized realities, because each of the interviewee is influenced by its role/responsibility, company behavior towards energy efficiency and other contextual factors different for each of the cases. The interviewee was free to express his opinion in each phase of the data collection.

5.3.2.1 Boundaries for the framework validation

The boundaries for the validation are referred to the current status of energy efficiency inside the firm, as well as asking information about the decisional chain toward efficiency measure, with the focus on the compressed air. The compressed air status is checked with a series of information, that investigate both the awareness of the interviewee on how the compressed air systems work and at what is the degree of involvement of the technology inside the production facility; when possible, this last part was accompanied by a visit of the compressed air system. Even for this purpose, we believe as much more powerful a visit to the plant, rather than phone interviews.

After the first introductory part, the on-field theory validation starts with the explanation of the scope of the work, and the showing of a schematic of how the framework and the macro-categories and axis are composed. In this first part, the single factors are not showed, because we believe that a higher focus on the meaning of each of the essential pillars of the structure is fundamental for the theory validation. Thus, a first feedback and eventual comments are asked during the presentation and explanation of macro-categories (to check the effective importance of their role in the adoption of the efficiency measures) and of the axes in which are composed the contextual parameters.

In the second part, the light is shed on the singular factors composing the axes, to understand how they are considered useful, clear and are checked their absence of overlapping.

5.3.2.2 Boundaries for the framework application

The boundaries for the application of the framework pertain the decision about the efficiency measures that are going to be asked to companies. The set, as presented in Chapter 3, is quite large. The decision was to focus on some of the most recommended measures, with some of them coping operational EEMs and some other pertaining the hardware. For a thorough and complete evaluation of the tool, is necessary some further specification on the EMs typology, because our believe is that, it may influence a lot the approach to the efficiency measure i.e. the way in which it applies to the different measures.

The typologies of efficiency measures are basically influenced on the past experience by the companies, and they are divided in three different groups:

- PAST experienced: this group is composed from efficiency measures for which it was made an investment plan, so they were recommended but not implemented for any reason;

- PRESENT: belong to this family all the efficiency measures that were recommended and adopted, so they are part of the actual company context. Present is referred to the fact that the consequences of the implementation are accrued during the whole lifetime of efficiency measure i.e. in the present.

- Possible in the FUTURE: are efficiency measures for which no recommendations were made, or for which recommendations are quite recent, meaning they have not already taken a specific decision about the implementation;

5.4 Development of the case-study protocol for data collection

The case study protocol, despite not following a pre-determined set of questions, should have a structured approach for the investigation of main findings and results of the on-field validation. The structure to be used was built-up on the basis of the results that we want to obtain asking that section. The first part of the protocol, should be informative, although different sections have different purposes. We find important the definition of the whole scheme to understand how information on different topics are gathered. After this phase, the attention is moved toward the schematic used for the validation of the framework, followed by the application of the model to the single efficiency measure for the final test.

5.4.1 *Data collection protocol: the interview*

The first part of the interview is divided in four main sections, where different data are gathered: in each of the sections, a brief introduction explains why this information is useful.

Section 1: Company information

This section aims to company specific information; the dimension and sector can have an influence on the energy consumption. The energy consumption over the total turnover can be a first indicator of how should be considered important the energy topic in the firm, to understand if higher expenditures are related to a higher focus on efficiency (whose status is checked in section three).

- Location;
- Sector;
- Dimensions (employees and size);
- Turnover [M€];
- Overall energy consumption [k€].

Section 2: Interviewee information

The information of the person in charge of decisions about the adoption, with her/his role and interactions with other people of different departments involved in the process, helps understanding how the company approaches to the energy topics. Moreover, the different level of expertise that can be found, highly depends on the experience, and may be influential on the energy efficiency approach. The interviewee is also asked on criticalities with other figures belonging to different areas, but that are involved in the process for different reasons.

- Role and experience;
- Responsibility in energy efficiency measures;
- Share of decision for an energy efficiency improvement;
- Criticalities in this context;
- Interaction with upper/lower roles (top management, energy managers, production department).

Section 3: Energy efficiency

Deeper knowledge about how companies approach and handle energy topics is of paramount importance to understand if organizational features have an influence on the awareness in efficiency issues and if, moreover, this affects the implementation rate of EEMs. The data gathered are about: indicator of performances for compressors, where used; certification documents for energy management (eventually the attitude to undertake other standard certification e.g. ISO quality or environmental management); last improvements in energy efficiency, cost of energy, presence of energy manager, top management and their active roles in decision-making about EEMs; what are the passages for the adoption of an efficiency measure.

- EE indexes and eventual certification documents;
- Last energy audit performed;
- Use of energy and last (period of time) improvements;
- Energy cost [€/kWh];
- Presence of energy manager/top management and their role on decision-making;
- Decision making process for efficiency measures adoption.

Section 4: Compressed air

Compressed air usage inside the plant and the estimate of consumption over the total electric, gives an idea of how much is embedded in the production process and if its role is perceived as strategic or marginal. This is an indication of the interest towards compressed air topics to understand if some of the entries are related to the adoption of compressed air EEMs.

- Total energy consumption or estimated [€] or [%/total electric consumption], in this last case are needed the total estimates of electric consumption;
- Uses as service;
- Total volume [m^3];
- Distribution system total length [m] and pipes diameter [inches];
- Utilization [h/dd; dd/y];
- Presence of a specific cost item for compressed air;

- Type and power of compressors.

5.4.2 *Validation of the framework*

This part of the analysis, starts with the explanation of the topics about the framework. For the evaluation of each of the items, was used an even Likert scale type ranging from 1 to 4, to render the final evaluation positive or negative, but never neutral. The different general elements are asked after their explanation, and they are four, accordingly to what have been explained in chapter 4. The framework is itemized with respect to the general structure composition, the scope of the research and the perspective used for the work. Then, we test the relevance of each of the macro-categories composing the model, before passing to the explanation of the contextual parameters, with the axes and factors. Each of the elements composing the axes and factors is further explained to test the absence of overlapping with other elements.

Framework		Completeness	Usefulness	Clearness	Absence of overlapping
	Structure	x		x	
	Scope		x	x	
	Perspective		x		
Macro-categories		x	x	x	x
Axes		x	x	x	x
Factors		x	x	x	x

Table 4: Performances indicators for the framework validation

The investigated elements, as seen, are not tested for each of the attributes. The following table explains what is the extent of each of the attributes matching the elements for the framework.

Framework items	Description of the attributes
Structure	Completeness: The structure, considered as a whole, is indicated as fully complete. Clearness: the structure of the framework is clear.
Scope	Usefulness: the scope of the work is perceived as interesting and may have practical outcomes in the as a support tool. Clearness: the scope of the work is to investigate the implications of the low adoption rates of EEMs, and supply a practical tool that can aid or support the decision of industrial practitioners; the clearness refer to the knowledge of this concept.

Perspective	Usefulness: the perspective of the framework is revealed to be interesting for the decision to undertake for practitioners of efficiency measures in compressed air systems.

Table 5: Details of performances indicators for framework validation

For the attributes on macro-categories, axes and factors, in a first moment is tested the completeness of each of the groups, in the second part, when each item composing them is explained, the usefulness of that item, the clearness in the definition, and the absence of overlapping with other items.

After the evaluation of single elements, the final review has the objective of testing which is the effort required to use the framework as an assessment element for the adoption of EEMs and the easiness of application. The answers, of course, are very dependent on the role and experience of the interview

	Description of the attributes
Framework utilization	Effort required: the application can be used without many efforts as a supportive tool for the decisions about EEMs adoption. User-friendliness: are tested the easy to use and applicability on all types of EMs

Table 6: Details of performances indicators for framework application

5.4.3 *Application of the framework*

Since many efficiency measures imply different evaluations and factors affecting adoption i.e. the sample is heterogeneous, we focus on the most recommended EEMs. A brief summary of the most recommended energy efficiency measures follows (48), with their ARC code, description, total number of recommendations and implementation rates:

ARC code	Measure	Recomm.	Impl.	% impl.
2,4236	ELIMINATE LEAKS IN INERT GAS AND COMPRESSED AIR LINES/ VALVES	8138	6541	80.38
2,4221	INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS	5129	2385	46.5
2,4231	REDUCE THE PRESSURE OF COMPRESSED AIR TO THE MINIMUM REQUIRED	4446	2205	49.6
2,2434	RECOVER HEAT FROM AIR COMPRESSOR	1626	518	31.86
2,4232	ELIMINATE OR REDUCE COMPRESSED AIR USED FOR COOLING, AGITATING LIQUIDS, MOVING PRODUCT, OR DRYING	1450	667	46
2,4226	USE / PURCHASE OPTIMUM SIZED COMPRESSOR	692	297	42.92
2,4224	UPGRADE CONTROLS ON COMPRESSORS	639	285	44.6

Table 7: synoptic of the most recommended EEMs, that will be analyzed for the framework application

The extent of the research study on singular EMs, firstly, tests the completeness of factors for each of them. The second part focuses on the evaluation of each of the elements influencing the adoption in a scale, comparing them to reliable standards for the EMs obtained from the theoretical validation. Discrepancies are commented and are elements of analysis to understand the rationale behind the differences. This heads to the last part of the evaluation, with the inquiries on the relevance in using the framework for the decision-making process and the test on the more awareness gained. The last point to investigate is maybe the most important, and give advice of the possible changes of the adoption decisions from the application of the framework to efficiency measures.

The summary of the parts investigated for the application here follows:

a. Degree of awareness of the existence of each singular factor for a specific efficiency measure;
b. Evaluation on the importance of single factors for specific efficiency measures;
c. Lacking factors for specific efficiency measures;
d. Common factors to many efficiency measures, how they are evaluated by adopters;
e. Pattern showing some criticality in the consideration of some factors and reasons behind the choice;
f. Differences in the evaluation of the measure with or without the framework (where possible).

CHAPTER 6
Theoretical and empirical validation. Discussion of findings

6.1 Theoretical validation

In the theoretical validation of the framework, are evaluated the levels to give to each of the contextual factors identified in Chapter 4, from each of the efficiency measures described in Chapter 3.

6.1.1 *Complexity factors*

The factors related to complexity are a total of five. As will be clarified in a while, all of them have different levels.

For the activity type and expertise required, only discrete and qualitative levels are present, so that each letter corresponds to a specific value.

The independency can be referred to other components or efficiency measures. This double nature of the factor, is translated in two different attributes for the factor itself: the first is quantifiable as low, high or medium, the second is a positive or negative orientation, depending on how it is influent for some specific efficiency measure.

The change in maintenance can be present where the installation of an EEM implies a technological change, or can be positively or negatively influenced.

The difficulties in accessibility may have a negative influence in the adoption; in some other cases, the EEM's adoption implies a change in the accessibility to some point (that may increase or decrease depending on the context).

Energy efficiency measure	Activity type[26]	Expertise required[27]	Independency form other components/EMs	Change in maintenance effort[28]	Accessibility[29]
Install compressor air intakes in coolest location	R	H/L	L[30]	0	I
Install adequate dryers on air lines to eliminate blowdown	R	M	L[31]	T	0
Upgrade controls on compressors	R/N	H/L	L[32]	T[33]	0
Install common header on compressors	N	M	M	+	-
Use/purchase optimum sized compressor	N	H	L	+	I[34]
Use compressor air filters	O	L	H[35]	-	0
Reduce the pressure of compressed air to the minimum required	O	M	L +[36]	-[37]	-
Eliminate or reduce the compressed air used for cooling, agitating liquids, moving product or drying	O	H	L	-(T)	I[38]
Eliminate permanently the use of compressed air	O	L	H	0	-
Cool compressor air intake with heat exchanger	N	L	H	-	-
Remove or close off unneeded compressed air lines	O	L	H	0	-

[26] Activity type may be: a Retrofit = R, a new installation = N, an optimization = O, a procedure of recovery = Rec;
[27] The expertise is categorized as: Low (L) if the maintenance personnel is enough, Medium (M) if engineering is required, High (H) if the support from an expert of the technology is needed.
[28] Changes with technological change = T; maintenance effort is decreased = +; maintenance effort is increased = -.
[29] Accessibility index may be: '- if accessibility problems negatively influence the EEM adoption, influencing (I) if the efficiency measure may change accessibility to some point, but the influence is negative or positive depending on the context.

[30] It requires the installation of additional filters and/or ventilation requirements.
[31] Controls may be installed on dryers;
[32] Common header has to be present; air receivers design is important to have effective savings
[33] The MCS continuous monitoring lowers requirements; if the frequency of L/U is increased, the preventive maintenance requirements increase; long-term maintenance savings with VSD up to 7-10%.
[34] For packaged type compressors, the accessibility problems are usually lowered a lot. In general terms should not be very influencing for the measure adoption.
[35] Its only to check that the performances do not vary with the different pressure given by the presence of the filter.
[36] Positively affects leaks
[37] Increase preventive maintenance activities
[38] Depends on the involvement in the production process

Eliminate leaks in inert gas and compressed air lines/valves	Rec	M	L	-[xii]	-
Substitute compressed air cooling with water or air cooling	N	M	L	-[39]	-
Do not use compressed air for personal cooling	O	L	M[40]	0	-
Recover heat from air compressor	R	H	L	-	-[41]
Recover heat from compressed air dryers	R	H	L	-	-[xv]

[39] Both in general are higher with respect to CAS. Open loop configurations are the worst from this aspect
[40] Substitution of technology
[41] The problem is not so high for packaged

6.1.2 *Compatibility factors*

Factors that explain the degree of compatibility of the measure with the system are a total of six: some of them are referred to the presence of particular conditions that can be present or not. This means that if that condition is met, one should check if the measure is influenced by that condition.

A clarificatory example is given: EEM = Use/purchase optimum sized compressor

Factor referred to the presence of a particular condition: ***presence of different pressure loads.***

Energy efficiency measure	***Presence of different pressure loads***
Use/purchase optimum sized compressor	H

If in my system are present two or more pressure levels, I check the corresponding entry: HIGH influence, means that the adoption of the EEM is highly influenced by the factor: i.e. by the presence of different pressure levels.

The technological compatibility is High, medium, low or absent (0).

The presence of different pressure load may be not influencing at all, low influencing, highly influencing, or have a positive/negative influence on that EEM.

The adaptability on different conditions in mainly referred to operating conditions of the compressed air system, but became adaptability to ambient condition for the measure

2,4221 (3.3.3), or eventually, to different heat operating condition for the measures about the heat recovery.

Sinergy with other activities have two different entries for each cell: the synergy may be quantified as high, medium or low in case of synergy with other efficiency measures; moreover, it may also be positive or negative if the is the action can be performed in parallel with similar maintenance activities, or if the measure should be implemented in synergy with the presence of other EEMs that require the shutdown of the CAS.

Distance from the electric service and presence of thermal loads, as the factor on the presence of different pressure loads, are referred to the influence given by the presence of a particular condition in the system. The distance from electric service may influence negatively the efficiency measure or may be not influential. The presence of thermal loads can result as positive or neutral.

Energy efficiency measure	***Technological***[42]	***Presence of different pressure loads***[43]	***Adaptability to different conditions***	***Synergy with other activities***[44]	***Distance from the electric service***	***Presence of thermal loads***
Install compressor air intakes in coolest location	H	No	(H)[45]	H	0	0
Install adequate dryers on air lines to eliminate blowdown	H	No	0	H -D	(-)[46]	0

[42] Technological compatibility required can be high (H), medium (M), low (L) or not influencing the EM.

[43] It may be not influencing (No), low influencing the adoption (L), high influencing the adoption (H), or the influence can depend over the technology (T). If the influence positively or negatively affects the adoption, this is further specified with symbols (+ or -).

[44] Sinergy with other activities has a primary indicator for the possibility of installation with other efficiency measures: High, Medium or low. The second indicator is the positive or negative influence on the synergy with similar maintenance activities (M) or required shutdown of equipment (D). The brackets indicate a conditional possibility

[45] Adaptability to the variation of ambient condition: is valid in case of movement of the compressor toward the external ambient

[46] Only for heated purge, refrigerated or blower regenerative adsorption dryers

Upgrade controls on compressors	H	No	++	H	0	0
Install common header on compressors	H	-	(+)[47]	H -D	0	0
Use/purchase optimum sized compressor	H	H	(+)[48]	H (+D)[49]	0	0
Use compressor air filters	L	No	0	+M	0	0
Reduce the pressure of compressed air to the minimum required	0	H	0	H	0	0
Eliminate or reduce the compressed air used for cooling, agitating liquids, moving product or drying	H	T[50]	-	L -D	-	0
Eliminate permanently the use of compressed air	0	No	0	H	0	0
Cool compressor air intake with heat exchanger	0	No	0	H +M	0	0
Remove or close off unneeded compressed air lines	0	No	0	H	0	0
Eliminate leaks in inert gas and compressed air lines/valves	0	L[51]	0	H (-D)[52]	0	0
Substitute compressed air cooling with water or air cooling	M	No	0	H +M	0	0
Do not use compressed air for personal cooling	0	No	0	H	-	0
Recover heat from air compressor	M	+	-[53]	M	0	+
Recover heat from compressed air dryers	M	+	-	M	0	+

[47] Is referred to adaptability to future conditions in case of installation of a pipe of bigger dimensions
[48] The installation of more compressors of lower dimensions influence positively the adaptability
[49] If the old unit is maintained, can be used as backup to handle shut-off periods for maintenance activities of other compressors
[50] Is a very influencing factor for substitution of vacuum pumps
[51] The measure can be directed towards high pressure lines, to achieve major savings
[52] Only for technologies to detect leaks that require the stop of the compressors.
[53] Refers to the adaptability of the recovery to the variation in heat demand

6.1.1 *Observability factors*

Factors that pertain the observability of the adoption of one efficiency measure to the current system conditions are a total of five. They mainly have an influence the working environment, but not only. Being easily quantifiable in general, for all of them positive or negative influences are defined. In some peculiar case, the context may influence both positively or negatively the implementation of the measure: in that case further explanation are given.

Energy efficiency measure	***Safety***	***Noise***[54]	***Air quality***	***Wear & Tear of equipment***	***Artificial demand***
Install compressor air intakes in coolest location	0	+	I[55]	+[56]	0
Install adequate dryers on air lines to eliminate blowdown	0	(-)[57]	++	+; (-)[58]	0
Upgrade controls on compressors	(-)[59]	(+)[60]	0	(+)[61]	(+)[62]
Install common header on compressors	0		0	+	0
Use/purchase optimum sized compressor	0	I	0	I	0
Use compressor air filters	+	+	++	+	0
Reduce the pressure of compressed air to the minimum required	+	+	I	+	++

[54] Reduction of noise, positively influence the working environment (+), increase negatively influence working environment (-). In some case the factor is influencing but not in a precise direction (I)
[55] Depends on where is installed the new unit
[56] Decreasing the T before entering the system lowers the moisture content, extending life of equipment.
[57] If dryer is not packaged
[58] Risk of corrosion for the adsorption dryer
[59] Failure of automatic controls combined with low air consumption is a major cause of over-pressurization
[60] In case of 24 h/dd, with installation of MCS, the noisy machines can be ran at night
[61] In case of sharing loads
[62] Load distribution minimize artificial demand creation

Eliminate or reduce the compressed air used for cooling, agitating liquids, moving product or drying	+[63]	+	I[64]	(+)[65]	+
Eliminate permanently the use of compressed air	0	+	0	0	+
Cool compressor air intake with heat exchanger	0	0	0	0	0
Remove or close off unneeded compressed air lines	(-)[66]	0	0	+[67]	+
Eliminate leaks in inert gas and compressed air lines/valves	+	+	0	+	++
Substitute compressed air cooling with water or air cooling	0	I[68]	0	0	0
Do not use compressed air for personal cooling	++	-	(+)[69]	0	+
Recover heat from air compressor	0	0	+[70]	+[71]	0
Recover heat from compressed air dryers	0	0	0	+[24]	0

[63] Can be increased if the substitution entails lower pressures
[64] Dependent on the new technology
[65] For substitution with lower P technologies
[66] To ensure safety a close-off valve need to be installed
[67] Lower piping corrosion
[68] Compressed air coolers are generally noisier, but not in all cases
[69] Improved if no filters are installed in end-use points
[70] Because of heat exchange, compressed air eliminates moisture content.
[71] Temperature control is a consequence of heat recovery, this influence positively the lifetime of equipment that works at a lower temperature

6.2 Empirical validation

As highlighted in 5.4.1 and 5.4.2, this part of the analysis will start gaining general information about the site, firm's dimension and sector, decision-making process dealing with energy issues and compressed air status, highlighting its use inside the facility, and, when possible, estimating the consumption over the total energy expenditure. This preliminary part is followed by the investigation on the framework: are properly evaluated the composition, objective and perspective of the work, together with the evaluation about the completeness of the elements composing the structure: macro-categories, axes and factors. In the last part, each of the factors was described to understand its relevance and the absence of overlapping with other factors, as well as understanding if their scope is clear.

6.2.1 *Blue company*

Location: Province of Reggio Emilia, Italy
Interviewee: Site Manager-Responsible of plant services from the specific site; in charge form 6 years.
The interview lasted 1:15 h and was performed on October the 18th directly to the site.

6.2.1.1 Company profile

Blue Company is an Italian company, leader in polyester packaging for the food sector with four industrial poles scattered around the whole Italian peninsula. The company has more than 150 employees in the national area and all the four sites have their own production department. The company is specialized in the design and manufacturing of thermoformed disposable plastic and paper products (cups/plates), for family use, catering business and fast food restaurants and packaging for the food service industry. For this reason, the quality of products and production environment is of utmost importance**.**

The employees belonging to the site are 46, but unfortunately information about the turnover where not available because they are reserved. I was assured by the interviewee that their company belongs to Small and Medium Enterprises, so the turnover is for sure less than 50 M€. Moreover, after an internet research, were present data on another industrial plant belonging to the same company: making a rough proportion with the employees' number, the turnover should be from 10 to 16 M€

6.2.1.2 Energy profile and decision-making process

The company have quite high interest in the energetic subject, since the energy expenses are between the 9 and 10% of the total turnover. The figure interviewed is directly in charge of taking decision about energy efficiency, and the projects proposed by the team are directly sent to the top management, that may approve them or not. This structured approach gives not high criticalities in the adoption of efficiency measures, despite the training of maintenance personnel in the adoption of new procedures implies quite a great effort.

The company is certified by the UNI EN ISO 9001 in terms of quality, and the management system is certified by the Hazard Analysis and Critical Control-Point certificate, to ensure hygienic and security conditions in the food sector.

The last energetic audit was performed, on a voluntary agreement[72] in 2015.

In the last two years, the high energetic expenditures acted as a catalyst for the installation of energy efficiency opportunities. The trigeneration group and the new compressor room are the major installed. The first was installed in 2015, and the returns from this investment, gave the possibility of the installation of the new compressed air generation units the following year.

6.2.1.3 Compressed air system status

Compressed air accounts for a big part of the energy consumption, despite the lion's share is given by a couple of big ovens. The compressed air in mainly ascribed to automatic features, from the cleaning of parts, to the blowing and transportation from ovens towards the area for shapes modelling. Is moreover true, that the utilization of high pressure application is dedicated to the line for the forming of glasses through blowing application.

The fact that compressed air is used for both process and service applications, make clear why the efficiency status is quite high, despite the compressors used for service and for the

[72] DDL n° 102; July, the 4th, 2014. Implementation of directive 2012/27/UE. The audit is mandatory for big enterprises as well as big energetic consumers, but adopted on a voluntary basis for the enterprises under the scope of this study.

plastic transformation are different. This is due to the high difference in the needed pressure on the end-use point, that otherwise had to be generated all at the higher level, inducting very high losses amount.

The compressed air equipment pertaining the generation side is quite modern; the distribution system is the one installed in the past, but the recent and periodic maintenance maintains it in good conditions.

Two different compressor types are used inside the plant: they are all screw compressors but the lubricated is used only for service purposes; the other is instead oil-free to avoid any contamination of particles to the products being worked. The plant is active 24h/day for a total of 5500 h/yy.

Type of compressor	Power [kW]	Control	Function
Screw lubricated	32	Load-Unload	Service
Screw lubricated	6	VSD	Service
Screw lubricated	10	Load-Unload	Backup for service
Screw oil-free	10	Load-Unload	Process
Screw oil-free	6	Load Unload	Backup for process

Table 8: recap on compressors, blue company

As can be observed from powers and type of compressors, the variability of the units is dependent on their final task. Plant and instrument air are far different from the process air in terms of dryness and contaminants (25), determining costly generation and treatment.

On the consumption of compressed air system, the metering is continuous in time and, as consequence, the performances can be detected easily by mean of a centralized control unit; every time a problem in pressure or load downstream the compressor discharge or in the distribution lines shows, a signal is sent to the central system that advise the maintenance personnel. This ongoing load profile monitoring is necessary for the proper operations in a compressed air system, and is suggested (25) any time plants have high demand variations over time: this is just the case of Blue company.

Last measures on compressed air were performed in 2015, because of the high variability of the load for the fluid used as general plant air, for which the new compressors and master control systems were installed.

Last efficiency measures adopted	Year	Cost investment
Leak repair	2016	Low
Installation of new compressor units	2015	High
Master control system	2015	High
Upgrade control on single compressor units	2015	High

Table 9: recap on last efficiency measures adopted, blue company

The availability of the master control system was possible only after the installation of the same brand compressors, compatible for working together; the second unit with the variable speed drive supplies the variable load when needed, and the bigger compressor is always running.

Validation of the framework

After the focus on the context being studied, the interview moves to the theoretical part, for the validation of the framework.

The interviewee is asked about the general characteristics of the tool and starting with the general structure, he points out that the tool is structured in a way that is easy to understand for the industrial end-user. Of course, he also paid attention to the fact that people having management skills, usually can have low knowledge on the pure technical side of the compressed air systems, and the tool is rightful addressed to people with positions similar to his.

Talking about the structure of the framework, he noticed that the *operational parameters* are evaluated prior with respect to the *economical-energetic* and *contextual* ones in a time scale. In general, when a measure is going to be implemented, the production department is in charge of the operational features to focus on, and only in a second moment, the project is evaluated under an economic-energetic point of view, to understand the feasibility. The other axes are quite important, and as explained in Chapter 4, the economic and energetic evaluation of saving are of utmost importance because, at the end, are the ones by which a decision can be influenced at most. By the way, he considered the tool as very powerful, because highlights aspects that in general are not labeled as important, or not enough to be considered with the implementation decision.
Among the three axes the *compatibility* one has revealed to be the most interesting to outline, because of the poor attention associated with this item. *Complexity* is always evaluated (even though not all the items, as it will be soon outlined) and the *Observability* are the results that follow from the installation so he believes are easier to see. Please notice that the first part of the framework showed are the macro-categories and axes, but not the single items that compose them; the general idea about the axes are asked and after this first comment, the single factors are discussed.
About the single items showed, under the *complexity* axes, he effectively takes a lot into account (implicitly) the *type of activity* to perform, as well as the *expertise* required to the implementation of the measure. These aspects, are in fact quite obvious, since the knowledge on who should implement the measure is always required for a comprehensive evaluation of resources to use; the same type of discussion was made for the *activity type*, that indirectly gives also information about time and resources to use and *independency from other components*, since the degree of involvement of other parts is always to evaluate. The *change in maintenance* effort and/or time and the *accessibility* issues are sometimes

underestimated because not explicitly considered.
On the *compatibility* features, some important outcome is shown. The technological aspects are considered implicitly, because of the trust the interviewee gives to the technology suppliers is quite high, so that he believes the technological solution proposed are always compatible with the existing system. Since they have good relationships from years, they feel confident of the final result, when the technology experts are in charge of the work. The firm does work with different *pressure loads* and this aspect acted as very influential for the decision about the new compressor room to be installed, i.e. when significant system modifications were performed. *Adaptability to different operating conditions* is considered as very important to outline explicitly, since the different compressor units are used for this purpose. The *synergy with other activities* was not so clear the first time it was explained, since for the interviewee the factor partially overlaps with the activity type; he suggested that the fact that some activity can be made in synergy with other EEMs, means that probably they are of the same type. This point was clarified easily, after the explanation that the type of activity explains what will be the type of effort required, and the synergy is related to the time match (and not with the effort on doing the action). *Distance from electric service* and *presence of thermal loads*, as suggested in the Chapter on the complete framework description, were considered useful only for some type of efficiency measure. The interviewee agreed about the fact that this last two items are important for that efficiency measures that are, in any case, evaluated as very important.
Most of the factors on the observability are considered as auto-explicative and, a part from the artificial demand they, despite being considered as very important, did not had the necessity of further explanations, other than their definitions.
The model is considered as complete, since it takes into account all the features that Blue company address when efficiency measures are going to be adopted, even though on this point the second feedback on the trial (with measures already implemented) is fundamental. Clearness is considered at a high level, despite some of the factors have to be explained before with detailed examples, it results as completely clear.

On the scope of the model, the first attribute is the usefulness. The interviewee, other than being very kind for the long time dedicated, appreciate the work because it was considered as very useful. Once all the factors were explained, he admitted that some of them are not explicitly considered and for this reason he suggests that, if implemented in some program for the energetic audit or in training management program, it can be a useful tool. On the other hand, the clearness is quite good (3 out of 4), he advises that the factors should be easier to understand for the applicability of the model in all the management contexts. Despite this aspect, the clearness for him was rated as very high.

The end-user perspective was considered as very useful, also because, as him suggests, is the only one for which he can give an evaluation.

Axes for the taxonomy of the model are considered as: "*not common but useful*" for him, meaning that the approach of having a taxonomy that considers the contextual factors can result a winning approach. The completeness is rated 4, but the clearness is asked for the single items composing the axes. No superimpositions are present, demonstrating that all the elements presented are quite clear and focused enough on specific aspects with their peculiarities.

The factors, as the axes, are revealed to be clear once explained deeply, and their clearness was, for almost all of them, rated to the maximum value; only the synergy with other activities and artificial demand are rated nearly the top but not at maximum because the explanation was made by mean of examples on efficiency measures. The usefulness was rated at maximum except for the technological compatibility, for which, in this specific context, the interviewee gives not much attention as revealed before. Absence of superposition was rated 3 out of 4 only for that factors for which a clarifying example on a specific efficiency measures give

The table recap all the features analyzed thoroughly in this part, with the ratings obtained by the presentation to the interviewee.

		Usefulness	Completeness	Clearness	Absence of overlapping
Framework	Structure		4	4	
	Scope	4		3	
	Perspective	4			
	Macro-categories		4		
	Economic-energetic	4		4	4
	Operative	3		4	4
	Contextual	4		4	4
	Axes		4		
	Compatibility	4		4	4
	Complexity	4		4	4
	Observability	4		4	4
	Factors		4		
Complexity	Activity type	4		4	3
	Expertise	4		4	4
	Independency on other components/EEMs	4		4	4
	Change in maintenance effort/cost	4		4	4
	Accessibility	4		4	4
	Technological	3		4	4
	Presence of different P loads	4		4	4
Compatibility	Adaptability to different operating conditions	4		4	4
	Synergy with other activities	4		3	3
	Distance to the electric service	4		4	4
	Presence of thermal loads	4		4	4
	Safety	4		4	4
Observability	Air quality	4		4	4
	Noise	4		4	4
	Wear & Tear	4		4	4
	Artificial demand	4		3	4

Table 10: synoptic on framework validation, blue company

6.2.2 *Green company*

Location: Province of Caltanissetta, Sicily, Italy
Interviewee: Maintenance responsible.
The interview lasted 1 h and was performed on October the 23rd directly to the site, then the maintenance personnel showed me the compressed air system for half an hour.

6.2.2.1 Company profile

Green is an Italian company in charge of maintenance and revision activities for electrical, mechanical and electromechanical tools. They have a single plant in the industrial area near Gela, and the company is accredited and works for the ENI group to the test and revision of electrical motors and of both hydraulic and pneumatic valves, for which a tight control of compressed air is used. The plant has 27 employees, most of which are divided between the electrical and pneumatic/hydraulic side. The turnover of the last two years ranged from 1,3 to 1,5 M€.

6.2.2.2 Energy profile and decision-making process

The energy consumption inside the firm has a percentage ranging from the 6 to the 9 of the total turnover. As consequence, the yearly energy expenses range from 100.000 € to 126.000 €. Cost of energy is 0,11 €/kWh.

The company is certificated in quality assurance for all the types of revision, by the UNI EN ISO 9001:2008, but has not any certificate for other issues, as energy management. As consequence, no interest in external energy audit have been shown throughout years, and the reason for the interviewee was that "they are not compulsory, and we have not the necessity of doing one of them until we judge the energy performances of the plant as good enough". The problem was that the "good enough" was not explicative of what they consider as a lower threshold under which act with such a plan.

Moreover, the interviewee, is in charge of all the quality and energy issues inside the plant: this means that poor attention was given to both aspects, because of this "spread" focus. In any case, he sincerely said that the energetic issue is not of primary importance from them, because of the top management scant interest in budgeting such type of plans.

No particular efficiency measures were performed in last years, apart from planned maintenance activities of different types and the close off of two compressed air lines because they have no more the revision of some type of valves; the production volumes were sensitive of this change.

Last efficiency measures adopted	Year	Cost investment
Close off unneeded compressed air line	2015	Very low

Table 11: recap on last efficiency measures adopted, green company

6.2.2.3 Compressed air system status

Compressed air consumption is medium, being used 8 h per day. They do not have a specific cost item for compressed air, but a rough estimate[73] gives that less than 7 k€ expenditure comes from the compression unit. All in all, this is not a high cost, and this is probably the reason why the efficiency status of the system is quite low, as will be show immediately.

Compressed air has different types of use in the production area: it is involved in cleanness of mechanical parts, as well as for the blowing and painting activities, for which the pressure is quite low. The pneumatic valves revision area, need a tight control of pressure because it has to calibrate properly the devices; in any case, the higher pressure reached does not overcome 6 bars so the use of a single compressor for feeding all the lines was sufficient.

The only compression unit is sited outdoor, and gives some problems in terms of higher noise in summer months (i.e. note that since this plant are located in Sicily, were the average temperature are far higher with respect to other places). The unit is present since 2008 and was never changed, as well as the ancillary equipment and distribution system.

The compressed air unit and distribution systems information are present in the following table:

Type of compressor	Power [kW]	Control	Function
Screw lubricated	30	Load-Unload	Process/Service
Screw lubricated	10	Load-Unload	Backup

Table 12: recap on compressors, green company

As highlighted before, there is no difference in air generated for the valve testing and service plant applications, apart from the pressure reducers for delivering pressure at the rated level. The compression unit produces air at 8 bars with the highest-pressure application being at 6.
This entails for sure high inefficiency, at least from the generation side, since the pressure

[73] It was obtained with a load-unload ratio of 0,25, because of what we experienced during the plant visit, and the unload coefficient of 0,25 from the technical documents of the compressors.

can be reduced a lot to the requirements by the highest-pressure demand side that is 2 bars lower.
Moreover, the other source of inefficiency was for sure the air receiver downstream the generation of the compressed air; it was dimensioned taking into account the old air demand that was far higher than the actual flow rate.
For this reason the measure asked in the second part, is on the minimization of the pressure to the minimum requirements.

Validation of the framework

After the focus on the context being studied, the interview moves to the theoretical part, for the validation of the framework.

The interviewee is asked about the general characteristics of the tool and starting with the general structure, he recognizes its completeness, that resulted moreover clear. The first comment on the framework structure, was related to the low availability of tools like this. He is aware of the fact, that usually, the only aspect that matters when an investment decision is the economical side, despite an investment in energy efficiency can generate savings that rapidly overcome costs; the structured way the framework can approach the EEMs, is evaluated very positively because he recognizes their lack in consciousness about the potential savings and what each implementation implies in terms of efforts. On the scope of the work, he believes that was clear; in particular he immediately recognized that the objective is to respond to a real problem, the inefficiencies in compressed air system, widespread also in their reality. The perspective of the end-user was estimated to be very useful, because he believes that the presence of a tool giving more awareness could be used to explain in easy way the possible savings and opportunities to which is in charge of the final investment decision (i.e. the top management).

On the macro-categories, he advises the importance of the economical-energetic, because takes into account all the information about the purchasing cost of new equipment or optimization procedures. Operative parameters are always considered for an investment on compressed air system, but their usefulness was rated 3 out of 4, this was because he believes that is not so useful to “point out something that for sure will be considered when an adoption decision of compressed air efficient equipment is in place”. On the other hand, we comment together that the fact that they are obvious, does not mean they do not have to be considered; for the relevance of the study ALL the factors to considered for an investment are important for the final decision. The contextual parameters are rated at maximum because one may understand the real implications of adopting one EM.

After the explanation of all the axes, they are rated at their maximum values, and he does not advise for any lack or overlap between them. He further comments that the three of them can be easily understand, once explained the observability definition and that the complexity, compatibility and observability are characteristics that give an explanation of "how the efficiency measure is going to behave when is embedded in each specific context".

About the factors, after their complete explanation, the distance to the electric service was revealed to be the only one rated with a 3 out of 4, because he believes this entail very specific technologies substitution that are advisable only in some type of firms. For the others, he was satisfied on the approach that was given to the work, because he found the factors as the most important to evaluate a whatsoever adoption. Moreover, he comments that the number of factors is quite "small", because if they were more, maybe the instrument would not have a practical application.

Level	Group	Item	Usefulness	Completeness	Clearness	Absence of overlapping
Framework		Structure		4	4	
		Scope	4		4	
		Perspective	4			
Macro-categories				4		
		Economic-energetic	4		4	4
		Operative	3		4	4
		Contextual	4		4	4
Axes				4		
		Compatibility	4		4	4
		Complexity	4		4	4
		Observability	4		4	4
Factors				4		
	Complexity	Activity type	4		4	4
		Expertise	4		4	4
		Indipendency on other components	4		4	4
		Change in maintenance effort/cost	4		4	4
		Accessibility	4		4	4
		Technological	4		4	4
	Compatibility	Presence of different P loads	4		4	4
		Adaptability to different conditions	4		4	4
		Synergy with other activities	4		4	4
		Distance to the electric service	3		4	4
		Presence of thermal loads	4		4	4
		Safety	4		4	4
	Observability	Air quality	4		4	4
		Noise	4		4	4
		Wear&Tear	4		4	4
		Artificial demand	4		4	4

Table 13: synoptic on framework validation, green company

6.2.3 *Orange company*

Location: Province of Caltanissetta, Sicily, Italy
Interviewee: Quality and energy responsible.
The interview lasted 1 h and 15 min and was performed on October the 23rd directly to the site. The engineer also showed the compressor room.

6.2.3.1 Company profile

Orange company is an Italian company, active from more than 50 years in the field of precision mechanics. The company has a turnover of more than 9 M€ and more than 115 employees. They have a great experience in the field and cover a wide range of services:

- Revision and maintenance, that comprises their big share of business volume;
- Production department of pumping systems, where they focus on the quality of products by means of innovativeness and ongoing r&d;
- Reverse engineering of mechanical components;
- Design and engineering office, to ensure efficiency and continuity to the production department;

6.2.3.2 Energy profile and decision-making process

The company should have quite high interest in the energetic subject, since the energy expenses are between the 5 and 6% of the total turnover. The figure interviewed is directly in charge of taking decision about energy efficiency, and the projects proposed by his team are directly sent to the top management, that may approve them or not. Despite the decisions on energy are in charge of him and other two engineers with the same role, some criticality rise for the lack of a unique figure for the management of energy issues, leading to a lack of the effectiveness in the management activity.

The company is certified in quality, with the implementation and maintenance of a quality management system complying with standards UNI EN ISO 9001:2008 and a safety management system that complies with standards OHSAS 18001:2007, both for the maintenance and overhaul of rotating and reciprocating machines and construction of pumps and spare parts.
Also, they are certified for the maintenance and manufacture activities by the UNI EN ISO 14001:2004.
No certifications for energy management activities are present, and they have not long-term objectives towards the reduction of the energy expenses.

Unfortunately, as explicitly declared by the interviewee, some problem arises in the decision about energy efficiency measure to undertake. On one hand, the engineers from the quality department and technical office have not criticalities with the production department personnel. On the other, the relationship with the management is not so clear and the attention is more directed towards the core processes that on service ones.

6.2.3.3 Compressed air system status

There are no available data on the compressed air total consumption, despite the unit is quite large; with the same calculation used in the previous example (but here the load/unload factor is estimated as 0,2), the total expenditure is 12.000€/y[74]. The interviewee stressed the point on how, from an energetic point of view, the expenditure is considered rightfully as a marginal cost, being the 1,3 ‰ of the turnover.

Despite the compressed air is not used as a process, is active all-day long. Utilization pressures varies between 6 and 8 bars. The generation range is between 8,6 and 8,8 bars (quite high with respect to the requirements), and the compressor, despite maintaining the right pressure is over dimensioned for the flow rate, with respect to the actual capacity. Its utilizations vary a lot inside the production department. They are used for the tool replacement in CNC machines to clean the spindle and for the actuation of the pneumatic actuators for the doors opening and closening. There are also used for blowing away scraps from threading operations and the drying of mechanical parts.

The compressor unit is only one, and the engineer advised the possibility and necessity of having more, at least as backup unit. Unfortunately, the proposal was refused from the top management since "only" in one case in the last two years there was problems with the compressor and they believe this did not entail big problems from the cost of lost production i.e. the problem was solved promptly by the maintenance personnel, but they did not effectively measure the cost of lost production.

Type of compressor	Power [kW]	Control	Function
Screw lubricated	30	Load-Unload	Service

Table 14:recap on compressors, orange company

[74] Energy cost = 0,13 €/kWh

There are not preventive maintenance procedures for the distribution system, neither for the pipes, nor for the fittings and connection valves. The compression unit is subjected to maintenance (provided from an external supplier) exclusively in case is required from the control system, but the other parts have not any sensor for the leak amount or pressure drop detection across the lines.

Validation of the framework

After the focus on the context being studied, the interview moves to the theoretical part, for the validation of the framework.

The interviewee is asked about the general characteristics of the tool comprehensive of the structure, scope and perspective. About the structure he believes that the general view is clear enough and complete as well. The showing of the macro-categories, axes and factors is evaluated positively because the framework represents a synthesis tool able to encompass all the aspects to undertake for an energy efficiency decision; The scope of the work is clear enough, but he had some comment on the usefulness. This lead to an overall rating of three out of four, since the availability of external consultants on compressed air systems permits them to have a quite clear picture of the situation of inefficiencies and opportunities. On one hand, this critic is to consider negatively, because the involvement of external consultants in all the decisions about efficiency in compressed air is highly influencing which and how decisions are undertaken. On the other hand, it was clear, that the negative influence was given from the low impact that a tool like this can have in their industrial context[75], and they are not experts about the technology. This permits to stress the point on how the framework can be used with easiness for the evaluation of decision, lowering the information gap with the consultant that make their proposals on compressed air investments; he admits that, at the end, end-user knows how the technology is actually used in its context, and this tool is more useful in his hands with respect to the supplier ones. The usefulness of the tool by the end-user, moved the discussion on the rating of the perspective, that for this reason is rated to its maximum level.

On the macro-categories, he believes the economic-energetic parameters are the most important, and the usefulness of the operative ones was rated high because helps to see

[75] The problem of the approval of EEMs for a system considered marginal, as the compressed air.

what are the physical characteristics involved in the adoption of an efficiency measure. Dealing with contextual parameters, ha suggested that some additional cost can result from the application of the framework on an efficiency measure, so this entail the partial overlapping of the economic macro-category with the contextual one. The problem is solved because the economic part takes into account only the investment cost that will be considered when the project is presented to the management, letting out the efforts in terms of resources, time, experience and so on. The framework was generally evaluated as comprehensive of the both types of parameters included in each investment decision (operational and economical) and moreover considers factors that depends on the contest: he admits this is never taken into account, so pointed out also the innovativeness

On the axes, no problems are advised and their names results as auto-explicative, so the ratings for all of them was rated as four.

All the factors result as useful to explain deeply the efficiency measures embedded in the industrial context. On the other hand, he believes the synergy with other activities contains information partially embedded in other measures. The information about the synergy with other activities to perform during downtime, where need for downtime is considered in independency from other components, and the synergy with other maintenance activities, where the maintenance effort from the adopted EEM is taken into account as a complexity factor.

In this case, a further explanation on the meaning of each of the factors resulted helpful for a complete evaluation: the synergy with other activities, points out the capability of one measure to be coordinated with others that own similar operative features, but does not take into account complexity issues in performing the activities. On the other hand, the maintenance effort refers to the eventual additional training or gaining of knowledge for new procedures that the EEM adoption implies, being not referred to the synergy with other activities. For the independency on other components, in which only the difficulties in implementing the intervention for the need of shutdown, the meaning is the same. After the explanation, the interviewee was convinced about the independency of the three factors, and rated them to their maximum. Since comments on the possibility of overlapping, should not be underestimated, the decided rating was 3 out of 4.

			Usefulness	Completeness	Clearness	Absence of overlapping
Framework		Structure		4	4	
		Scope	3		4	
		Perspective	4			
Macro-categories				4		
		Economic-energetic	4		4	3
		Operative	4		4	4
		Contextual	4		4	3
Axes				4		
		Compatibility	4		4	4
		Complexity	4		4	4
		Observability	4		4	4
Factors				4		
	Complexity	Activity type	4		4	4
		Expertise	4		4	4
		Independency on other components/ EMs	4		4	3
		Change in maintenance effort/cost	4		4	3
		Accessibility	4		4	4
	Compatibility	Technological	4		4	4
		Presence of different P loads	4		4	4
		Adaptability to different conditions	4		4	4
		Synergy with other activities	4		4	3
		Distance to the electric service	4		4	4
		Presence of thermal loads	4		4	4
	Observability	Safety	4		4	4
		Air quality	4		4	4
		Noise	4		4	4
		Wear&Tear	4		4	4
		Artificial demand	4		4	4

Table 15: synoptic on framework validation, orange company

6.2.4 *Red company*

Location: Province of Palermo, Sicily, Italy
Interviewee: Quality and energy responsible.
The interview lasted 1 h and was performed on October the 25th directly to the site. The engineer also showed the compressors room.

6.2.4.1 **Company profile**

Red company is a Sicilian based company, involved in the tires production and regeneration. The company has worked in the plastic and rubber sector since 1954, representing one of the leader in the Sicilian market of tires, involved both in the production and commercial sector. Their production department entails two different working principles: semi-integral heated and preformed (cold working). Moreover, since 1984, they moved to the ringtread tires regeneration, with ring preformed shapes. Production process involves a prior inspection to evaluate the integrity of the structure and the availability to be subjected to regeneration, thanks also to the shearography testing. Then the removal of material from the treadwear is made by pneumatic driven mechanical tool. It follows the repair of wear parts and the preparation for vulcanization process. The last passage is the final inspection. The annual turnover is 2,5 M€ and the number of employees is ten, being not more than a family-run industry.

6.2.4.2 **Energy profile and decision-making process**

The energetic expenses cover a big share of the total turnover, around the 7%; the most of the them are attributable to high effort given from the vulcanization process (major share of the two) and the compressed air backpressure needed to maintain the tire under specified pressure during the aforementioned process.
The interviewee is an engineer in charge of responsibilities in the production department: he is responsible of energy and quality management inside the plant. The decisions about energetic issues are taken with the help of the site manager and owner, that owns a technical background as well. In this case, the decision-making process is quite straightforward because was tested in years: structured and shared information provide easiness in the adoption of efficiency measures, involving less risks in the final results.

The site was certified by UNI EN ISO 14001, but they have not the quality certification because of their ineffectiveness in gaining competitive advantage at the expenses of competitors. For the energy monitoring inside the plant, they have a periodical (1 each two years) visit from external auditor, despite this is not finalized to obtain the ISO 50001 certificate.

Efficiency is considered as a point of utmost importance, since some processes are high energy-intensive. They rose their awareness after many years of very inconvenient electrical bills. They concluded that an external expert to enhance their efficiency capability would help, and this effectively works. In the last year, many efficiency measures in compressed air system were performed, from the changing of compressors to the modification of control units.

6.2.4.3 Compressed air system status

Compressed air plays a role of utmost importance inside the production plant. The service functions are ascribed for cleanness and blowing of parts after the mechanical/chemical working. Moreover, the shearography test is needed to underline eventual internal anomalies of the tires, comparing the ambient and vacuum pressure carcass profiles. Inside the production process, the backpressure of air is needed during the chemical forming, to ensure the profile maintains during the whole working time, that can last up to 40 minutes per tire.

Compressed air system is quite modern, even though this is not true for all the equipment and the distribution system. The last measures provide modern units and satisfying performances.

The two compressed air units are not so powerful, with a total installed capacity of 13 kW. The working time is 16 h per day and they are two because of the different working pressures for the process and service lines. The old system was composed by a single unit, but the air consumption was too high, with lot of pressure reducers, i.e. of losses.

Type of compressor	Power [kW]	Control	Function
Screw-lubricated	10	VSD	Process
Screw-lubricated	3	Load-unload	Service

Table 16:recap on compressors, red company

As aforementioned, the last efficiency measures were installed in this system, providing high savings estimate within less than two years, because the dimension of the actual units is not big.

Last efficiency measures adopted	Year	Cost investment
Use/purchase optimum sized compressors	2016	High
Upgrade controls on compressor	2016	High

Table 17:recap on last efficiency measures adopted, red company

Validation of the framework

After the focus on the context being studied, the interview moves to the theoretical part, for the validation of the framework.

The interviewee is asked about the general characteristics of the tool and starting with the structure, considered clear and complete: the fact that the compressed air have an active role in their production process, influenced the interest in underlying the usefulness that this tool can have in their facility. The scope of the work was very clear and rated as very useful, because of the gainable awareness on the topic; he moreover, believes that the focus on a single technology is a crucial point. On the perspective, is was rated positive for the approach toward energy efficiency by the end user; he said that "knowing better the consequences of the adoption may also create trust, if the tool is reliable". On the other hand, his comment was that a similar tool can be used from the technology provider that can use it for the assessment of the possible measure to propose inside that context. Indeed, in their case, the decision about an energy efficiency measure is generally suggested by the external expert rather than being considered from them, unless the system does not perform as expected. The importance of the perspective was anyway valuated as very positive because his comment was on the possible *extension* of the model to another perspective, and not on the substitution of the end-user perspective with the technology supplier one.

The part on the macro-categories was fully agreed, and he points out that is important to consider at first the topics on the economic aspects, but also the energetic ones (we remember that their attention is on the possible gaining of the ISO 50001 for the energy management). Then, the attention is never moved on "how" the implementation is made in practical terms i.e. what are the factors to consider with the technological and economic.

The axes are rated at their maximum both for completeness and clearness: he believes that maybe there is a difference in their importance, and that the complexity and compatibility, for sure will be gain more consideration with respect to the observability ones.

The factors were considered very important, and only after the explanation of the singular elements, he evaluated the whole framework as very positive and auto-explicative, except for the artificial demand part, for which he did not know the meaning. After some example on where the artificial demand can be lowered with the adoption of efficiency measures, he agreed both on the importance, clearness of the item, as well as on the absence of overlapping with others.

Level	Group	Item	Usefulness	Completeness	Clearness	Absence of overlapping
Framework		Structure		4	4	
		Scope	4		4	
		Perspective	3			
Macro-categories				4		
		Economic-energetic	4		4	4
		Operative	4		4	4
		Contextual	4		4	4
Axes				4		
		Compatibility	4		4	4
		Complexity	4		4	4
		Observability	4		4	4
Factors				4		
	Complexity	Activity type	4		4	4
	Complexity	Expertise	4		4	4
	Complexity	Indipendency on other components/ EMs	4		4	4
	Complexity	Change in maintenance effort/cost	4		4	4
	Complexity	Accessibility	4		4	4
	Compatibility	Technological	4		4	4
	Compatibility	Presence of different P loads	4		4	4
	Compatibility	Adaptability to different conditions	4		4	4
	Compatibility	Synergy with other activities	4		4	4
	Compatibility	Distance to the electric service	4		4	4
	Compatibility	Presence of thermal loads	4		4	4
	Observability	Safety	4		4	4
	Observability	Air quality	4		4	4
	Observability	Noise	4		4	4
	Observability	Wear&Tear	4		4	4
	Observability	Artificial demand	4		3	4

Table 18: synoptic on framework validation, red company

6.2.5 *Violet company*

Location: Province of Palermo, Sicily, Italy
Interviewee: Quality and energy responsible.
The interview lasted 1 h and was performed on October the 24th with a phone call.

6.2.5.1 Company profile

Violet company is part of major corporation with many manufacturing facilities in Italy, and one abroad. Their ATECO code is 10.20. They are specialized in production and distribution of canned sea food, for which they are one of the main leaders in the national area. 6 different production lines are present in the interviewed facility, and for all of them the use of compressed air is fundamental; from cleaning activities on the cans to the packaging system. The plant has 105 employees and the total turnover is slightly less than 50 M€.

6.2.5.2 Energy profile and decision-making process

The energy consumption is around the 1% of the total turnover, that in general is not a high percentage; this is justified by the high turnover. Since the turnover is on the upper threshold of SME's, this quantifies in a total of almost half million € per year.

The interviewee is the site manager, and is in charge of all the energy management inside the plant. The interventions of energy efficiency are agreed by its team, composed of four people; one of them has the critical role of ensuring that all the processes (production more than service) are performing under the established conditions; for this, they have performances monitoring system, despite they have not any certification (ISO 50001) i.e. they lack a complete Energy Data Management system, that other than showing consumption data, creates specific reports.

There are not any technical international standard certificate (ISO), but they are in line with BRC standards, for the compliance of food health and safety, recognized by the Global Food Safety Initiative (GFSI) to promote and make stronger this concepts on all the supply chain. Moreover, they are certificate with the International Food Standard, being part of the selected firms able to supply safety products, in compliance with contractual specifications.

The last energy audit was performed in 2016, the results are in the next paragraph. Energy cost is around 0,11 €/kWh on average of the last two years trend.

6.2.5.3 **Compressed air system status**

30% of energy expenses are attributable to electric energy, whose major share consumption is compressed air. For this reason, added to the fact that high air quality is required for cans sterilization and cleanness, compressed air, despite not directly involved in the production, is highly monitored for the performances and consumption. It comes out that compressed air is source of the 15% of the total energy consumption; for sure not a negligible task. Other than cleaning of glass and aluminum cans, the production of anchovy paste involves compressed air for the appropriate dosage of dough inside the small tube but not for the filling, for which is involved mechanical equipment. The production of nitrogen and air knives for shears of tuna pieces are the only involvement of compressed air in the production process. The transportation lines are compressed-air driven, both with pressure and vacuum generators.

Type of compressor	Power [kW]	Control	Function
Screw-lubricated	60	Load-Unload	Service
Screw-lubricated	40	Load-Unload	Service
Screw-lubricated	40	Load-unload	Backup
Screw-lubricated	22	VSD	Service

Table 19:recap on compressors, violet company

The compressor room are two, because of the distance from different production lines, with a total installed capacity of 162 kW. Two compressors are in the first room, with a total power of 82 kW. The other serve the transport and air knives processing.

Compressed air status involves modern equipment, despite the distribution system has not being changed from at least two and a half decades. They believe that no many leaks problems are present, because of the performances of the machines and monitors pressure drops exclude this possibility; for this reason, they do not act proactively on the line, but only when a change of performances shows.
The last audit performed in 2016, found a good air quality (of primary importance in all the plant), and the compressors that performed well with the usual maintenance requirements. The assessment decreased the compressed air consumption of the 20% with very good preliminary energy savings (not accounted yet, since they will be available at the end of the year).

Last efficiency measures adopted	Year	Cost investment
Install adequate dryers to eliminate blowdown	2016	Medium
Eliminate air leaks	2016	Low

Table 20:recap on last efficiency measures adopted, violet company

After the focus on the context being studied, the interview moves to the theoretical part, for the validation of the framework.

The interviewee is asked about the general characteristics of the tool comprehensive of the structure, scope and perspective. They are all ranked at their maximum. The interviewee pointed out that the specification of a series of factors can be an auxiliary tool when dealing with energy efficiency, and further comment that this should not be specific only of one technology but it can be adapted to other energy intensive systems. Firstly, the specification of "others" means that, in the violet company, compressed air is rightfully recognized as an important energy consuming system. This is very important, since not all the companies interviewed have complete clearness on this point. Secondly, with "other system" he refers to the refrigeration systems since are the more energetic expenses for them. High refrigeration expenses are needed to stock the fish, in order to preserve the product quality before the production.
As specified in the first chapter, this tool assumes a strategic role also because the compressed air is widespread in industries of any type, being a cross cutting technology. The opportunity to have such a tool can be extended to other technologies of this type, because heating and cooling systems are among the ones that found extensive application in manufacturing industries.
For the perspective to use, he believes the tool is appropriate for industrial end-users, since he recognized that usually service providers they lean on, have much more competences and they have only the possibility of accepting purposes[76], but not of proposing something.

The importance of the macro-categories is very high for him, since he pointed out that the tool is able to show the baselining of actual performances through the operative parameters, the economic and energetic outcomes, whose proposals have to be screened from the top management.

The axes is which are branched off the contextual parameters, are revealed to be useful, clear enough and with no overlapping concepts, other than easy to understand.

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[76] In any case, the company trust blindly on them, since they provide services from many years, without compelling cases.

The factors have been explained one at the time, and the most important points to focus the attention were that: first of all, the complexity issues like activity type and expertise have always been considered because of the implicit importance in each of the efficiency measures. On the compatibility, he revealed that maybe in this cluster there are more factors that are not considered very much for the adoption decision. The presence of different pressure load, can affect a lot the decision on some type of measure; he said: "this factor is implicitly considered in the measures with too high-pressure discrepancy applications, but maybe could be checked with more attention in the ones where the differences are not so high, in systems where a lot of pressure reducers are installed". Adaptability to different conditions is a great point to focus on, but considered more important for the possible future system variations with respect to the change in demand (that is always taken into account). Synergy with other activities is revealed as very interesting to consider, because may be an indicator of how and what efficiency measures are suggested to be performed together. The presence of thermal loads is another important aspect, and in his personal experience it was underestimated because of the possibility that was sifted when the compressors were installed, but then they understood that the enthalpic level of the fluid was too low to consider the heat recovery opportunity.

On the observability factors, the additional benefits in the reduction of artificial demand was particularly appreciated, because the framework points out in what of the efficiency measures this have an influence. Moreover, the wear and tear of equipment is considered as very useful, because effectively it's not highly taken into account for the adoption, but can be a point to further encourage people in charge of decisions.

One single comment was made on the completeness of the factors, because the time needed for the implementation is not explicitly considered in the model. This is true, but is a direct consequence of the type of activity that is going to be performed, and so can result as redundant (giving more that the required weight to a factor negatively related to the adoption, may hinder the measure implementation more than required); the site manager agreed on the explanation. This last point, that was commented together with the manager, is rated 3 out of 4, but, in any case, the final evaluation was rated as positive.

		Usefulness	Completeness	Clearness	Absence of overlapping
Framework	Structure		4	4	
	Scope	4		4	
	Perspective	4			
Macro-categories			4		
	Economic-energetic	4		4	4
	Operative	4		4	4
	Contextual	4		4	4
Axes			4		
	Compatibility	4		4	4
	Complexity	4		4	4
	Observability	4		4	4
Factors			3		
Complexity	Activity type	4		4	4
Complexity	Expertise	4		4	4
Complexity	Indipendency on other components/ EMs	4		4	4
Complexity	Change in maintenance effort/cost	4		4	4
Complexity	Accessibility	4		4	4
Compatibility	Technological	4		4	4
Compatibility	Presence of different P loads	4		4	4
Compatibility	Adaptability to different conditions	4		4	4
Compatibility	Synergy with other activities	4		4	4
Compatibility	Distance to the electric service	4		4	4
Compatibility	Presence of thermal loads	4		4	4
Observability	Safety	4		4	4
Observability	Air quality	4		4	4
Observability	Noise	4		4	4
Observability	Wear&Tear	4		4	4
Observability	Artificial demand	4		4	4

Table 21: synoptic on framework validation, violet company

6.3 Discussion of findings: framework

The final summary and comments on the on-field evaluation of the framework by industrial end-users is the first step for the validation of the work. The problem analysis started with the characterization of efficiency measures, and the model permitted the step from the analysis to the synthesis of peculiar characteristics of the technology, summarized in factors. The feedback from practitioners in the industrial world is maybe the most important passage of the whole work, representing the prove that what has been done have also empirical evidence before its final application.

The framework structure, scope and perspective positive evaluation means that the tool is presented in the right way to the target, and this is an indication of the capability of having wrote the model in the right way, recognized as important and innovative at the same time.

The heterogeneity of the sample is considered of primary importance to not underestimate the possible influences of the dimension, basically for organizational changes inside the companies[77], and sectoral application, for the intensity of energy and the use of compressed air as service or process applications. The five companies for this first part of the work were carefully selected to this aim. Table 22 summarizes the different sector, dimension and turnover (where available, otherwise an estimate is provided) of selected firms.

[77] Thollander et al. (5) recognizes that the implementation of standardized energy management systems among industrial SMEs in very limited

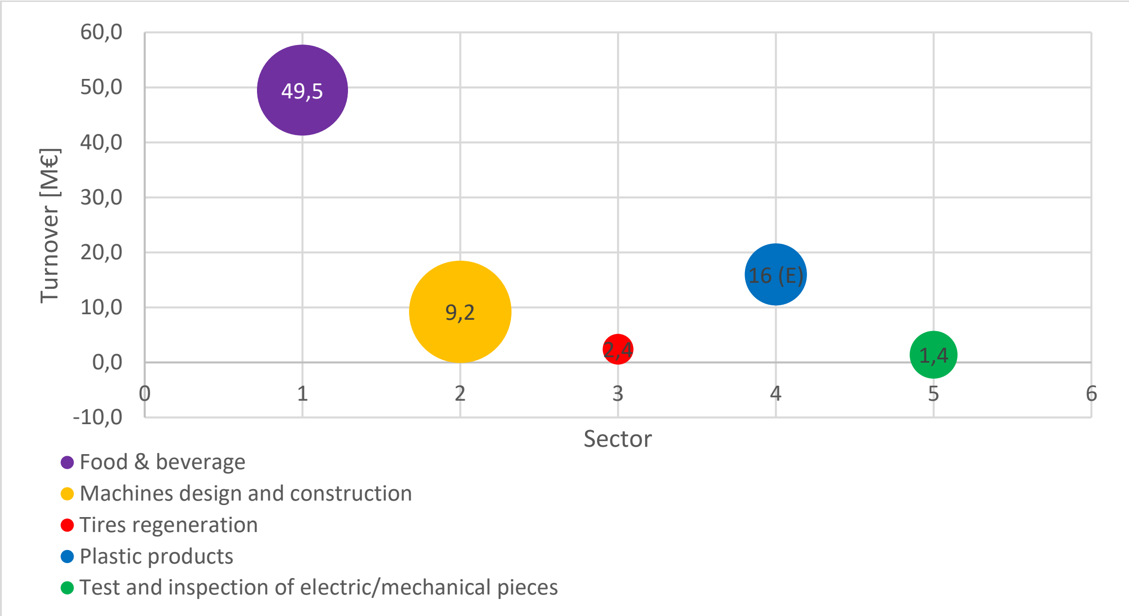

Table 22: heterogeneity of the sample for the framework structure validation

Please notice that the final results are rated as totally good, since no one rate, for each of the individual values was rated as negative (1 or 2 in the scale used). Each of the attributes describing the main items of the framework are deeply analyzed in the next section.

6.3.1 *Top-level analysis: framework structure and categories*

Usefulness: the items to which is applied this attribute are the scope and perspective of the model. The ratings, have been rated as very positive. In one case, red company, rated the perspective as 4, but this was signed as 3 because he pointed out the possibility of extending (and not substituting) the perspective to the suppliers of the technology. The rating on the scope was rated as 3 from the orange company; here the comments were about the scope, owing to the availability of external consultants that can be exploited to have a complete awareness on the energy efficiency topics for the selected technology. In this case, the value was rated as positive only after a further discussion on the importance of internal awareness, to act proactively for the adoption of a measure.

Completeness: about the completeness very satisfactory results come from every company in each type of sector, demonstrating that the comprehensive review of each single efficiency measure (Chapter 3) was very useful for this purpose. They do not advise any lack, except for the time needed for the installation, advised by the violet site manager. As was explained in the section dedicated to the validation by the single companies, in reality, the addiction of such item was not considered because of the possible redundancy in considering it in the type of activity; as pointed out by Fleiter (127), the higher degree of change (advised by activity type) typically necessitates change in the structure roles, power and status of employees and higher difficulty; this factors implicitly consider more time in general, so that it may not be added as a single factor.

Clearness: this attribute is found both in the structure and scope of the framework and all the interviewed people agreed on the clearness of the whole instrument. For a further enhancement of framework clearness, during the interviews was showed a unique table containing all the features and the different levels of detail for each of them (Appendix), so that they could have a guide while the tool was explained in detail for each of the items composing it. The rate of clearness is the highest of the five, with no any instrument lower than 3.

The average of the total ratings is collected in Table 23 to summarize the results; please note that, being all the values given by the interviewees between three and four, are reported the frequencies of the maximum value[78]:

		Usefulness	Completeness	Clearness
Framework	Structure		5	5
	Scope	4		5
	Perspective	5		
Macro-categories			5	
Axes			5	
Factors			4	

Table 23: average ratings on the top-level items of the framework

6.3.2 *Bottom-level analysis: evaluation of single macro-categories, axes and factors*

Usefulness: This item describes how each of the factors result of some utility in explaining the implications coming from a potential adoption of the EM. The operative parameters in two cases were ranked with three out of four, but with a deeper analysis was discovered to be a problem of the less influence they have on the decision with respect to the economic-

[78] Being the samples a number of five, the indication 5 means that all the respondents rated that entry as 4 (maximum), the indication 4 means that all the respondents except one rated the entry as 4, etc..

energetic parameters, and not on their absolute value. They were rightfully judged as the first to evaluate for such a type of investment. Technological compatibility was rated not to its maximum value only one time. The comment here was on the availability of the technical support to understand what are the technological constrains or opportunities for the measure, but the use of the framework is oriented also toward the acquisition of independency from other figures, with a primary tool to make a correct evaluation of the possible compatibility of technologies with the existing system.
In another case, the evaluation of the distance from electric service was considered too specific for some of the measures, thus for the description of the others it can be avoided. This is correct, but since this can have a high influence on the measures for the change of technologies, it is worth to integrate them in the tool.

Clearness: clearness of single factors involved the understanding of the single features to apply to the efficiency measures i.e. the ones that will be tested during the application phase of the framework. The findings are very positive, with the recurring (two out of 5) comments on the unawareness of knowing information about the artificial demand concept. In reality, it was not known by any of the interviewees, but in some cases the example on specific efficiency measures was made to further clarify the additional benefits from the reduction of artificial demand; in these cases, the attribute on the item was rated as 3 out of 4. The example of synergy was made on maintenance, downtime or similar operation activities to explain better the concept of synergy, that, after all, was evaluated as clear.

Absence of overlapping: The feedback on this attribute, that was not present in the first part dealing with the structure, is able to give information on the exclusivity of each of the items composing at different level the macro-categories, axes and factors. The axes are revealed to be the ones with less problems from this point of view, with the maximum rating from all the practitioners; they advise that complexity, compatibility and observability are well defined and separated characteristic through which is easier the explication i.e. scope of each of the factors. On the macro-categories, effectively there are no problems at all, but in the first explanation to the engineer of the orange company, he critically argued that contextual factors may influence the cost related to the efficiency measure adoption, thus one influence the other. This was not the case of our framework, because the added hidden costs (accrued from the translation of the quantifiable contextual factors) are not considered in the first investment evaluation, and for this reason are the ones that may hinder or give a positive outcome to the final decision about adoption.

Facing the factors, it was advised the highest number of comments and suggestions owing to the quantity of factors, as easy predictable. Three of the five cases did not advise any further descriptions. The activity type and expertise, were considered as partially overlapped because of the implicit difficulties in one activity usually prescribes major expertise. In reality, as pointed out by a couple of example, the engineer agreed that the expertise is an indicator of the technological complexity, and the activity type is an indicator of the structural difficulties embedded in the measure. For instance, a new installation of filters does not require at all the technology experts. The problem for this misunderstanding was partially created to the omission of the levels in which the activity type and expertise were declined (new installations, optimization… maintenance personnel, technology expert, see 6.1), so that this further explanation was needed.

The other point was on the partial overlapping of the synergy with other activities like maintenance and downtime with the independency form other components/measures, and maintenance effort requirements were seen as partially overlapped. This problem, is implicitly embedded in the taxonomy of axes, that are organized by the characteristics of EEM and not by its nature (technological, economic…), but, as explained in 6.2.3, the synergy is a positive outcome of compatibility, while the need for higher or lower maintenance or the requirement for shutdown are clearly another aspect, linked to the implementation and maintenance difficulty. As a further example, the downtime is a negative outcome, but the synergy with other planned activities that require downtime may hinder the adoption in the present, but increase its likelihood when the planned downtime is expected.

		Usefulness	Clearness	Absence of overlapping
Macro-cat.	Economic-energetic	5	5	5
	Operative	3	5	5
	Contextual	4	5	5
Axes	Compatibility	5	5	5
	Complexity	5	5	5
	Observability	5	5	5
Complexity	Activity type	5	5	4
	Expertise	5	5	4
	Independency on other components/ EMs	5	5	4
	Change in maintenance effort/cost	5	5	4
	Accessibility	5	5	4
Compatibility	Technological	4	5	5
	Presence of different P loads	5	5	5
	Adaptability to different conditions	5	5	5
	Synergy with other activities	5	4	4
	Distance to the electric service	4	5	4
	Presence of thermal loads	5	5	5
Observability	Safety	5	5	5
	Air quality	5	5	5
	Noise	5	5	5
	Wear &Tear	5	5	5
	Artificial demand	5	3	5

Table 24: synoptic, framework validation

Basically, up to now, is proven the availability of the model to be understood by the industrial end-users. The next step, is instead focusing on the possible practical outcomes of the study in a future, as an assessment tool. For this reason, questions about the efforts in the use of the framework and its user-friendliness are asked; contemporarily, was evaluated the utility of the framework as a decisional tool to be used as an ancillary service.

6.4 Application of the framework: trial on single efficiency measures

Once the structure of the framework has revealed to be suitable for the industrial context as an additional tool for decision-makers in energy-related field, this part of the chapter is oriented on the application of the model to some of the most recommended efficiency measures (48), but for which implementation rates are not satisfying (for most of them the values are under the 50%, Chapter 5 for information on the EEM that are going to be analyzed).

For a thorough and complete evaluation of the tool, is necessary some further specification on the EEMs typology, because our believe is that, it may influence a lot the approach to the efficiency measure i.e. the way in which the framework applies to the different measures. As pointed out in the first part of the chapter, the data come from different type of companies, both for number of employees (10-133) and sectors, ranging from the food and beverage to the paint manufacture; the heterogeneity of the sample is quite useful for the discussion of the single efficiency measure approach, depending on how important is considered the technology and what is the organizational envelopment for such type of decision.

The typologies of efficiency measures are basically influenced on the experiences companies have, and they are divided in three different groups:

- PAST experienced: this group is composed from efficiency measures for which it was made an investment plan, so they were recommended but not implemented for different reasons (explained throughout cases);
- PRESENT: belong to this family all the efficiency measures that were recommended and adopted, so they are part of the actual company context. Present is referred to the fact that the consequences of the implementation are accrued during the whole lifetime of efficiency measure i.e. in the present;
- Possible in the FUTURE: are efficiency measures for which no recommendations were made, or for which recommendations are quite recent, meaning they have not already taken a specific decision about the implementation.

The singular efficiency measures are asked also having in mind this basis: to have a final comprehensive view of whether the tool applied for differently oriented measure, has a different impact on the adoption of the measure or not. For this reason, on a total of 15 different efficiency measures 4 belongs to the past experienced by companies, 7 shall be adopted in the future and 4 are already implemented.

The single efficiency measures are thus categorized under this clustering method and not with the temporal line of the interviews, both for ease of understanding and for the structured discussion of findings for each category.

A synoptic table is present at the end of each of the discussed (possible, made or not) efficiency measures to evaluate the importance of factors for that EEM i.e. which factors is considered influencing the decision. The importance of the factors of course is different depending on the efficiency measure and context, and this is the reason why each table considers the evaluations by the interviewee with respect to the values that comes from the theoretical validation. This means that the entries in the Table 7: synoptic of the most recommended EEMs, that will be analyzed for the framework application are turned into reasonable values of the factors for the specific efficiency measure, ranging from zero (not influential) to five (the most influential). Please notice that the gap between the reasonable values coming from theory and evaluation given by the interviewee is not an index of some error, but consequence of the subjectivity of the inquiry.
The important points are, firstly, the lack of some factors in one of the two different validations that is present in the other: this mean that a factor that was not considered at all in some case, is demonstrated to have some influence in the other. Secondly, the difference in overestimating or underestimating some of the factors are discussed briefly after the showed results.

6.4.1 *Blue company*

I come back to the blue company, for the application of the framework on two specific EEMs. The first efficiency measure inspected was the ***control on compressors***, since the company performed both the single control unit upload for the compressor, and the installation of the centralized control for all the plant's compressors. This measure belongs to the "***present***" family i.e. the EEM was adopted.

Before the installation, the old compression unit had a load/unload control, but was revealed to be too energy consuming because of the high load variability during all day, and as known, the units can be started and stopped only a limited number of times during the day (25). The variable speed drive was prescribed as the best fitting technological choice to cope for this problem.

As in all, the efficiency measures, the operative parameters are of utmost importance, but the temperature was not considered since the upgrade of the control was performed in a new unit with the variable speed drive and mainly the temperature problems should be checked if the variable speed drive is going to be installed in a compatible unit already present. The other two operative parameters are considered as crucial to match the air requirements.

The economic-energetic parameters, as well as the previous ones, are considered as the most influencing to take the decision. The economic outcomes have to be analyzed in detail for the complete investment evaluation.

The contextual parameters in this case are a lot and very influencing; this measure, in fact, is one of the most "full" of factors; as consequence, is more likely that some of the factors may be underestimated or not considered by the industrial decision-makers, as it will be clear after the single EEM analysis.
The activity type is considered as a new installation and the expertise required is very high; both these parameters are considered as very important, because influences how the implementation phase is performed and what are the needed resources. The burden of maintenance activities in general should be less than before, because the centralized control system uses on board compressor's control microprocessors, that give information when control problems arise; the maintenance cost may be lowered by 7-10% for the installation of a VSD. The lower maintenance effort was not rated as highly influential for the decision-maker, despite he knew the consequences. Independency from other components was underestimated: on one hand (i) he considered rightfully, that the installation of a common header was required along with the EEM adoption (25); on the other hand, (ii) he did not consider the problem of re-dimensioning the air receiver and the possible installation of the central control (to check the inlet flow rate entering the dryers). This lead to the partial consideration of this factor as influential. The accessibility problems were considered for the new installation.

The technological compatibility is to consider as quite important for the installation of a central system able to handle different compressor typologies. The interviewee does not have idea of whether the VSD could be installed on the old compressor, but the compressor would be changed in any case. Adaptability to different operating condition is the reason why the measure is installed, so this factor is the most influencing and this was rightfully considered. The activities require long time to be performed and this has been made during the lower production period of the year, very close to the summer time, when the plant was closed; the consequence is that the synergy factor is very important.

On observability factors, the safety issue was considered as important, but the decision-maker was unaware that the malfunctioning of automatic controls is one of the two major reasons for the over-pressurization of the compressor units. Noise reduction, through the utilization of noisy units working during the night was not possible because the compressors in use are only two; moreover, the interlocutor admitted that even though this parameter would be considered, have a very low influence on the decision (or have not at all importance). The wear and tear of equipment can be diminished with the load sharing of compressors, this direct consequence was not considered a lot in the decision.

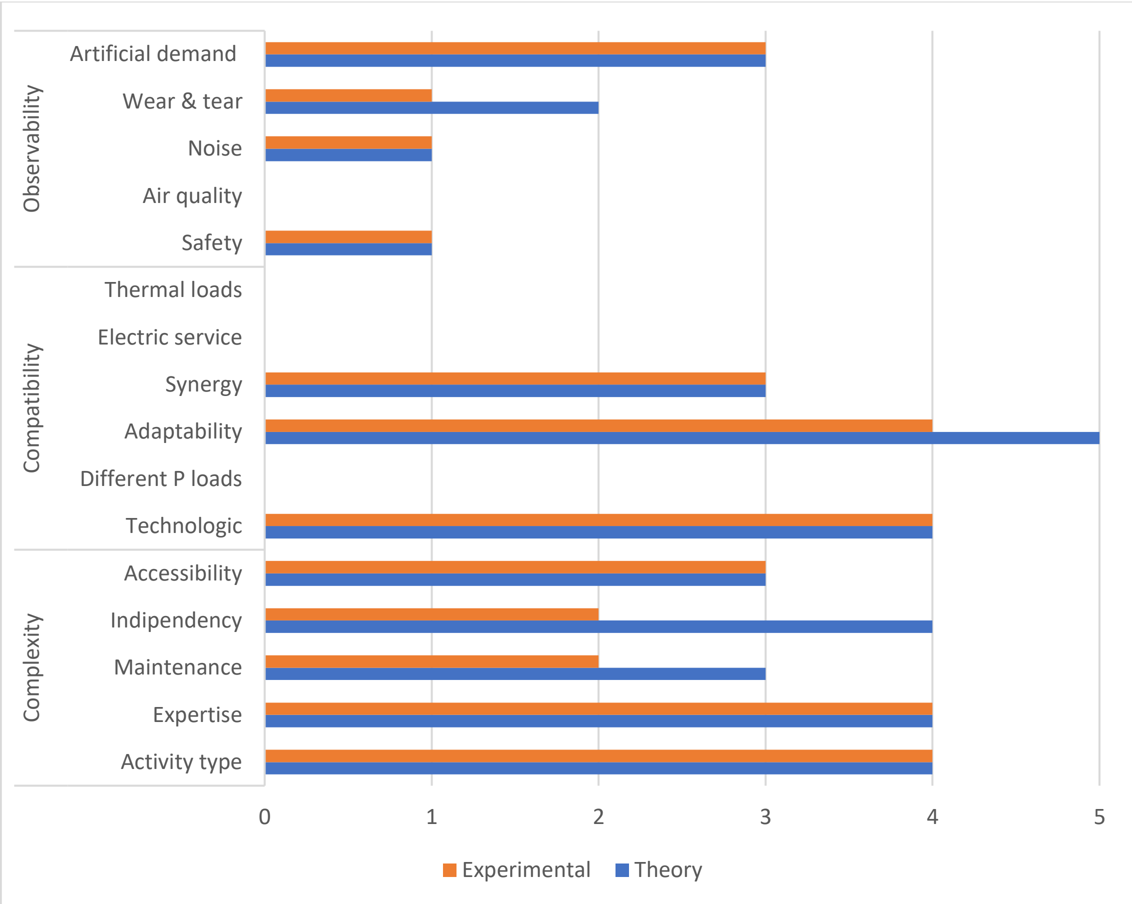

Figure 21: Upgrade controls on compressors, blue company

No high discordances are present between the two, and since the theoretical validation ratings are underpinned on a subjective basis, a little change in the values is more than justified, but can anyway act as a thrust for further discussions. The unique discrepancy is showed in the independency from other components, because the re-design of some of the system components were not evaluated properly, as well as the possibility of controlling the dryer units, other than the compressors.

The general trend shows, in line from what expected to efficiency measures that are already adopted by firms, that the parameters are almost all considered with the right level of importance (a part for some oversight) and that the firm is able to correctly evaluate all the most important parameters. Little discrepancies, for which the manager admits their low consideration, would not be enough to change their decision about adoption.

Thanks to high time effort dedicated from our presence the manager of Blue company was asked about another measure that instead could be adopted but it wasn't because it was considered as not important enough. This makes the EEM belong to the "***past***" family. This passage is fundamental to obtain interesting results from the empirical validation, since it may highlight what are the stronger factors that may be used like a lever for the adoption decision. Moreover, not being adopted, the discrepancies between how the factors should be rated and how much they actually are, should be more evident in this case.
The efficiency measure that is going to be presented is highly dependent on the control mode of the compressors, that was recently upgraded, to explain also how the measure change its convenience once the context is changed.

Install compressor air intake in the coolest location was the prescribed measure.

Screw compressors are the one for which the efficiency measure lead to an increase of the specific efficiency in scfm per kW (128) if the control mode is appropriate. The application is suggested in VSD controlled compressor with better performances on oil-lubricated compressors with respect to oil-free.
Since the situation of the compressors type and controls is composed by different compressors with variable speed drives, the opportunity for increasing the performances could be exploited. They have not performed this type of efficiency measure because the compressor ambient is the same of the past units, in an external ambient with no different aspirations depending on the ambient conditions.

This entail for sure a lower efficiency in summer months with respect to the cool ones, and the suggestion, in this case, is to differentiate the intake air aspiration with the help of a temperature control sensor to detect what are the best conditions.

The payback time highly depends on the initial expenditure, that in this case should entail the connection with the internal ambient and the sensing temperature device, as well as additional filters elements. The energy savings for this measure, usually, are not that high (48), and this may be an important factor hindering the adoption.

Operative parameters to check, pertains the new average inlet temperature, but this implies a different flow rate (increasing with the lower inlet temperature) and the pressure reduction from filtering devices.

Consequences on the context from this adoption are plenty; the activity type and expertise are quite high, because of the required knowledge on the lowest possible temperature to ensure good performances of the units is required. The type of activity, in this case, entails a retrofit to the existing system, but also new equipment presence is to consider. On this second point, this will not would be a big problem because of the closeness of the two environments. Accessibility in the new room will be lower with respect to the present conditions, affecting negatively the adoption. Independency from other components is influenced because of the additional ventilation requirements that should be checked with the technology expert. Maintenance requirements do not change, apart from the temperature control device, that is not influencing a lot.

On the compatibility issues, the technological compatibility is important because of the possibility of installing the measure only to some compressor typology. If this was known by the adopter, he could have thought on the possible benefits without the help of the technology expert. Adaptability to different (ambient) conditions is highly increased by the installation, and this aspect was not considered at all on a potential installation. Synergy with other activities can be performed on additional filters or on the control units with the general compressor control; the interviewee did not consider as important the first, but paid attention on the second aspect, that would have not be considered if the framework did not underline this point. The different of pressure loads do not influence this measure, as well as the distance from electric service and the presence of thermal loads.

On the observability factors, the safety is not influenced as well as the noise and the artificial demand. The air quality in an internal ambient is in general better than the external one. The moisture content is lower and this may lower the wear of the compressor units, extending the life of components, and is considered a good factor to point out from the adopter.

As can be seen in the synoptic table for this EEM, the importance of adaptability is highly underestimated, and this is the main reason why the measure was not installed (the awareness on the measures potential). On the other hand, the independency from other components would be probably underestimated, as well as the maintenance requirement for the temperature control device.

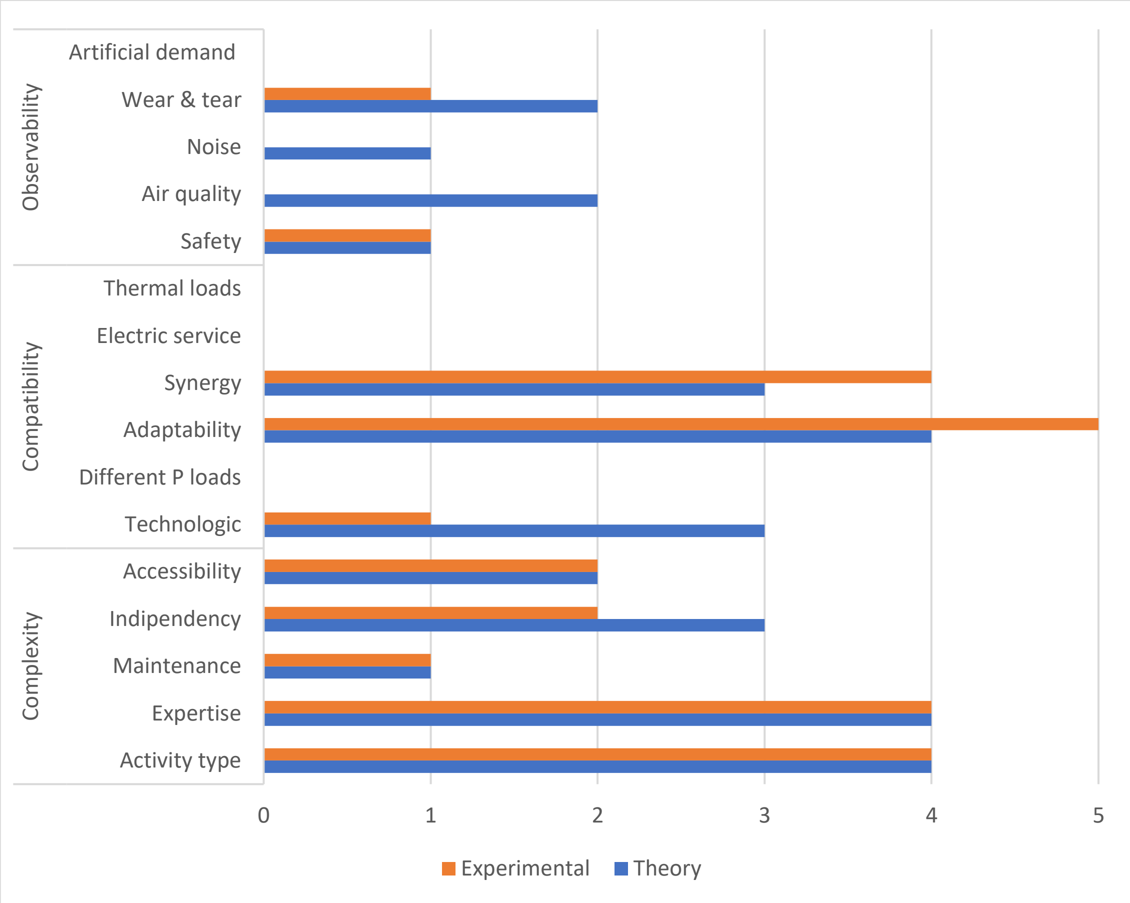

Figure 22: Install compressor air intakes in coolest location, blue company

The overall results are revealed to be very interesting, because, as the Blue site manager pointed out, the increased awareness resulting from the framework application, will be probably enough to consider the installation of the measure. He moreover recognized that the implementation should be performed at the time when the new compressors and controls were installed, since this would not be an additional demanding task.

What is quite evident from the overall evaluation by the Blue company, the difference in the "type" of efficiency measure, have an influence in the final result by the framework application. The first, was about the adopted measure, for which the high consciousness, revealed that all the influencing factors are properly considered. Many more differences in the proper evaluation are revealed for the efficiency measure that can be adopted, but actually it has not. The factors not considered properly, are influential for the decision, and this may change the way they approach the measure.

Finally, the evaluation of the applicability of the framework was tested asking the two performances indicators. The effort required, does not seem to be a large problem. Despite during an investment decision one should enter in the technical details of each of the factors and trying to evaluate them quantitatively to test their impact, the effort of using this tool in parallel with the investment decision is neither considered time consuming, nor invasive. The user-friendliness is considered high, especially because were tested two completely different types of efficiency measures, so was proved the adaptability, that was relatively easy to understand for each factor applied to each EEM. The different ways in which some factors is applied to one or the other EEM (fluid flow rate is compressed air for the first measure, heated water/air for the second; technological compatibility in one case is defined as the change in performances by compressor types for the decrease of inlet temperature, in the other is the availability of producing heat to be recovered).

6.4.2 *Brown company*

Brown company is a facility with more or less 40 employees, and actual turnover of more than 6 M€ located in the Sicily central area. It is specialized in the production and reworking of plastic pipes and PVC material through thermos-forming activities; they use a particular technology which patent have been taken from a northern Europe industry; they are proud of their results in term of quality of products and affair volume. They have two big compressors and another one exclusively for emergency back-up use.

The interviewed person, was the engineer in charge of quality and energy management, because of the lack of different figures for each of the roles. The company were certified in 2010 by UNI EN ISO 9001, recognizing their quality management efforts.

Extrusion and main plant air are fed from unique compressed air room, located in the back of the plant. The compressors seem to operate quite reliably, and they were all changed in 2010, as well as the whole compressed air system, comprehensive of piping and end-use equipment.

Here, some overconfidence was created in regards of their system, because of the misconception that, being the system relatively new, they do not need any application of preventive maintenance procedures to locate, estimate and repair leaks. The maintenance is performed for the compressor units, in accordance to what is reported in the screen, but until the monitoring system does not give advice of any pressure problems across lines, they do not feel the need of increasing the performances of the system, but more in general of any of the efficiency measures. This is maybe the best condition for the application of the framework in an industrial contest: this preliminary discussion showed a lack of awareness in the analysis of CAS; our aim is to demonstrate whether the tool is able to create an increased consciousness on what should be taken into account from a technological point of view.

When asked about the possibility of eliminating leaks, the interviewee argued that the most important leaks can be detected without any problem because the compressed air leakages are easily identifiable for their noisy characteristic, so at the moment they do not feel the need for a preventive periodic maintenance on leaks. The problems to outline here are two: firstly, is to advise the unawareness on the potential given by other methods of identifying leaks as ultrasonic or chemical foam detection; secondly, the noise generated during the production processes, would for sure cover the noise generated by the leaks, unless the leaks size is very high.

Because of the high unawareness on the primarily important concepts on the compressed air leaks location estimates and repair, the decision on the efficiency measure to deeply analyze was immediately recognized as the ***elimination or repair of leaks in compressed air lines***, that belongs to the "***past***" EEMs.

The estimation of leaks strongly depends on the baseline of current systems condition, both in terms of flow rates and pressure requirements. As highlighted in CHAPTER 1, this is the most advantageous intervention on CAS both for payback time and savings over initial expenditures, being also the most implemented.

The application of the framework was performed only for this measure in this company, thus a deep analysis has been performed.

The first part was dedicated on the comments about the role of economic energetic parameters, as well as on the ones pertaining the technical side. The decision-maker agreed on the fact that these are the information needed for each decision on a general efficiency implementation. The specification of the operative parameters is highly customized for the use on a technology, and he believes the importance is more on the variation over time of the parameters that on their fixed value.

The importance, as always, is given to the economic and energetic side, defined as "constraining" for the decision. In any case in the timeline, the savings are evaluated after the assessment on what are the potential source of efficiency, as well as the costs and time to pay-back the investment. Then the final approval, of course, is in charge of the management.

The contextual parameters start with complexity: the type of activity seems to be not that difficult because are not performed new installations; on the other hand, he pointed out that the phenomenon is so spread that, despite the activity is easy, the effort is quite high. On the expertise required, it usually depends on the type of technology used for the detection, and this was correctly considered of medium importance; a further comment was given here on the possible different types of technologies, that may change the perception owned by the decision-maker. Independency from other components is rated very high; the leaks reduction influence positively the pressure of the line, that may be increased, with the positive consequence that translate in the elimination or reduction of some supply side equipment i.e. compressor, in the best condition. This aspect was not taken highly into account because the interviewee is quite skeptic on the facts that the savings can lead even to the substitution of compressor. The maintenance activities, since not planned in the current business organization, should be increased to maintain the enhancement of performances given by the adoption of the efficiency measure. The accessibility problem is maybe the most important for this efficiency measure; this seems to have a great importance for the interlocutor, since he pointed out that some parts of the line are too difficult to reach for their distance from the floor, and others are underground.

On the compatibility issues, the technological is not advised because this measure is operational, not implying the use of a new technology[79]. The presence of different pressure loads basically does not affect the measure, despite the prioritization of the high-pressure application is suggested to increase the savings; this was recognized as an important factor from the engineer but, unfortunately, they have not different pressure levels. No other aspects on compatibility are present, a part the influence given by the synergy with other activities (efficiency measures) as the pressure reduction and the possible synergy with shutdown of equipment if some particular technology is used for the leak detection.

The part on the observability outcomes is very important for this efficiency measure. The interviewee recognizes the importance that a periodic leaks inspection and repair has on the safety; the only problems they had since the system was modified, fortunately does not entailed safety problems, but he recognized it could had. Generally speaking, the wear and

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[79] The different technologies that can be used to perform the measure are accounted in the factors on complexity, and in general each system can be treated with each of the technologies, so that the technological compatibility is not a problem.

tear increase with the increase of the pressure, but in this case the differences in pressure created in the pipe by the leak, have a much more negative effect owing to inhomogeneous fluid passage. The noise generated is much less and the leaks are the major cause of the increase of artificial demand; on the former the interviewee argued that each noisy leak is repaired every time they can hear it, the latter aspect was not considered at all, and he recognized barely the importance.

In the following table are summarized all the importance given by the interviewee.

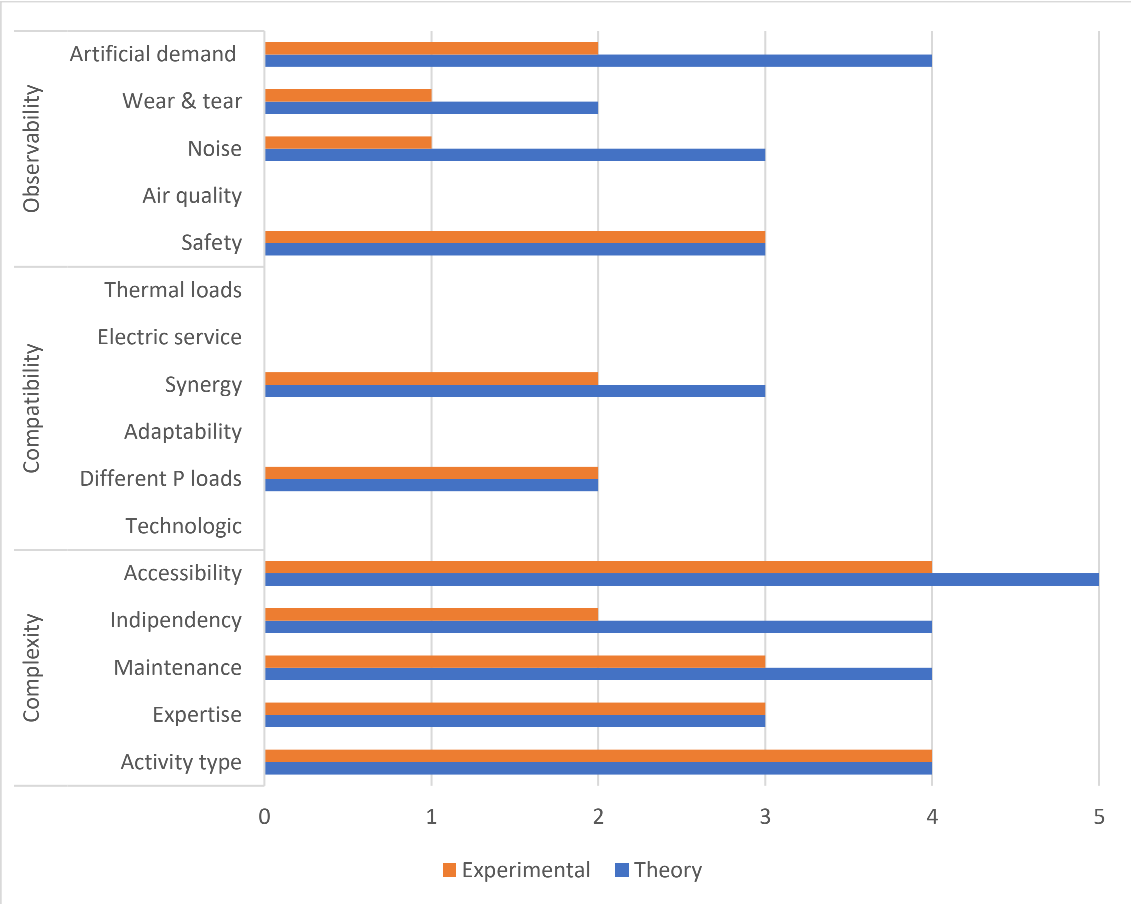

Figure 23: Eliminate leaks in compressed air lines/valves, brown company

As can be advised in the chart, there are a lot of differences on what should be considered for the adoption decision and what is actually taken into account. The big differences, mostly regard positive aspects of the installation; this means that a better consideration of that factors could lead to a different final evaluation of the EEM's potential. The interviewee, when asked about this hypothesis, said that probably the final result would not be changed; this primarily because (i) the framework also underlined the negative aspect he was aware, that were the main reason for the lack of the adoption, and then, because (ii) the implementation depends largely on the effective savings and not primarily on contextual parameters. The accessibility problem, along with the scope of the efficiency measure, that is extended to all the distribution system, and the prescription for higher maintenance efforts are the most influential factors; the framework has revealed a capability in underlying them, because the interviewee admitted that despite important, they would not be considered explicitly for the (non) adoption.

In this case, the framework seems to be not powerful enough to change the way of approaching energy efficiency. We believe that this behavior is mainly attributable to organizational problems with respect to the effective applicability of the framework. To support this theory, effectively, the final evaluation about the effort was rated at its maximum, because he believes is not too complicated i.e. the factors are easy to understand and to apply to each context, if the user has at least a basic knowledge background in compressed air technology. On the user-friendliness, he gave a positive feedback, mainly because of the simplicity in reading the instrument and applying to a whatsoever efficiency measure.

6.4.3 *Violet company*

Information on the company are available in the section 6.2.5. The decision on going again to the plant, was made because the easiness of reaching the site, and moreover for the availability given by the person in charge of the decisions, even because the first part of the interview was made by telephone. They have installed several efficiency measures in the last year and a half, but he was asked also on the possible efficiency measures they have not adopted but they thought on. For this reason, this is a "***past***" efficiency measure.

The decision on the efficiency measure to describe, was thus moved to the ***elimination of compressed air used for the transportation system*** for the cans and aluminum tubes along the production line, with vacuum grippers to lift them. In that part of the line they have compressed air-driven vacuum generators and they believe there is a possibility of enhancing performances with the replacement of technology that was dated. They ultimately did not update the system because of the high investment cost and the shutdown of the entire line that would mean losses for the cost of production disruption; they are in fact active 24 h/dd.

The framework application provides a basis for the complete description of the efficiency measure prescribed: one prior consideration is that, they would reduce the use of compressed air with more modern system, but a valid alternative would be the installation of a motor driven vacuum pump.

Despite data on the load cycle were not available, the idea of using compressed air vacuum pumps is appropriate under two different conditions:

- Different levels of vacuum and/or more application: and this was not the case of the installed system; ×
- Low duty cycle; for what seen inside the line, maybe this condition is fulfilled; V

First of all, the needed pressure and air flow rates should be considered for the substitution: the new system should provide a certain vacuum level to reach the lifting capability required, despite the products are not heavy at all. Economic and energy savings are of utmost importance; one should see the available motor-driven pump cost, with respect to the changes they forecast with the compressed-air driven system.

In this case, the activity type is a new installation and this require for sure the experts to be involved in the substitution process, negatively affecting the adoption decision, despite the installation should be easy enough (62). The independency on other components is considered as important, because the high involvement of vacuum system for the proper production line working. Accessibility for the substitution may be an issue, but for the location of their system, it should not be so problematic.

On the compatibility factors, the technological compatibility is being rated as very important, because the measure cannot be applied on all the systems. Presence of different pressure loads, as briefly introduced in the bullet points, is quite important also in this case (here the absence of the factor, may positively influence the decision on the new technology), and the interviewee was not aware at all on this point. Adaptability of different operating conditions is not influential, because of the need of a single vacuum pressure level. Synergy with other activities advise the possibility of installation when the production line is down, this is considered a very important factor; for sure the substitution of technology will not be made stopping the normal operations activities. The distance from electric service is a fundamental factor, but they fortunately do not incur in this type of problem, and rate it as quite low.

On the observability factors, the safety and wear and tear are not highly influential for the adoption of such an EEM, as confirmed by the interviewee. The air quality depends on the installation decision but high improvements with noise reduction may come from the new installation; the electric driven pump, other than being much more efficient has a very low influence on the noise and is highly recommended to improve the working environment.

The interviewee, also in this case was not aware of the potential improvement in working environment quality, also because he stated that he "noticed the high noise coming from by the compressed air vacuum generation area" only when we talked about it.

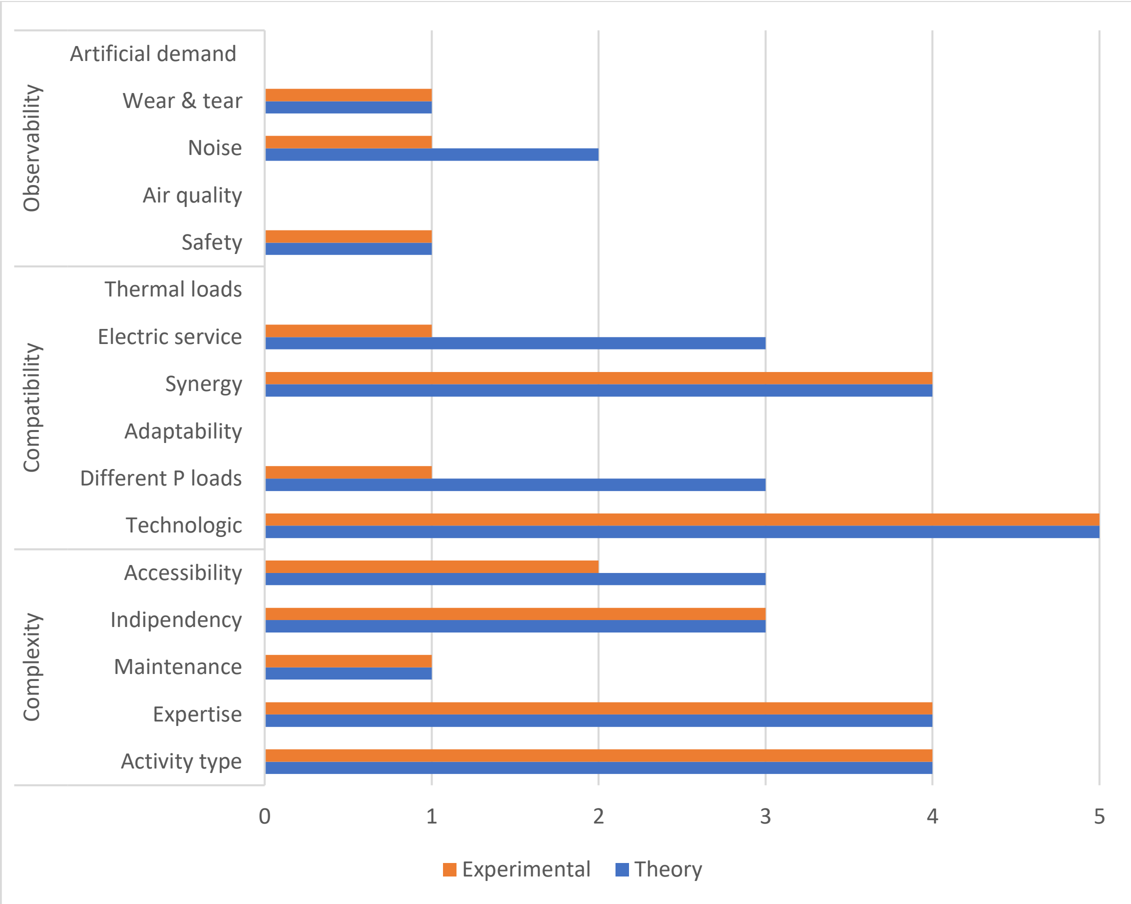

Figure 24: Eliminate or reduce compressed air used for vacuum applications, violet company

At the end, the framework in this case resulted as highly impressive in outlining factors for which the engineer was not aware, but can be noticed, that none of the negative ones was underestimated. Maybe in the future, when the lines will be stopped for the periodical maintenance he can think on the application of this measure, depending on the investment cost, but more aware of the savings (in general terms, not only the pure economic ones). The final evaluation was revealed to be very interesting, because the analysis of an efficiency measure that was not undertaken in the past, revealed the high potential of the framework. The easiness of applying the framework was highly appreciated by the interviewee, and some of the factors that are very important for the adoption, were not evaluated properly. He admitted that, despite their compressed air use is wide and energy consuming, they have not awareness on some of the potential measures that can easily fit in their context. User-friendliness, was rated 3 out of four its maximum level because he admits that (since as explained, they are not that experts in the technology), it should be combined with some additional information of how that factors is declined when applied to a singular EEM. This performance indicator was instead rated to its maximum if supported by all the explanations on the single technological change, that were suggested during the application. As was explained in detail after this comment, the tool would be in any case supported by all the implications that the single factors can have, when applied to a single EEM (refer to the detailed entries in 6.1).

6.4.4 *Orange company*

The efficiency measure that has been treated with the engineer, was the same for which they made the proposal to the top management, but that was refused i.e. it belongs to the "***past***". Other than the considerations on the applicability of the framework, we want to understand to what extent the focus on the positive influences that the measure has on their industrial context and working environment, may encourage the top management on changing their decision towards the adoption. Remember that the actual cost of compressed air with a rough estimation is 14,000 €/y (refer to 6.2.3).

The production departments are in two different areas, and the compressor unit is strategically located between them, in a shaded area that shelters it from the sun. The panels of the compressor are open in summer months, to provide more ventilation to the compression unit, but no fans are present to increase the convection effectiveness. Some problem was faced for the overheating of the compression unit, when more compressed air users require air contemporarily. The solution to this problem is to have two different and more compact compression units in the two different sites. Firstly, this will decrease a lot the length of the distribution systems (even though the two areas are not that far), the crossing of the outside environment, exposes the piping to bad conditions. Secondly, the differences in the production processes are very high, so that each of them should be ran independently. Thirdly, since the lack of a monitoring system, handling more compact units may diminish difficulties in their maintenance and management of loads/pressures.

The efficiency measure prescribed was the ***use/purchase optimum sized compressors***. The operational parameters are considered very important for the baseline of performances of the system, both pressure and air flow rate are evaluated properly. The efficiency measure in most of cases is hindered by the high initial expenditure required, so that this factor is the most influential.

Passing to contextual parameters, this is a retrofit, because the installation is always a substitution of an old technology, and the expertise required during the installation is quite high. The independency from other components was rightfully evaluated as one of the parameters highly influential, despite the interviewee did not think on all the possible impacts on distribution systems and other equipment units. The maintenance efforts are not that different if the type of compressor is similar, so the maintenance should be evaluated with a mean value; in the proposal, the types of compressor was accessorized with a VSD, that usually lowers a lot the cost of maintenance (65). The accessibility factor does not have any influence on the adoption.

On the compatibility factors, the technological is influencing the adoption because different types of compressors exist, and the presence of different pressure loads is rightfully considered of paramount importance because may influence the decision on one or more compressor to be installed. The adaptability to different operating conditions may have an influence on the installation of different compressors with respect to one big unit or to the installation of a VSD for adapting to changing demand; quite impressively, this was not evaluated as a parameter so influential. On the synergy with other activities, if the old compressor is not sold, there will be no need for line shutdowns during maintenance for the new units. This was not considered an opportunity for the interview, but he recognized the importance of the possibility of adopting this measure in synergy with others (upgrade of controls, reduction of the pressure to the minimum requirement, heat recovery from new units).

On the observability factors, the noise variation was not considered as influential, but in this case positively influence the adoption because, for the summer months, they actually open up the compressor room (i.e. a box with plastic walls mounted outside) in order to ensure the continuity of production, increasing a lot the noise level. The wear and tear of equipment is generally lowered if the compressor is optimum sized.

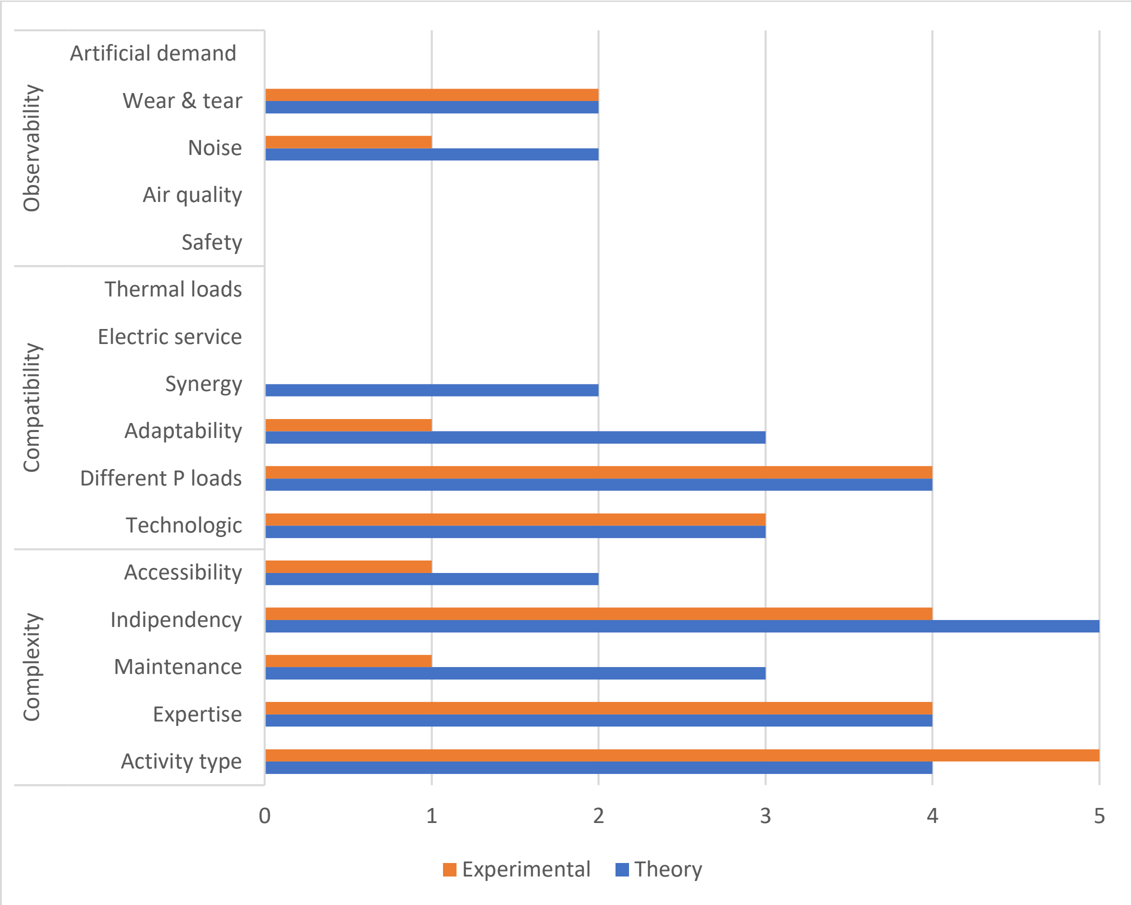

Figure 25: Use/purchase optimum sized compressors, orange company

The main differences in the lack of some factors can be advised in the part related to the synergy with other activities, referred to maintenance activities on new compressors. Maintenance procedures were not considered influential for the adoption, but the lack of new maintenance should be considered positively affecting it. Moreover, the independency was considered as important but did not take into account the negative outcomes of implementing some other efficiency measures before the purchase of new compressors. All in all, no high differences can be advised, and the framework application demonstrates that the interviewee, in this case, is able to properly evaluate almost all the influential parameter related to this measure.

The orange company was also asked about a second efficiency measure, the ***repair of leaks***, because is a much less expensive measure and does not require any new installation, but only organizational features to be taken into account. It belongs to the ***"future"*** efficiency measures.

The importance of operational and economic-energetic parameter was rated as the most important. The influence of contextual parameters has more or less the considerations advised for the Brown company (6.4.2), despite the only differences advisable in their ranking was the increased awareness on the independency form other system components and EEMs, that was evaluated close to its maximum. The absence of different pressure levels made rank the factor as slightly less important, and the further benefits of artificial demand were rated as very important as well.

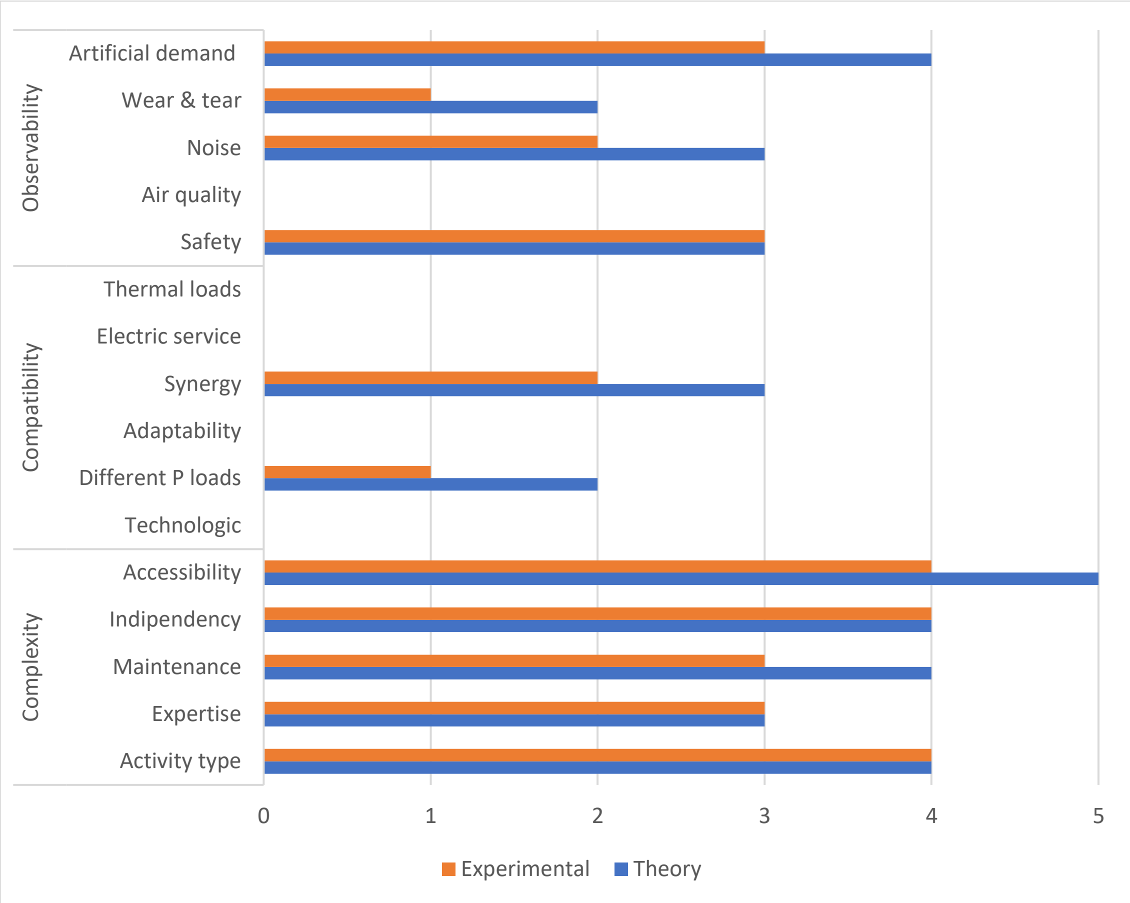

Figure 26: Eliminate or reduce compressed air used for vacuum applications, orange company

Considering both the efficiency measures proposed to the company, we can immediately advise some difference. Of course, primary differences depend on the intrinsic diversity of the two EEMs, being the former related to an hardware and the second recovery procedure. In both cases, a part from minor differences, the evaluation of the factors level has a quite good evaluation, even though some difference is advisable. The efficiency measure for which was not made an investment decision, is considered with slightly less balance (difference between theoretical and empirical application) on the overall evaluation: the positive influence of maintenance was not rated as influential when it should be, as well as the adaptability. Overall, the framework was considered of primary importance in outlining some of the positive influences, that for sure are important for the single efficiency measures, but not enough to move the decision about adoption. In this case, we can advise a higher-level problem, because of the scarce importance compressed air has on the final budget, that is translated to the investment cost the most influential factor in absolute. In the other case, instead, since the lower effort in terms of investment and structural changes of the system (highlighted thanks to the framework application), the interviewee was more positively impressed by how the factors were clearer once used the tool.

The opinion of the interviewee was that the framework was considered as highly powerful, because give an increased awareness of factors without adding any effort by the decision-maker, other than some training (that was made interviewing the person on the validation part) to understand how the model works and has to be applied to the singular EEMs. The effort, for this reason, was rated to its maximum value. On the user-friendliness, he rated it as very easy with some additional support in the explanation of the impact of a single factor on the EEM.

6.4.5 *Grey company*

This company is based on the northern coast of Sicily and is a leading internationally active in supplying products for microelectronic. The plant is wide and the annual turnover is approximately 12,5 M€. The employees in the site are around 133. Its business is spread across different type of activities, but the plant visited is specialized in producing micro-electronic particles for aerospace applications.

The interviewed is the site manager, in charge of safety of the entire site. Its delegated to ensure quality and energy inside the plant, and he has a team of 3 people working with him. They are certified both with ISO 14001 and 50001, and they have moreover planned the reduction of the emissions on a 5 years horizon. The role of the manager is of paramount importance for the decisions on energy efficiency measures and he shows how an investment of this type is usually made. The decisions on the energy topics starts from the team, and the team itself keeps constantly monitor and manage energy expenditures, and which processes require to be more efficient.

The compressed air system is spread all over the plant, because of the many uses inside the firm. There are two different compressor rooms, one for the process air and the other for the general plant and instrument air. The quality standards of the former are stricter, but no precise data were available on the quantity of contaminants allowed. The prescription of compressed air manuals (25), is that one may ensure the same quality standards for all the air applications. The lack of this procedure, creates, in fact, a sort of preferential direction that lead the interest toward the efficiency measures in the line for which quantity of contaminants are lowered.

The fact that not high attention, or at least not high as it should be, is given to the plant air system is for the low influence on the energetic expenses of compressed air. The compressed air expenditures, own a very low share of energy, because of the presence of three big ovens (with account for almost the 80% of the total). Despite the compressed air is widespread all over the plant, the consumption does not overcome the 4% of the total energy expenditure[80].

The total installed capacity is slightly more than 100 kW, with lubed compressors for the plant air and oil-free machines for the process ones. Some investment was made in the last five years for the change of compressor controls. Owing to the high variability of demand they decided to change the compressor controls, installing also a new little compressor with a variable speed drive. Maintenance is always performed at best because of the central control system for the baseline of the performances of compressors.

The efficiency measure that was prescribed at the time when the new controls were installed, belonging to the "***past***" EEMs, and is the ***heat recovery from the compressors***. The main problems with the installation was basically two: (i) their heat demand for service applications is almost all covered from the additional heat produced inside the plant, coming from the huge boiler rooms feeding the ovens and (ii) the compressor room is located so far from the offices that the enthalpic level was not enough for their application. Since the problems for the non-adoption are quite important, we do not claim that the framework may be served as a tool to move the decision toward positive outcomes, but in any case we should control the capability of the framework to foresee all the problems arose during the decision.

The operative parameters of course, here, are the temperature and the flow rate of the fluid (that may be air, water or a mix of components, depending on the application) and the economic and energetic parameters are always considered of primary importance.

[80] Energy expenses in the last year accrued to a total of approximately 650 k€

On the complexity items, the activity type is rated as not so important, because involves a retrofit. The expertise required is high, and this is a first reason for the lacking adoption. The independency from other system components is high, the lower requirements for HVAC are the only impact on other systems, but the savings derived from this impact are the energy savings already considered in the economic-energetic parameters. The other possible impact is on the installation of a temperature control system. The maintenance is increased, but these systems usually do not require high efforts, apart from the temperature control. The accessibility problems for the installation are very low in packaged compressor, despite problems may arise in the heat distribution from the heat source to where is required. The interviewee agreed almost in all the points, with the exception of the accessibility, considered a very big problem in their specific contextual situation.

On the compatibility issues, the technological compatibility is required for the implementation of the measure but fortunately this is quite easy to assess (being present only screw compressors, the heat recovery is possible). The presence of different pressure loads influences the measure because, usually, the higher recovery potential is present where the pressure is higher i.e. higher temperatures are reached. The adaptability to different conditions (variability of requirements in the demand side) is a very important factor, but should be checked together with the presence of thermal loads, that is referred to the availability of the right amount of heat by the demand side; these are of course the most important parameters to consider, and this was confirmed by the site manager. The distance from electric service and synergy with other activities are not factors influencing the efficiency measure.

On the observability side, since this intervention does not influence the compressed air directly, most of the factors are not influenced. The air quality can be enhanced because of the heat exchange with the aftercooler and the wear and tear can be decreased because of the compulsory tight monitoring of temperatures.

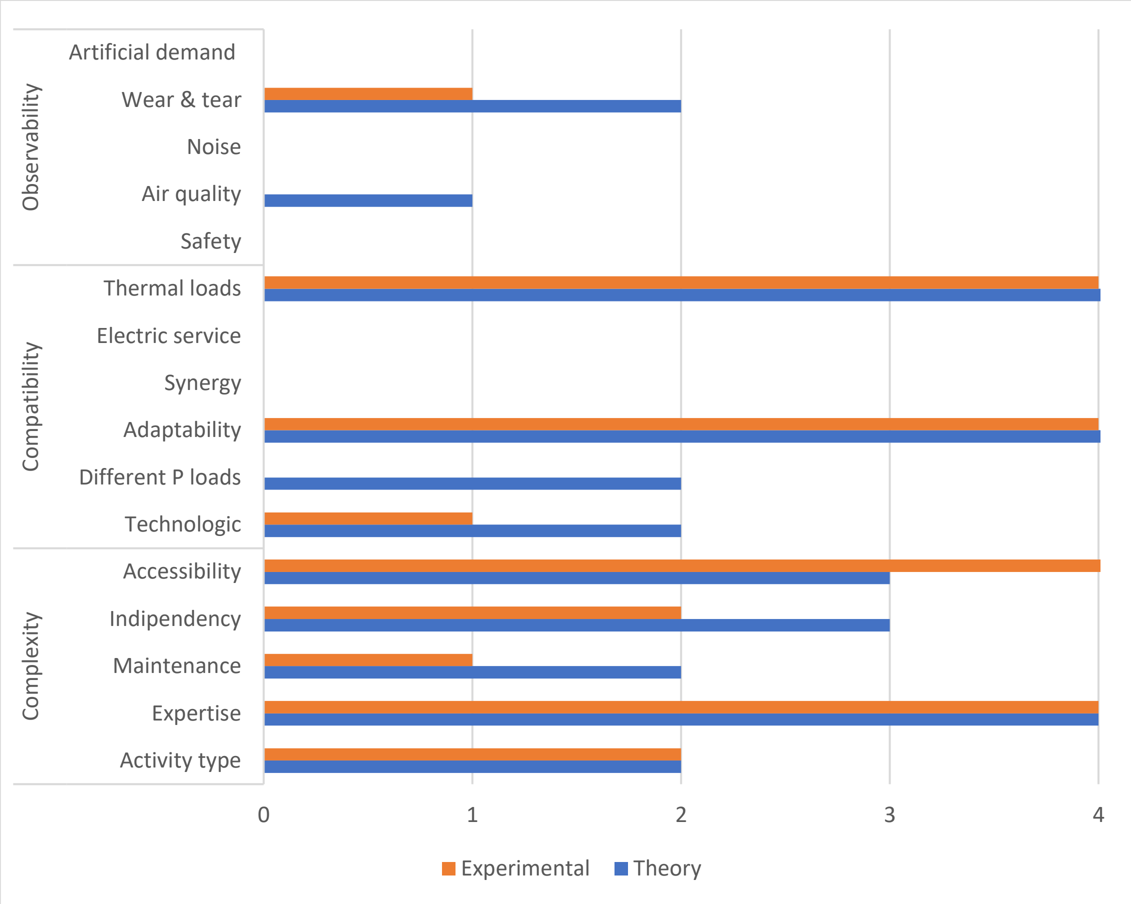

Figure 27: heat recovery from compression unit, grey company

The overall application advised only some differences in the evaluation by the theoretical and on-field evaluation. The only sensible differences are found in the lower consideration of high-P applications as more suitable source for the exploiting of compressed-air heat generation, and the lack of consideration of higher air quality for the additional heat exchange with the hot fluid for moisture removal. All in all, almost all the factors were considered properly, but the reasons for the final decisions about the implementation were for the low possible amount of savings owing to the low heat requirement for services, that is almost completely covered by the boilers. This mean that in this case the framework would have not changed the decision from one side to another, but, the thoughts of the site manager were that it is comprehensive of all the problems and benefits coming from the decision, especially the reason why they do not adopt the measure i.e. the presence of thermal load; the thermal capacity, indeed, was not enough to justify the investment. The user-friendliness required by the framework application in his opinion was very high, he in fact, immediately recognized the "*presence of thermal load*" as the proper factor that was the one influential for the lack of adoption.

6.4.6 *Green company*

The trial was made on the efficiency measure that seems to be the best in applicability, but that was not performed for low time and awareness on the possible positive outcomes and impacts, belonging to the "***future***" set of EEMs. Since they are not interested in compressed air efficiency measures, as explained in 6.2.2, and the proposed EEM to analyze is maybe the best fit for their situation

The ***reduction of pressure to the minimum required*** was chosen because, despite the need for an optimum sized compressor will be major consequence of savings owing to the different flow rate and pressure generated and required, this entail too high investment costs. The interviewee clearly explained that high investments are not planned for an EEM on a system which operating cost, despite higher than the optimum, is not as important as others.

The pressure reduction can be achieved in many ways, but basically the check of compressor performances to a different discharge pressure should be ensured to see if this leads to effective savings. In this case the technical manual may give some information about the compressor performances.

The activity type belongs to a simple optimization, without any structural change in the system, and this was rated as a factor of utmost importance for the decision-maker, because the optimizations are an indication lower involvement. Expertise in this case is dependent on the possibility of addressing the performances/discharge pressure relation simply consulting the compressor technical manual or the eventual need for a technology expert; was rated as very important. Maintenance personnel may be involved in controlling if the effective savings are achieved, but no more than this. The independency from other components is null, but the measure positively affects the leakage rate and helps with capacity problems (25); the negative outcome is that lowering average system pressure requires caution, because large changes in demand can cause the pressure at points-of-use to fall below minimum requirements (25).

On the compatibility, the technological aspects, as pointed out earlier, may be checked because of the type of compressor performances variation in dependence of the downstream pressure; it was rated as very important to consider, because the difficulty on the analysis of this reduction may hinder or support the decision about adoption. The presence of different pressure loads does not entail any variation on this measure, because the compressor unit in only one. Adaptability to different operating conditions is not influenced if the minimization does not entail the modification of some ancillary equipment (dryer, receiver, etc..). The activity is that easy that should not be prescribed in synergy with others.

Observability factors are influenced by the measure. The safety of having a distribution system with lower pressure is increased, even though the pressure will be high also in the new configuration. The air quality is not influenced (only indirectly). The noise of the compressor should be lowered but this aspect is considered as marginal. The wear & tear of components and operating equipment are reduced if the pressure is decreased, and this factor was not taken into account by the interviewee. Artificial demand is ultimately another aspect quite important; the pressure reduction entails the reduction of artificial demand, and as consequence, the demand requirements are lowered; the person did not consider at all this further parameter. Talking on this aspect with the interviewee, he points out that, since the actual compressors generated flow rate is higher than the requirements (it was designed when another two air lines were present), this element further increase the gap between supply and demand, increasing the possibilities for the adoption of an efficiency measure for the compressors substitutions.

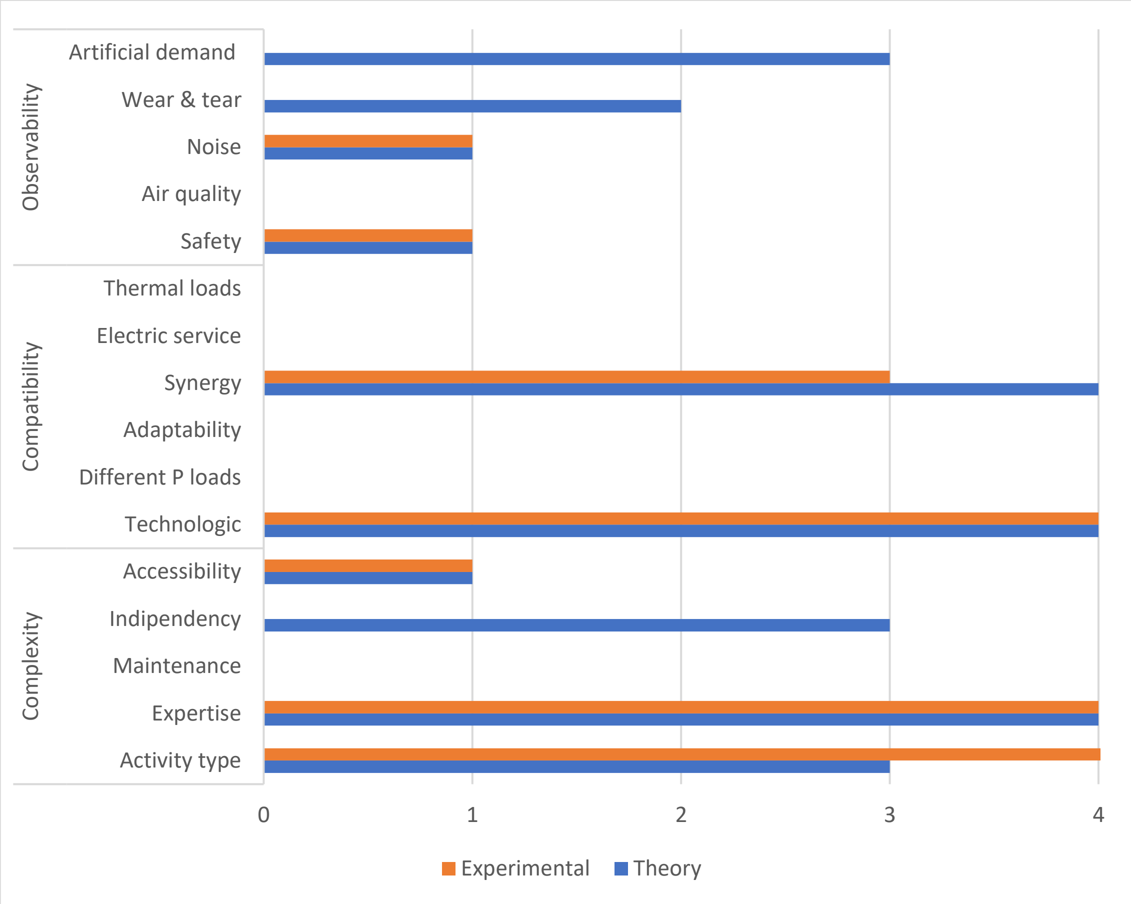

Figure 28: Reduce the pressure to the minimum required, green company

The strong possibilities of having a high level of awareness are exploited by the potential savings and easiness prescribed by the efficiency measure. The underestimated factors belong basically to the complexity and observability categories. The framework has revealed, in this case, major lacks in the proper evaluation of the efficiency measure, and the fact that three of them can be influencing for the adoption contributed to the effectiveness of the tool. The independency from other components and EEMs was not considered at all, and has a positive impact on the adoption, as well as the low wear and tear of equipment and the reduction of artificial demand. These impacts all contribute to the full evaluation of the user-friendliness because it was very easy for the practitioner to realize the effects of the application of the EEM. Moreover, he believes that the effort required is not that high. Here, the comments were on the low impact that the framework has, in terms of increased difficulty with respect to the actual situation. He suggests that the effort, rather than not being increased too much (that is our goal), is decreased, because the possibility of evaluating better the EEMs provides the opportunity to exploit at bets their compressed air system.

6.4.7 *Light blue company*

Light blue company is a little reality in the central part of Sicily, born in '97. They manufacture of plastic pipes and fittings and tanks, but they perform also thermoplastic and plastic welding. In the last years, they specialized in the production of special PEAD pieces, obtained from pipes, succeeding like few in the national area, to the production of fittings of 1000 mm diameter. The products entering the market, are granted by welding operation control automatic systems and the same are proven by mean of normalized destructive tests with certificate equipment. The actual turnover is 1,5 M€ and the employees are 13. The company is little more than a family-driven, with a strong but simple hierarchical organization.

Despite having a very high production capacity, and a high production margin, the crisis in the sector is quite high, because they have to face the regional market. They advise problems in spreading their products in the whole national area because of the dimension of their final products. As consequence, they do not produce continuously, but, on average, the production of 2 weeks at full production output, is enough for supplying the monthly demand (or more).

The interviewee is the owner that is also in charge of being the facility manager, thus the energy topics are under his control. The decisions for the improvement of efficiency starts directly from him, and the process is quite straightforward, because for whatever service they turn to the service providers.

With respect to energy consumption, we estimate the full production capacity for 9 weeks/year with a total expenditure of 52 k€. The energy consumption was lowered in the last year, thanks to the photovoltaic installation that dramatically reduced the cost of energy. They are thinking on the certification 50001, but actually they are waiting for the potential of the new system in place. Other efficiency measures in last years were the replacement of pumps that were oversized.

Last efficiency measures adopted	Year	Cost investment
Replacement of oversized pumps	2016	High
Installation of photovoltaic power station	2015	High

Table 25: recap on last efficiency measures adopted, light blue company

Compressed air consumption data are, unfortunately, not available. In any case, the interviewee considers compressed air efficiency important in the facility, despite not used directly for the production process. Compressed air system is used mainly for marking operations, transportation of material and actuation of valves.

The total installed capacity is of 32 kW on two compressors, but, in reality, they are never working together. A control system adapts to the demand requirements activating one or the other compressor, because there are three different production areas. If two out of three are not working, they realized that the purchase of a new compressor was energetically more convenient (payed back in less than three years) that using the big one at a lower pressure.

Type of compressor	Power [kW]	Control	Function
Screw oil-free	22	Load-Unload	Service
Screw oil-free	10	Load-Unload	Service

Table 26:recap on compressors, light blue company

Despite the company performed efficiency measures and have quite a high interest in maintaining low energy cost, neither energetic audit was ever performed nor specific maintenance procedures on compressed air, other than usual filter replacement.

The suitable efficiency measure suggested, for the high saving potential with the lower possible effort (even though it cannot be evaluated with the use of the framework) is the ***elimination and repair leaks in compressed air lines***. The high potential is also given from the length of the distribution system that extends in three different areas.

The measure is performed with the help of the service provider and should be prescribed every year, at most, to ensure the high performances are maintained in time. At the moment, they have not installed any monitoring system to detect the pressure drops along the distribution system i.e. the presence of leaks; this means they feel pressure drops only in case of bad performances of the system.

Starting from the energetic and economic parameters, they are considered, as usual, the most influential to take a whatsoever decision about energy efficiency.

About contextual parameters, starting with complexity, they agree with the expertise required that depends on the method used to detect leaks. The activity type influences a lot, and positively, the adoption because it is an optimization, that in general, does not require the stop of the production. In any case this is not a problem since they are not productive continuously. The independency from other components is low and positively affects the other system parts, they were highly aware of this. The maintenance activities should be increased a lot, this parameter is considered has possibly influencing the possible decision (negatively). The accessibility problem was not considered too much, but they recognize the importance because part of the pipe is located on the roof.

On the compatibility, the technologic is not influencing the measure. The different pressure loads are influencing the prioritization of the high-pressure parts, but they have not this problem: this will be considered in light colors in the synoptic table. The only other factor that can influence the adoption is the synergy with other activities, to consider only when the shutdown of equipment is prescribed for the measure or to consider the activity in parallel with the diminishing pressure related efficiency measures. Since the former is not influenced for the discontinuous production and the latter as well for low availability of capital, they are rated again in light, despite the importance was recognized.

On the observability factors, they consider as very important the safety that is recognized a fundamental factor. The noise reduction is not that important because the highly source noise leaks are detected and adjusted as soon as possible, regardless on the adoption or not of the measure. Artificial demand was rated as important, but not as expected.

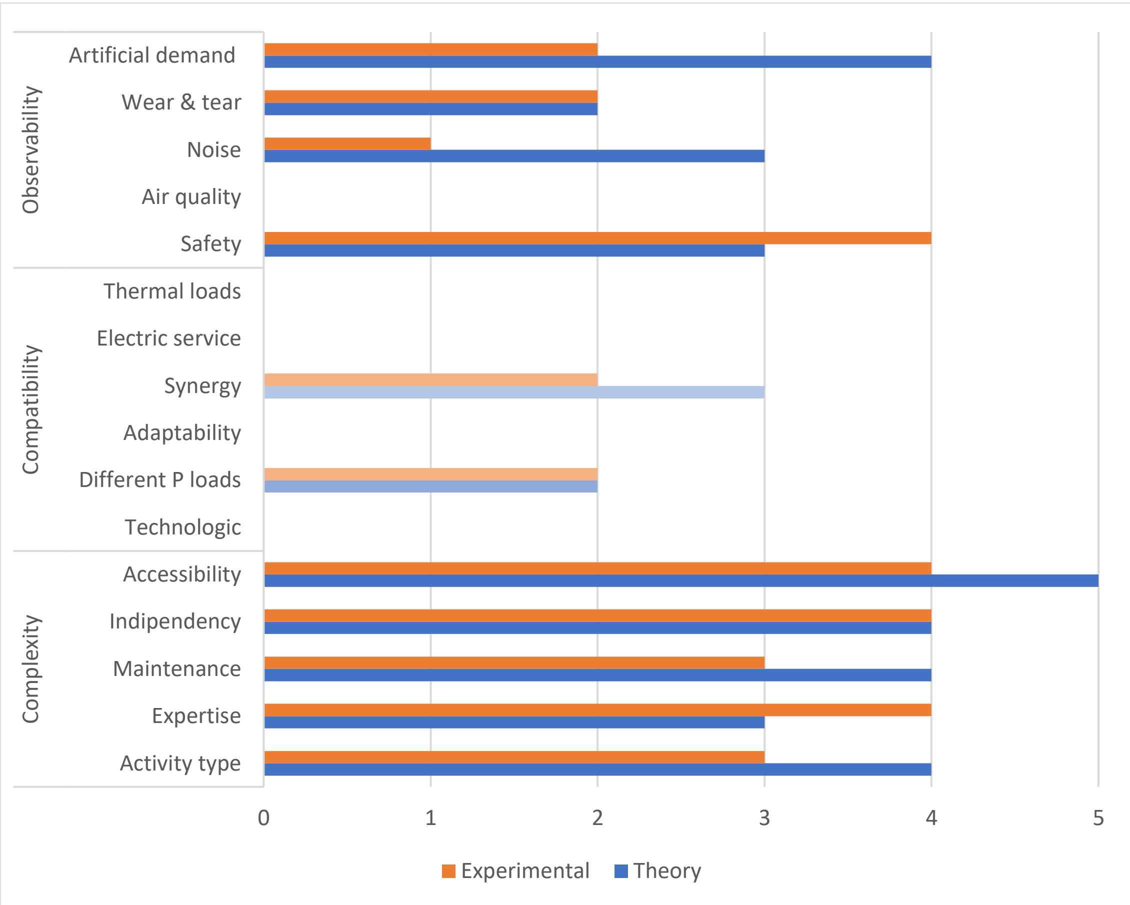

Figure 29:Eliminate leaks in compressed air lines/valves, light blue company

The company, overall, was highly impressed on how the framework is applied to the energy efficiency measure. They have not high experiences in compressed air efficiency measures, and they find the framework as very influential. Their positive attitude in accepting suggestions and comments on the possible implication of the EEM adoption, leaded to the maximum ratings both for the effort and user-friendliness of the tool. On the first, they admitted of how, for the leaks repair, the difficulty in using the tool is very low; when each of the factors was explained, the interviewee immediately recognized the possible outcomes of the factors in their context. The framework resulted also able to point out some of the factors they were unaware or for which they do not pay enough attention: artificial demand and noise reduction. The fact that the number of factors is low, and that most of them are auto explicative without further comments, is the further reason for the maximum rating of the user-friendliness item.

6.4.8 *Red company*

The potential efficiency measure analyzed with the interviewee of the red company, was the ***movement of aspiration in a cooler place*** with respect to the actual conditions, in which evidently the compressor is influenced by the vicinity to the oven. Being potentially adoptable is a "***future***"related EEM.

The efficiency measure can easily be adapted to the conditions of the system because they own two screw-lubricated compressors.

On the contextual parameters, they believe to have a big influence, and the expertise and activity type are in line with what expected by the theoretical part. The independency from other components or EEM is not evaluated high in influence, and eventual additional ventilation requirements were not considered; only after having shed the light on this point he recognizes the importance. The maintenance activities have a low influence for the interviewee. The accessibility, on the contrary, is evaluated as very high because he believes the compressor is more manageable in the actual position, with respect to the targeted one.

Compatibility is considered as important but only before knowing the measure can be easily fitted to the compressor they actually use. Compatibility with ambient conditions have a big impact but not in this case, since the new potential position is internal.

On the observability factors, the safety is not influenced as well as the noise and the artificial demand. The air quality in an internal ambient is in general better than the external one. The moisture content is lower and this may lower the wear of the compressor units, extending the life of components, this would be considered very important and influencing for the interviewee.

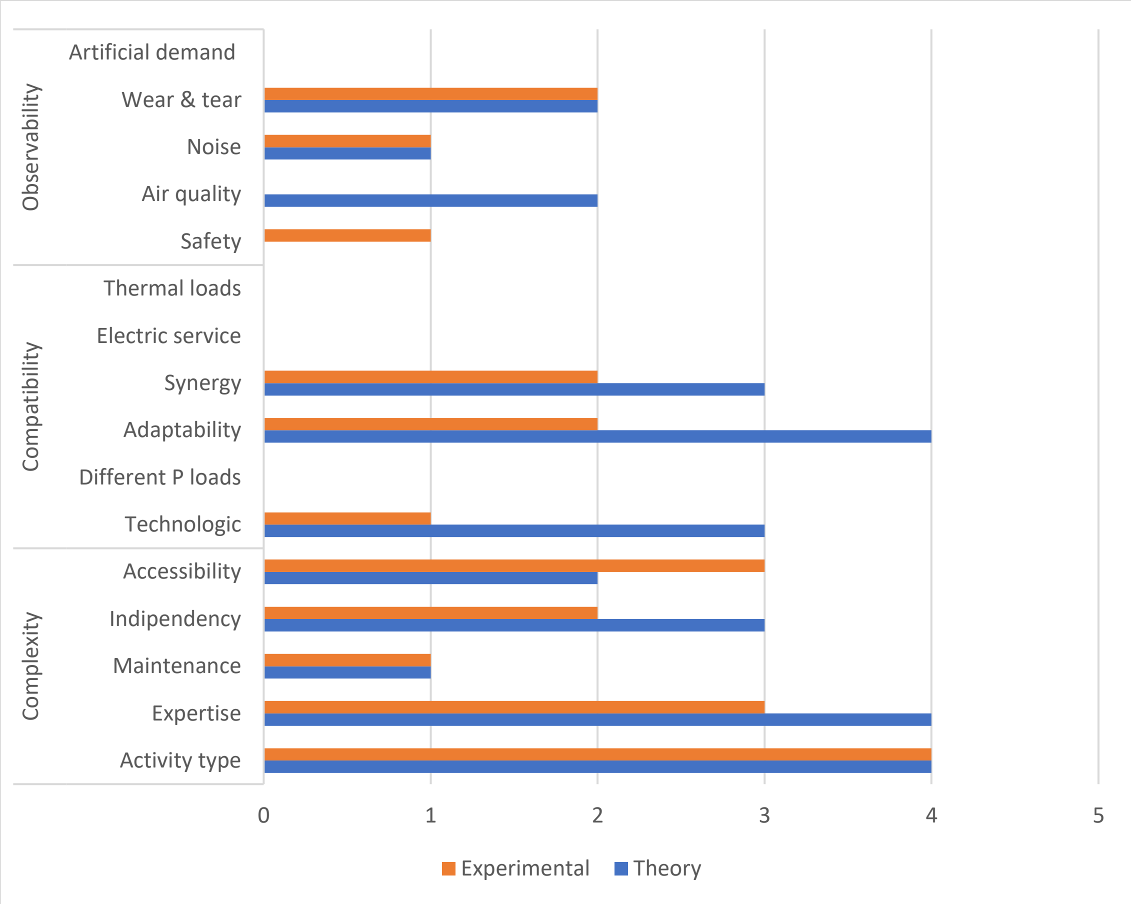

Figure 30: Install compressor air intakes in coolest location, red company

A prior comment on the results of this application, as can be easily seen by the chart, is that there are a lot of discrepancies, meaning that the factors that should influence the adoption, were partially hid by the unavailability of information on what implies this EEM and how affect the current performances, other components and the working environment. The interviewee recognized the strong utility that the tool can have, because in a relatively short time (half an hour, because he was aware of the model, as explained in 6.2.4) he, at least partially, owned a lot of information from the tool. The consequences were the rating of both effort and user-friendliness to their maximum.

6.4.9 *Indigo company*

Indigo company is a Sicilian based company specialized in the manufacturing and distribution of eco-friendly decorative paints for furniture, metallic parts and residential/offices buildings (ISIC 2022). They are deeply involved in environmental aspects and believe in quality as the first aspect to gain relative advantage. They distribute their products all over the world, and their turnover is almost 10 M€, and the number of employees is 22.

The production process pertains chemical bindings of substances and the production process entails four different parts, for which compressed air is barely used:

- Making the paste: with the pre-mix of the pigment with the solvent, additives and the resin, needed to humidify the pigment, in this phase the mixing is performed with low contaminants compressed air;
- Dispersing the pigment: since most of the paint is a water-based one, the most suitable method for the agitation of the high-speed agitation by a toothed tool connected to a rotating shaft, to mix homogeneously the pigment with the solvent
- The paste is than thinned, with the addition of further solvent, where from the quantity will depend the type of mix;
- Than the finished paint products are directed to the canning part of the plant. The filling of cans is performed thanks to compressed air, as well as the pre-cleaning of jars prior to the filling part.

The interviewee was the site manager that leads the energy efficiency activities and is moreover responsible for any related project. This, is in any case, is not his primary task, because he is responsible of the quality and safety, as well as management and addressing of facility-related needs. Despite when asked about energy efficiency he recognizes the importance of the topic, he said that the company is quite satisfied by their actual energy consumption, because of the modern co-generation plant that have been installed in 2013, to drop off the energy prices. From this installation, the energy consumption passed from the 3,2 to the 2,1% of the total turnover.

Compressed air, despite being intensively embedded in the production facility for different purposes, and tight monitored in the phases dealing with the production process, do not represent a significant cost with respect to the total energy use (we do not have data on this, but he believes is no more than the 12% of the electric consumption); they operate three compressors, for a total of 60 kW, active on two turns per day.

Type of compressor	Power [kW]	Control	Function
Screw lubricated	30	Load-Unload	Service
Screw oil-free	10	VSD	Process
Screw lubricated	15	Load-unload	Service
Screw oil-free	5		Back-up

Table 27: recap on compressors, indigo company

The last important efficiency measure on compressors was in 2008 with the installation of a control system for the handling of demand variations in time. A backup compressor, and a second compressor with a variable speed drive were installed.

Last efficiency measures adopted	Year	Cost investment
Upgrade compressor controls	2008	High
Use/purchase optimum sized compressors	2008	High
Eliminate permanently use of compressed air	2008	Low

Table 28: recap on last efficiency measures adopted, indigo company

In this case, was asked the opportunity of asking two different type of efficiency measures, at the expenses of the time that would be dedicated to the plant visiting.

The first efficiency measure description and analysis is related to a "***future***" EEM, that entails a modification of the current system conditions. In particular, the interviewee was asked about the possibility of ***eliminating or limit the use of compressed air used for the dense phase transport***, with the substitution of some blower technology.

The application should require not so high effort, but basically, they were not at all aware of the possibility of this technology substitution. The energy savings may have a very active role in the incentive toward this type of adoption. Since no plans have been performed on this efficiency measure, we have no idea of the economical and energetic aspects. Rightfully, he thinks on flow rate and pressure, when asked about the parameters involved.

This is a retrofit and entails a technology substitution; as always, the activity type is recognized as highly influential for the decision. On the expertise, he recognized that technology expert is needed and evaluated this factor as the most influential, even because their lack of knowledge in the potential new technology installation. The independency from other EEMs or components is rated at very low importance level, despite he recognized that, being strictly in contact to the process lines, other component may be influenced by this technological change. The maintenance for the blowers is very low, so this factor should be considered as marginal. The accessibility problem is quite evident, because of high involvement inside the line.

The compatibility issues on technology are very strict, and evaluated as high. The different pressure loads have not any influence, but this is the case of this technological substitution (blower vs compressed air; in other type of substitution i.e. electric vacuum generation, this parameter may have a much higher influence). Synergy with other activities is considered the most important factor since the measure implies the stop of the entire production line to be installed, with a negative influence on the adoption. The distance from electric service is recognized as important, but not influential in this case; the interviewee recognized that the framework was effectively able to shed the light on this factor and underlined the possible importance in other contextual situations.

Starting with safety as the first observable factor, the influence is very low, because since the process is automated, there are no high risks. The blowers are generally low noise sources with respect to compressed air driven transport equipment, but noise in any case is present also for other uses, so the improvement is not highly influencing in this case. Wear and tear of equipment should be reduced for the low pressures, but since the tradeoff with the higher flow rates this is not influencing a lot.

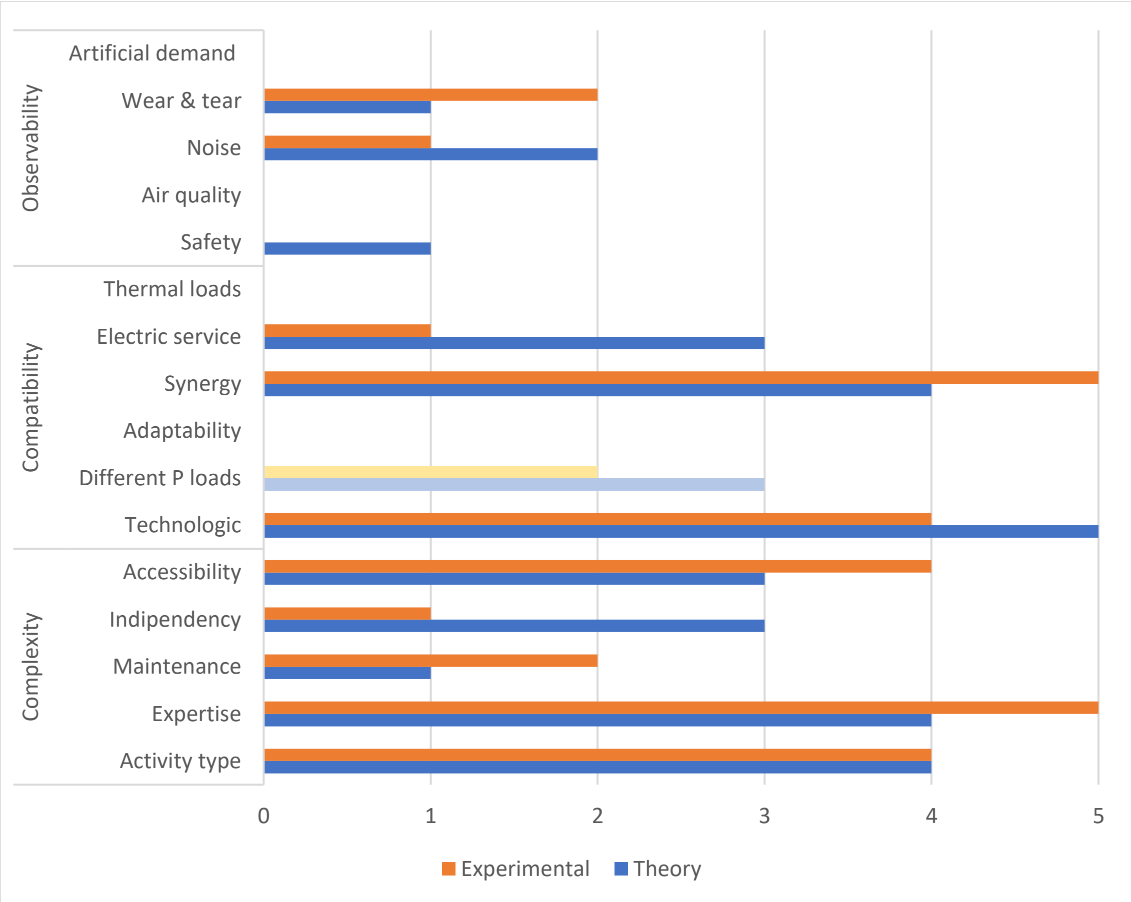

Figure 31: Eliminate or reduce compressed air used for dense phase transport, indigo company

The company improved almost 10 years ago all the system, comprehensive of compressors and controls, in order to better handle demand variations. The second energy efficiency measure was on a measure already implemented in the facility ("***present***"); this was the ***installation of the variable speed drive and the master control system***.

This was a new installation, and the system modification was made together with the purchase of new compressors. All the operational and economic parameters are considered for the installation. The substituted units are much more performing and have less power requirements.

About complexity factors, both expertise required and activity type are considered as very important and influential for the adoption. The independency from other components is very low, the factor highly affects the adoption of the EEM. This is demonstrated from their decision to install two different control systems together, because they recognize how one may influence the proper working of the other. The VSD technology was never used before: the maintenance procedures are straightforward and the effort is reduced with respect to the past; this is considered but, unexpectedly, this was revealed to have not a big influence on the decision[81]. The accessibility problems are not considered at all, but the interviewee recognize its importance.

The technological compatibility is evaluated as one of the most influential factors, because when they made the investment, it was considered as a tight constrain (the new compressor motor owns the VSD). The adaptability to different operating conditions was the most influencing factor for the decision, and the synergy with other activities is very high, since they decided together the controls, compressors and new equipment.

Among observability factors the noise reduction impacted, but is not a discriminant at all for the decision; they have not considered the benefits of having a lower possible wear of equipment. Artificial demand reduction was considered as not influential for the adoption because they did not know the further benefits brought by this factor; in fact, he recognized the importance once this was pointed out.

[81] Maybe the company has not big difficulties in maintenance activities, and their reduction is not considered to be so influential. This, have a further prove for the second asked EEM, because also in that case, despite with lower difference, there is a discrepancy in the theoretical and experimental evaluation of the maintenance effort required.

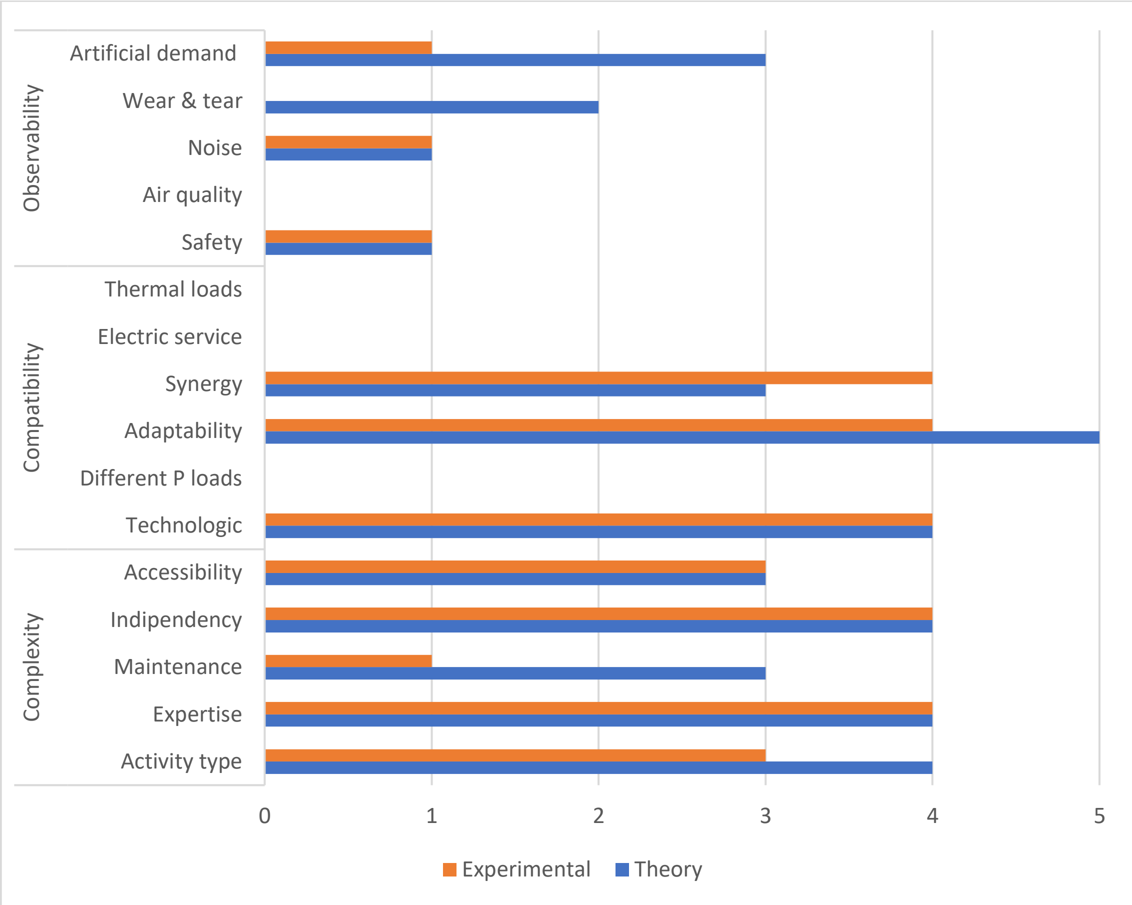

Figure 32: Upgrade controls on compressors, indigo company

The final evaluation of the framework was positive also in this case, and the efficiency measures, after being analyzed in detail, shows not high differences in the two types of evaluation. As mentioned during the discussion on single EEMs, they had a proper evaluation of almost all the parameters in the case of the present efficiency measure; this is expected, because the fact that they adopted it, make them able to take the right position for the factors that effectively influenced the decision. In the case of the first EEM, the independency from other components and maintenance was underestimated, but the framework used resulted in increased awareness how they can influence the adoption. The effort required in the use of the tool was not at all rated as difficult; he suggests that it can be used, rather than in parallel, as a preliminary tool to check the most suitable EEM to be applied, depending on the level assumed by factors during the application. For the user-friendliness, it was not rated at its maximum, but three out of four because almost all the factors level, have not a precise value referred to a specific change of the technology. The interviewee précised that the applicability was enhanced by my presence, that explained all the details of each of the factors for the specific technology substitution.

6.4.10 *Yellow company*

Yellow company is a Sicilian company based in the South of the island active in the food and beverage sector. They are one of the most important quality brand in the wine sector. Their production process starts from the grapes pick-up to the bottling and selling of wines. They have a unique site for the production plant and the use of energy covers between the 3 and 4 % of the total turnover, that is slightly more than 3,5 M€. They have 10 employees and their company is family-run one.

The interviewee is the owner and responsible for all the topics about safety, quality and energy, together with his brother. The decision chain is this that simple that does not need to be explained; they are, all in all, the decision-makers about whatever system inside the production plant, and, as consequence, they are strongly supported by technology service suppliers for each type of services. They, in any case, recognize the high expenditures and consider as very important the possible savings in energy field

They do not use any indicator of performances for the compressors or other equipment and they have not any of the quality international certifications, apart that their products are conform to the BRC standards. Moreover, they do not retain necessary any external audit for the performance monitoring.

The company performed many efficiency measures in the last years, among which there are also some efficiency measures on compressors.

Last efficiency measures adopted	Year	Cost investment
Purchase of new water boilers	2014	Medium
Purchase of new steam boilers	2014	High
Substitution of LED lamps	2015	Low
Use/purchase optimum sized compressors	2016	High
Upgrade control on compressors	2016	Medium

Table 29: recap on last efficiency measures adopted, yellow company

The interviewee was asked about the compressed air use inside the plant, specifying that they believe is not a big cost item. The use of compressed air is use in the transportation line, used for the cleanness of bottles and for pneumatic actuation other than for the sterilization of bottles.

The compressed air consumption is estimated to have a little share in the total of the electric energy expenditure because of the high dimension of refrigerators for the conservation of wine under certain conditions. The efficiency measures that were tested in this case were two.

Type of compressor	Power [kW]	Control	Function
Screw oil-free	20	Load-Unload	Service
Screw oil-free	10	Load-Unload	Backup

Table 30: recap on compressors, yellow company

The consumption of compressed air is highly discontinuous, because this is a production process active only for 3 or four months per year. In that period, they are active up to 16 hours per day, for 5 or 6 days per week.

The decision on the potential efficiency measure to be implemented, in this case was dictated by a practical and easy rationale: they have tons of refrigerating capacity and the area in not that far from the compressor. This means that the compressor could theoretically be moved easily to that location, or, more realistically, can be used some ducting to refrigerate the intake.

The consequences of the potential ***installation of compressor air intake in a cooler*** location were discussed with the interviewee, as part of the "***future***" potential adoptions.

The operative parameters involved with this measure are both the inlet temperature and its variation in time, the flow rate modification ad consequence of the temperature reduction, and the eventual pressure drops for additional filters on air compressors.

On contextual parameters, the type of activity was ranked quite high, as well as the expertise required for the implementation. The independency from other components are not that high, and ranked quite low. Maintenance procedures were not considered as an important parameter; in theory, they are ranked only one point. The accessibility problem can be very influencing for the adoption of the measure, but was ranked with a total of three.

The compatibility of the technology is recognized to be high, because of the problems entailed with certain type of compressors: he evaluated this as influencing, but not so much, maybe because this problem is not evaluated properly for its absence in this context. The adaptability to different ambient conditions is influencing only for the movement toward an external ambient: is influencing a lot the adoption but, another time, not in this situation. Synergy is the only other parameter (about compatibility) to consider: the measure is usually performed in synergy with the compressor and control unit substitution: they had the opportunity in 2016, but they were not aware of the potential savings.

On the observability, the wear and tear, as well as the air quality are influenced, and he did not consider this a lot.

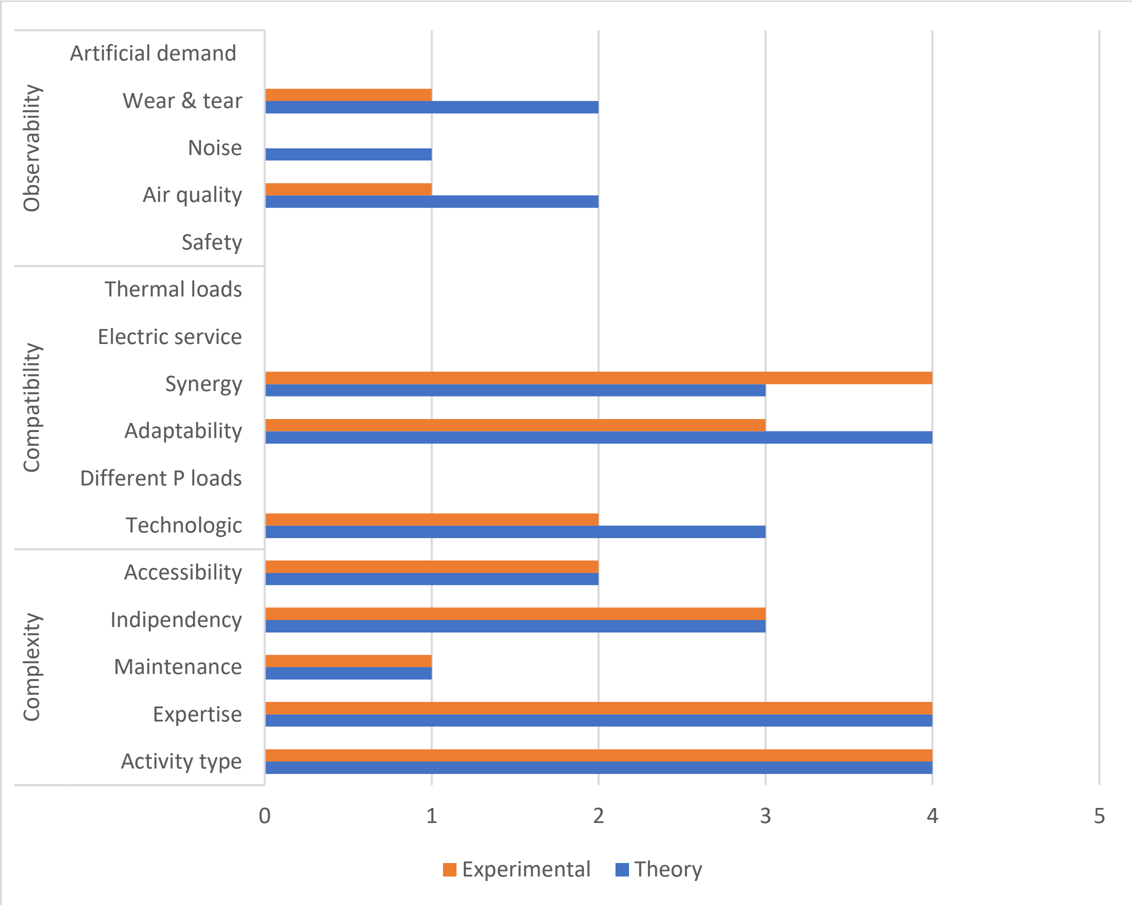

Figure 33: install compressor air intakes in coolest location, yellow company

The yellow company is extremely involved in energy efficiency topics, and they have an annual inspection for the detection and ***elimination of leaks in compressed air lines,*** that, of course, is a "***present***" energy efficiency measure. Thus, the interviewee was asked on the applicability of the framework for this measure.

About the economic-energetic parameters, he knows the high savings potential coming from the adoption of the measure. Moreover, not any downtime is required because the inspection is simply made on the bigger leaks, detecting leaks only earing them.

The considerations are quite similar to the ones reported by the light blue company, with the exception of considering the maintenance activities as not so influential, because they know that the effort is not that high. On other hand, since they had some problem in the past with low accessibility parts of the distribution system, they consider accessibility as the most influential parameter for the adoption. Sinergy with other activities cannot be evaluated properly because they perform the activity regardless other similar activities, so this parameter will be in light colors.

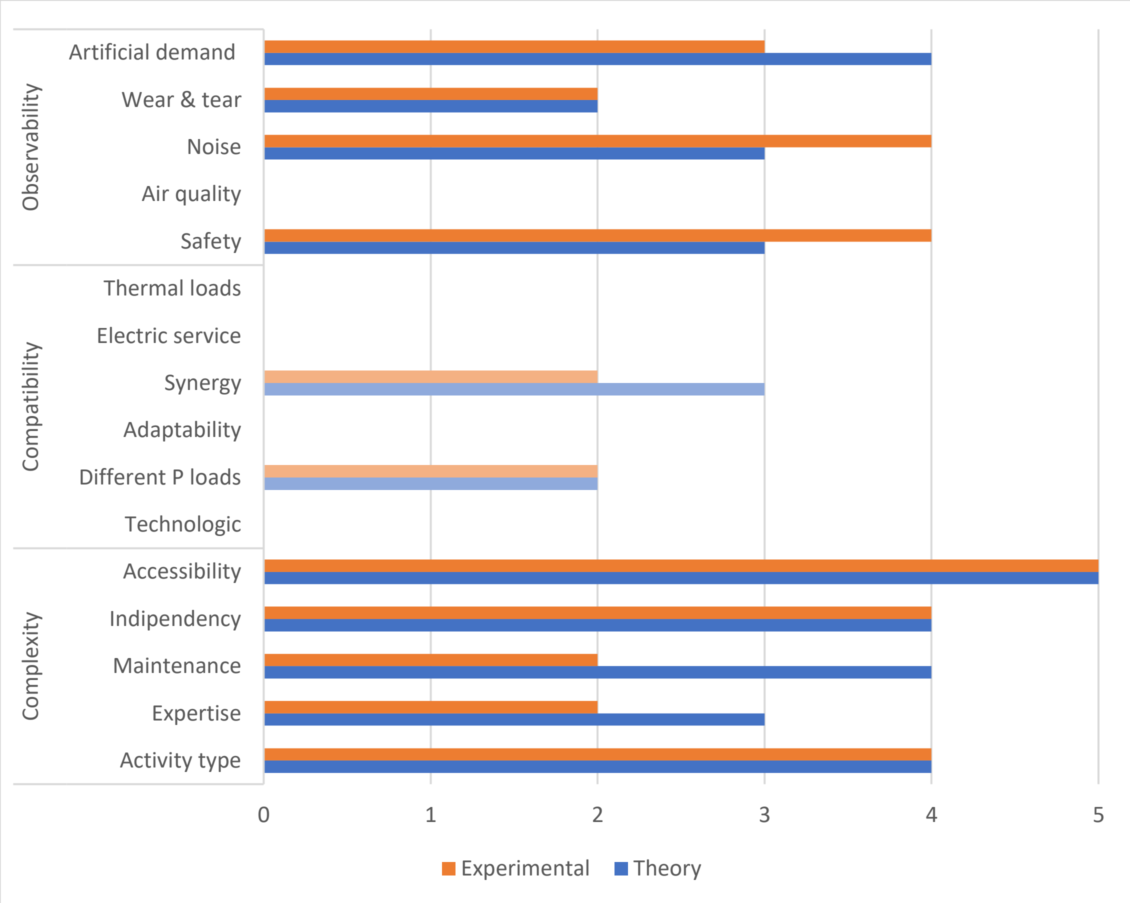

Figure 34: eliminate leaks in compressed air lines/valves, yellow company

The company, demonstrated in general high attention of the topics about energy efficiency measures, and with the focus on compressed air as well i.e. they are highly conscious of the fact that efficiency is a primary driver for gaining competitiveness. The framework application, for this reason resulted very useful in its application. The fact that they rightfully considered all the factors that actually influence the adoption of an EEM, creates an increased willingness to further improve their situation, and in this optic, the framework is seen as a very powerful tool. This is true on the manager opinion, because the tool can be applied easily in two different situations: (i) when a decision is going to be undertaken, as a primary assessment of what will be the influential factors, or (ii) to create awareness on the potential efficiency measures to adopt, according to their needs. Effort in the use of the framework is considered as not high at all, because all the factors can be checked without the need of difficult calculation or performances monitoring.

6.4.11 *Pink Company*

Pink is a family-run company, that from 4 generations produces and distributes EVO oil mainly in the regional area, but not only. They recently have initiate the selling in UK and

France. The employees are 18, for a total turnover of 12 M€. For their own choice, they are far away from industrial zones, both for the easiness of handling olives in the territory and because in this way, they believe they are not influenced too much from other industries.

From the energy management point of view, they have not any type of certification. They are certificate only with the BRC[82], revised and updated every year, and UNI EN ISO 9001:2015 for the quality management system.

As usual, in this type of little realities, there is not a proper figure that is oriented only towards the energy management; they, in any case, recognize the high expenditures and consider as very important the possible savings in that field. This lead them to the installation in 2016 of a photovoltaic system for the auto-production of energy; this is not active yet because of bureaucracy issues but they estimated the production of 50 kW, where slightly more than 32 are the needed for their installations, the other part will be sold; they estimated 18.000 €/y of savings.

Primarily, their consumption is attributable for the lion share to the big oven that operates nearly at 220°C, and the second electric utility is the compressed air. The oven was recently substituted for a more efficient unit; the old one was very energy consuming. Both these last efficiency measures were performed in 2016:

Last efficiency measures adopted	Year	Cost investment
New efficient oven purchase	2016	High
Photovoltaic system	2016	High

Table 31: recap on last efficiency measures adopted, pink company

The compressed air, is the second electric utility consumption source, after the oven. Its use is not directly attributable to the process, because is mainly used in the second part, for the filling and bottling operations. The quality standards are very high, for the contact with the glasses bottles and the product, the presence of four different filters meshing is a prove of the achieved quality. The first air contact with bottles takes place in a sterilized chamber; when the bottles arrive to the bottling area, they should be already sterilized, but this further passage, called "secondary sterilization" ensures the absence of contaminants before the filling process. Moreover, since the oil is very dense, the air helps filling the

[82] Global standard for the food safety

bottles rapidly. Compressed air is then used for the vacuum generation for the bottle transportation, in a welding machine and for the marking of labels.

The only compressor is active 16 h/dd for the week, 8h/dd during the weekend. The compressor is quite small, with a 12 kW unit, but an auxiliary unit is present for backup, to ensure the continuity of the service. Maintenance procedures in compressed air are limited to external filters substitution, but all the others are periodically inspected by the service provider once every six months.

Type of compressor	Power [kW]	Control	Function
Screw oil-free	12	Load-Unload	Service
Screw oil-free	10	Load-Unload	Backup

Table 32recap on compressors, pink company

The compressors were changed only one time since 2003, owing to the increased demand, that lead to the expansion of the bottling and transportation line.

The interviewee was asked about one measure that was already installed in compressed air, to evaluate how the decision has been made and what conditions should have been taken into account more than what was considered at the time, this is a "***present***" EEM.

Use/purchase optimum sized compressor was the efficiency measure analyzed. Consider that no changes in technology were involved.

Being obvious the importance of the economic-energetic and evaluating rightfully the operative parameters, the light is shed on the contextual ones.

The complexity related factors are the most influential for the measure, being rated at very high values. Accessibility problems were not changed after the implementation (with respect to their previous situation); this was the less influencing parameter of this axis. For all the others, he gave a value of at least three. The owner admitted that, despite their units are not so large, they had a lot of problems to connect properly all the lines, and the compressor performances and working conditions are the most important ("it is the major hardware") for a satisfying efficiency level of the system.

Among compatibility factors, technology was considered to have a low influence on the adoption, even though, after a more detailed explanation of the implications of adopting other technologies, was given a rating of three. The presence of different pressure loads was considered lower that what expected, and this should be a very influencing parameter, since the presence of different levels on their line, for which are involved many pressure reducers.

On the synergy, it was not considered the possibility of using the old units for the feeding of the line during the planned downtime for maintenance activities, and this effectively is not applicable to their context because of the presence of the backup unit. Moreover, the opportunity of selling the old unit, was considered more interesting than having a second, old, backup compressor. Effectively, the evaluation of synergy as influential is more attributable to the high synergy with the adoption of other efficiency measures.

About observability, the noise was highly reduced with the installation of new units, so it is considered an influencing factor. The wear and tear, is taken into account as "extended life of equipment" embedded in the new installation, and was considered very important.

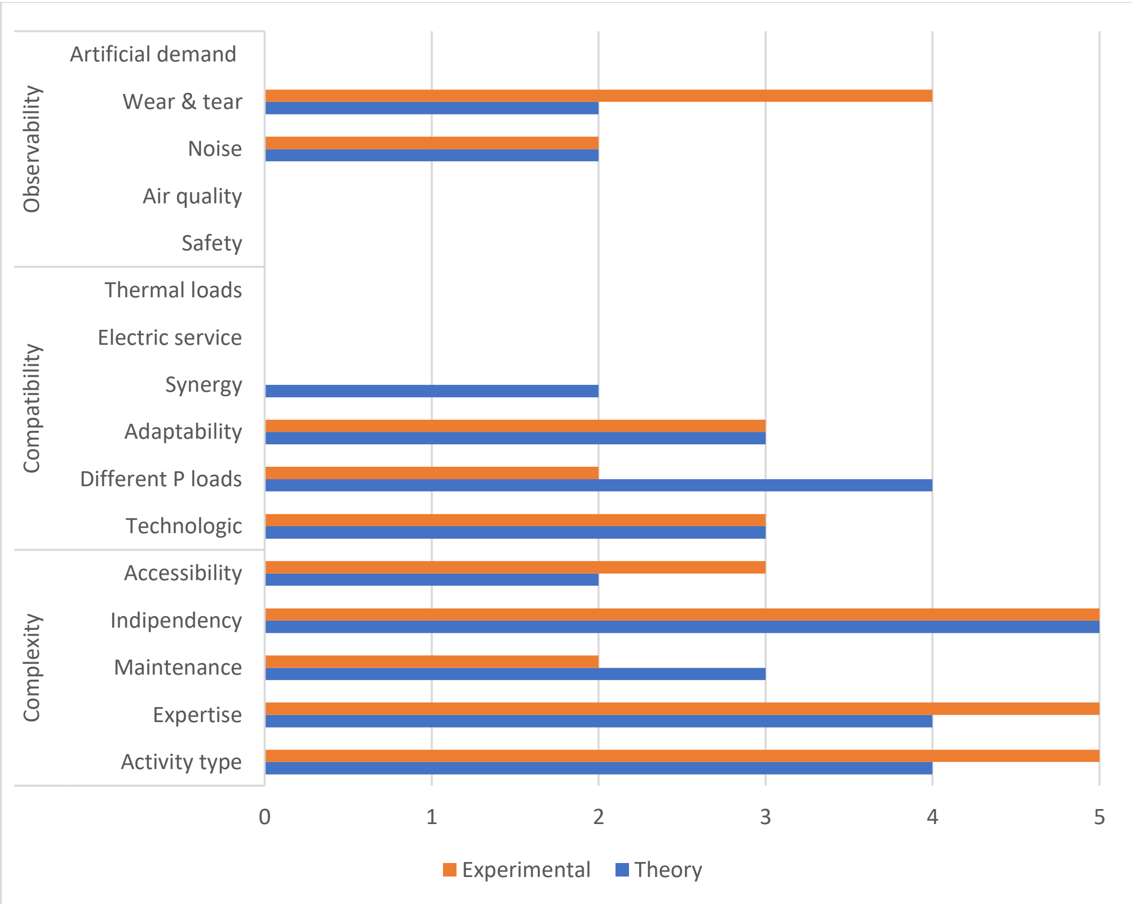

Figure 35: Use/purchase optimum sized compressor, pink company

The interviewee was asked about the final comments on the application of the framework on this EEM, and he was impressed on how, some of the parameters was not taken into account and can be focused with easiness with the model. The fact that the difference of pressure levels in the line should influence the adoption of more compressors of different power was not considered, and maybe this factor would be change their final decision. This was the reason why the effort and the user-friendliness were rated both at their maximum level.

6.5 Discussion of findings: application of the framework

This last part of the chapter, analyses deeply the result of the application campaign to a variegate number of firms with different characteristics. The three types of efficiency measures for which different final evaluation were made, are described in the dedicated sections.

Company	User-friendliness	Effort in use
Blue	4	4
Brown	4	4
Violet	3	4
Orange	4	4
Grey	4	4
Green	4	4
Light Blue	4	4
Red	4	4
Indigo	3	4
Yellow	4	4
Pink	4	4

Table 33: final evaluation of the applicability of the framework

6.5.1 *Discussion on past efficiency measures*

The sample of the four different companies that have experienced the suggestion of some kind of EEMs, but have not been implemented, is homogeneous. Three out of four, have more than 100 employees, and the interviewed person in that cases were the site manager or the engineer in charge of the quality and energy management. The first thing to observe is that, only one of the respondents is certified for having a structured energy management system, and, in the other cases the person in charge of the energy (and as consequence of the efficiency related to energy) issues was only one or, at most, a team of 2 people.

The answers provided by the site managers were highly reliable, with the demonstration of having more knowledge on the energy efficiency, because of the importance of energy in the company culture; some others are more oriented to the technical side, when the interviewee had more responsibilities on production. Regarding the littlest company, despite having knowledge about the importance of energy efficiency, was not that interested in efficiency measures in compressed air, because of the marginality of the use of the service. Moreover, the last company was complaining about efficiency problems in other parts of the plant, and the compressed air marginality is advised even in the lack of prescribed periodic maintenance of the plant, despite this have been suggested by the service provider.

All in all, we can divide the suggested but not implemented efficiency measures, by the impact the framework had in its application, with the recap of the most interesting part of the analysis.

The violet company situation was revealed to be the most interesting for the purpose of the study, since the application of the framework resulted, other than in increased awareness by the interviewee, in the possible positive outcomes for the decision of changing from compressed air to another technology. The project was set aside at the moment of the proposal, both for the risks in stopping the production line and for the lack of time. We would say, after the application of the framework, that the awareness was not complete on some point: the high noise produced and the difference of pressure load were considered as being marginal factors but they both tilt the scale towards the new technology. The importance of the distance to electric service was underestimated, but maybe was weighted subjectively because does not represent a problem in their context.

For the Orange company, the problem of not implementation, was revealed to be mostly behavioral, because of the lack of interest in energy efficiency in the specific technology and the priorities given to other technologies. In this case the awareness on the efficiency is high, but is not enough to pass from the *conceptualization* of the possible savings, to the *implementation* phase. In reality, for what we have observed, the awareness is high on the basic concepts on compressed air systems (leaks, pressure drops, maintenance activities, generation and functioning of installed controls), but the EEM discussed was enough straightforward to be aware of. Their knowledge anyway, at least in part, comes from the overheating problems faced during summer months. The use of the framework for the installation of the new specific compressor has revealed to be useful in promoting the possible noise reduction due to the lower effort by each of the compressors, and on the absence of further maintenance procedures required. The negative outcomes of the adoption, with also the need of other efficiency measures suggested before the purchase of new compressor units (synergy with other activities), further convinced the manager of the low likelihood for the adoption of the measure even in the future.

This Grey company investment was evaluated when other efficiency measures were adopted in the system, but they know it would not be useful in their context for the savings that would have been achieved from the recovery on other sources. In this case the decision for the adoption would be never changed from the application of the framework[83]. In any case, even if there were not the presence of any other heat source, they believe the enthalpic level would not be enough for the measure adoption, because of the distance from the offices where heat should be directed. The framework is revealed very powerful in pointing out the factor that mainly hindered the adoption, being recognized in "*presence of thermal loads*". The framework, despite on a factor that was not so influential for the adoption decision, helped in gaining awareness from the high-pressure applications potential, that generally are suitable for more recovery (he does not consider this parameter because in their plant the HP equipment generates to low air flow rate to be recovered) and from the better air quality.

The last company on this "family" of efficiency measures is the Brown, interviewed on the application a preventive maintenance program to eliminate or reduce leaks, or, at least the single application of the detection and reduction of leaks along the distribution lines. The problem with the implementation was the overconfidence on current system performances; this misconception was created by the recent installation of the system, and, despite suggested by the technology supplier, the leak management was not evaluated as important. For the comparison to the suggested theoretical outcomes of important factors and of the actual considered by the interviewee, high awareness was created by the application of the framework, but in this case the strongest reasons that hindered implementation were behavioral. Awareness affected almost all the factors toward the adoption of the measure: artificial demand, wear and tear of equipment and noise reduction.

A comment on the framework use with the efficiency measure to outline, was that the different level of expertise required to the adoption of different technologies to reduce leak, can change how the factor is perceived, so in this case he believes the importance of the factor will be very subjective.

Company	EEM	Reason for not implementing	More awareness on pros	More awareness on cons	Changing in adoption decision
Orange	Use purchase optimum sized compressors	Organizational	2	1	No

[83] In the synoptic table, this will be indicated as N/A in the availability of changing the adoption decision

Violet	Eliminate or reduce the compressed air used for cooling, agitating liquids, moving product or drying	Organizational; Awareness	2	1	Probably Yes
Grey	Heat recovery from compressor	Technological	1	0	N/A
Brown	Eliminate/reduce leaks	Behavioral; Awareness	2	1	No

Table 34: synoptic on the potential efficiency measures not adopted in the system

6.5.2 *Discussion on efficiency measures adopted in the system*

The efficiency measures tested belonging to this category are four. The sample is variegated, and goes from big firms to more little realities. Despite the application of trial efficiency measures resulted very useful for the pointing out of what and how are considered the critical factors, our primary scope for this group, was to understand if the applicability of the framework, together with the usual assessment tools for the evaluation of an investment, lead to different results to the measures that are already implemented. The results are, in part, similar to what was expected: where the decision overcomes all the perceived barriers for its adoption i.e. when an efficiency measure is adopted, is no more influenced by any other factor. This is true even in that cases in which the evaluation of factors results different from what expected from theoretical validation.

As can be seen from the four interviewed companies, some of them underestimate positive factors, but they implemented the measure in any case. This was the case of observability factors for the Indigo and Blue company. Moreover, the positive consequence of installing a control system on the maintenance effort was not considered as important.

6.5.3 *Discussion on potential efficiency measures*

This sample is the one with the higher number of efficiency measures to test, and is, accordingly to the framework development and application, the most interesting. The choice about the measure to propose was made basically following two different strategies depending on the situation:

1. If the interviewee recognized or have knowledge of some of the measures that can be implemented in the future, the framework is applied on the basis of the theoretical information gained from the first part of validation of the model. This efficiency measures are categorized as Planned;

2. If the interview was not able of recognize a particular efficiency measure, he is asked about one efficiency measure that can be applied, reasonably to the context dependency. This efficiency measures are categorized as Suggested.

The sample, in this case, is composed by seven different firms, and covers five different efficiency measures. The measures entail little involvement in hardware operations and high involvement in operations.

Name	Employees	Turnover [M€]	Involvement[84]	Installed capacity [kW]	Efficiency measure	Suggestion/planned
Blue	46	Unknown (10-15)	N	64	2,4221	S
Green	27	1,4	Y	45	2,4231	P
Light Blue	12	1,5	N	32	2,4236	S
Orange	115	9,5	N	30	2,4236	S
Red	10	2,5	Y	13	2,4221	P
Indigo	22	9,8	N	60	2,4232	S
Yellow	10	3,5	N	30	2,4221	S

Table 35: synoptic of attributes belonging to firms subjected to the study on potential efficiency measures adoption

Of the seven interviewed firms, for only two of them (Green and Red), there is a direct involvement of compressed air in the production process. All the others, in any case, have high involvement of compressed air in some phase before the finished products. This means that, even though in some cases compressed air in not evaluated important as an energy cost item, they have to ensure the continuity of the service.

Most of the firms interviewed were Small enterprises, with less than 100 employees. Their behavior facing energy efficiency topics is crucial to understand how they approached to the planned or proposed efficiency measures. As is ready available in the Table 35, the dimension and the direct involvement in the production process is not linked with the installed capacity i.e. with the consumption of compressed air. The Interesting factor, is instead, that only the firms that uses compressed air in the production process, have some efficiency measure planned in the future. The efficiency measures, in this case, were anyway among the ones with the lowest payback (2,4236) or lowest investment cost (2,4231),

[84] Involvement in the production process: Y if the air is in drect contact with the products in the phase

demonstrating how the economic aspects are important for the small realities, when awareness is high enough.

For the discussion about the results of the framework application, we have decided to divide the efficiency measures with respect to which one was suggested or planned in each case; in this way, since some cluster is present, there will be presented the differences accordingly to the firm 's characteristics. Then, is discussed the effectiveness of applying the framework singularly to each of the EEM.

6.5.3.1 **Install compressor air intake in the coolest location (2,4221):**

The complexity factors are all rated very close to their expected value, except for little discrepancies with underestimation of importance of two of them for the company that have compressed air in the production process (Red). In some way, this may be an indication of how the interviewee, in this case, feels less the complexity issue, because acknowledges the importance of the improvements that can be reached with the adoption of an efficiency measure. This happens also for the compatibility factors, for which the red company was the only one underestimating the influence of "negative influencing factors"; the adaptability to operating conditions (even if this underestimation comes also from the fact that in its case he does not face the factor for the adaptability) and synergy with other activities. The difference from theory and experimental validation are useful in pointing out also the general unawareness on better air quality coming from low air temperature. The noise problems are not evaluated in 2 of the 3 cases, because the movement in their cases do not have an impact on the noise generated i.e. the compressor will not be moved, with the consequence of lower noise generation. Last but not least, the wear and tear is considered correctly (maximum difference equal to one) from all the potential users.

The potential adopters differently react to the final adoption results with the framework application: the yellow company was unaware at all about the possibility of performing this efficiency measure, because never suggested by the technology suppliers, main actor in the proposal of efficiency measures to perform. On the single efficiency measure his answers were in line with the factors' level identified form theoretical approach. The utility of the framework, in this case, is recognized in identifying the efficiency measure and in proposing it, because they were unaware on this possible technology substitution. They moreover advice that the possibility of having additional information on how contextual situations affect factors was important to understand entirely the implications.

The blue company manager, was positively impressed the way the framework explains the single efficiency measure, and he recognized the utility and effectiveness on having this as an additional support tool when taking the decision: on the other hand, he believes that for some factor, being highly customizable, should be made some clarification (in the case of the on-field interview, the application was easy enough because further clarification on implications were made by me).

The red company was aware of the potential savings coming from the adoption of this measure, but he advised that, with the application of the framework, he was more convinced on the adoption, because of the awareness on the better air quality (fundamental for their production process). He believes that, since the decisions about energy efficiency are usually adopted on the basis of the economic profitability, if there is the presence of more alternatives, the framework may direct the decision toward the EM for which complexity, compatibility or observability factors have a positive influence.

All the interviewed people, give a very positive evaluation on the applicability of the instrument. They gave the maximum rank for the effort and user-friendliness required to use the tool, because the factors, if descripted properly, give the possibility of considering all the implications of the efficiency measure without being too complicated to understand. The framework, as advised by the blue manager "is properly revised to be used without considering too many factors but, at the same time, gives the possibility of have a proper evaluation of the complete set of information that comes from whatsoever type efficiency measure in compressed air".

6.5.3.2 **Eliminate leaks in inert gas and compressed air lines/valves (2,4236):**

For both the efficiency measures, the awareness and capability to evaluate properly the factors (measured as differences from the influences given from theoretical validation) seems to be higher compared to results given by the brown company (6.4.2). This can be, at least partially, attributable to the fact that, the consequence of the non-adoption, resulted in a lower capability of give an objective evaluation of factors.

The firms have very different characteristics, but this does not seem to influence a lot how the framework is used or evaluated. The light blue company is more open on the possibility of adopting the efficiency measure, maybe for the availability of time in which the compressed air system is not active.

The fact that compressed air is a marginal utility, seems to influence more the Orange company, that despite acknowledging the high potential that can be reached, knows the priorities given by the top management in other technologies with respect to compressed air. The problem here is the approach that the company has in the regards of the "not high potential technologies". The framework in this case, can't be more than an indication on the potential outcomes that can give the adoption of an EM, but the interviewee is skeptic on influencing positively the adoption decision, that are hindered by high economic barriers. In his opinion, it may have an influence on the low cost and effort efficiency measures.

Despite this problematic arose during the application of the framework to the Orange company, he recognized (as the light blue) that the effort made to understand the implications is not difficult at all, utilizing the framework; in his opinion, it may be used as a "shortcut" to properly evaluate efficiency measure. On the user-friendliness both of them commented that each implication have to be explained properly for each of the efficiency measures; if they were explained as it was made by me during the application, they both would give a rank of 4.

6.5.3.3 **Eliminate or reduce the compressed air used for cooling, agitating liquids, moving product or drying (2,4232):**

The role of compressed air inside the company, also in this case, is considered marginal with respect to other utilities. In spite of not being used directly to the process, they have very high use of compressed air for dense-phase transportation of material, and they believe this is the main use of compressed air consumption inside the plant. This reason, in parallel with the high interest demonstrated in how the framework applies to EEMs, resulted as crucial for the decision of deeper investigations on the topic. The framework, in this case, resulted effective, and the effort required to use it was evaluated as not high. The only advise, was on the right reading of each of the factors for the specific technology substitution, because the measure is too general. This means that in this case the user-friendliness is high because of the presence of the interlocutor (me) ready to explain how each of the technologies substitution is influenced by parameters (different duty cycles for different technologies, etc..).

6.5.3.4 **Reduce the pressure of compressed air to the minimum required (2,4231):**

In this last efficiency measure suggested, the potential of the framework was exploited very positively, because the awareness gained on an efficiency measure planned in the future (even if not specified if that future would be far or not), and the degree of adaptability it has for the various type of efficiency measures, is demonstrated to be quite influential. In this case a further advantage was given from the additional benefits that comes from observability factors. Some other factors were considered as not influencing for the decision; the synergy with other activities and the independency form other components have this characteristic, with the second having a quite high influence on the adoption, as demonstrated by the final comments of the interviewee.

CHAPTER 7

7.1 Final considerations

Energy efficiency has revealed to be a major force and an operative solution to cope with industrialization negative outcomes worldwide, mainly the increasing of emissions and pollutants. The situation has been shown to be different in countries with different industrialization levels. The OECD countries consumption in last years, confirmed how efforts toward energy efficiency can result in a brake for the growing trend. The industrial sector is the second for energy consumption, following the transportation, and presents a huge unexpressed potential for energy efficiency; it represents an opportunity for the cost reductions that can, moreover, lead to an increase of competitiveness. The energy efficiency gap literature focused to the unexpressed potential due to the existence of barriers, for which many authors provides taxonomies; major efforts lead to the possibility of proving experimentally their impact in SMEs. SMEs are, moreover, the target of many studies, because the lack of a proper management structure inside the firm, has been revealed one of the main reasons for the low adoption rate of energy efficiency solutions. Among promising ones, it is particularly interesting focusing on technologies that are widespread in many different industrial contexts, i.e. cross-cutting; they are not directly embedded in the production process, but usually represent a non-negligible share of energy consumption for companies.

In this work, the focus has been given on compressed air systems, starting from a thorough literature analysis showing an high unexpressed potential in terms of energy efficiency.

Many of the compressed air energy efficiency measures, do not seem to be quite expensive, with some exception being those that imply a major change in terms of components, or implying a shift in the layout (48). But, interestingly, previous studies found that major barriers in implementing EEMs in this cross-cutting technology are the need of consultancy by an external service provider for the adoption of most of the efficiency measures, the lack of awareness on their potentiality, but also the lack of knowledge by industrial practitioners in recognizing efficiency measures that can overcome cost-benefit analysis.

All these aspects have a contribution for creating and in maintaining the energy efficiency gap in compressed air systems, being evident on how the low implementation rates are not justifiable from a mere economic or energetic point of view. For all these reasons, in order to support companies in the decision-making process over EEMs in compressed air systems, it is apparent the need for a practical instrument, directed to industrial end users, able to immediately show companies the capability of understanding factors driving the decision-making on those EEMs, thus possibly giving a better idea regarding major barriers and opportunities coming from the adoption of an EEM.

So far, EEMs adoption is mainly driven by energetic and economic factors, so decision-makers often tend to underestimate, overestimate or, at worst, not consider, some important aspects that may became crucial for the final decision about adoption.

Literature efforts for the adoption of characteristics of energy efficiency measures are revealed to be very useful in pointing out some of the so called *non-energy benefits*, in order to increase the awareness on the real potential achievable by the adoption of a measure. All in all, the potential for the complete and whole characterization of EEMs is not exploited as it should be. When referred to a specific technology, in fact, there is the lack of a tool for detailed assessment of the implications entailed by the measure.

The proposal of a technology-oriented framework, is instead able to handle all the aspects coming from such type of adoption; the implications can act before the implementation, during the installation, or accrued during the lifecycle of the EEM. In order to conceive a comprehensive tool, to be used for a decision about the efficiency measures in compressed air system, the objectives where: firstly, the pointing out of all the factors, resulted of primary importance to check if they are all considered by end-users; secondly, with the framework development, results evident how the different factors varies with different EEMs, and which are the most influential efficiency measures for certain operating conditions of the compressed air system and firm's characteristics.

The contextual parameters are identified to be the best solution for answering the research questions, and the definition of the three axes: compatibility, complexity and observability, has revealed to perfectly fit the factors referred to the compressed air system energy efficiency measures. The full set of factors is as follows.

Complexity factors are revealed to be:

- Activity type to perform;
- the Expertise required for the installation of the measure;
- the Independency from other system components or other efficiency measures, that explain the degree of involvement in the production context;
- the change in Maintenance effort;
- the Accessibility factor, referred to the difficulty in the physical or resources access.

Compatibility factors are:

- Technological compatibility that will be used with the efficiency measure adoption;
- the influence given by the presence of different pressure loads;
- the adaptability to different conditions;
- the synergy with other activities, both referred to other efficiency measures that are suggested in parallel, to synergy with similar maintenance activities or to activities to be performed when the line is down;
- the distance from the electric service, resulted a crucial factor for some efficiency measures that implies the passage from compressed air to other technologies;
- the presence of thermal loads, crucial for the efficiency measures on heat recovery.

Some of the observability factors belong to the literature stream about non-energy benefits, but contrarily to that, the nature of the proposed factors is neither positive nor negative, since they assume a specific value only when referred to a singular EEM. Some of the factors are strictly related to the working environment, some others are referred to the lifetime of equipment, others are compressed air specific:

- Safety;
- Air quality;
- Noise;
- Wear and tear;
- Artificial demand.

Since the experimental nature of the model need some theoretical evidence before of its empirical evaluation, the industrial literature on compressed air related energy efficiency measures provide some hints for the levels to give to the factors. This is true, despite, for some of them, was not possible an absolute evaluation, being highly influential in relation

to the specific contextual situation. After that the synoptic table for the contextual parameters was completed, we obtained the test of the first type of validation, concerning the capability of the framework to fully describe each of the efficiency measures under analysis.
The validation of the framework proceeds with the application to five different SMEs, concentrated mainly in the southern part of the country, to test how the structure, perspective and scope of the work are evaluated by industrial practitioners. Each element of the framework was properly evaluated, starting from the macro-categories, and passing to the analysis of each element belonging to the contextual parameters. The four attributes used for the evaluation are the usefulness, clearness, completeness and absence of overlapping parts. For the last part of the validation, the application phase, the field of efficiency measures was narrowed to the most recommended by the IAC (48), and they are moreover tested using three different sets of EEM, grouped in "families": (i) EEMs not implemented in the past, (ii) EEMs adopted, (iii) and the ones that may be potentially adopted.

The validation (both theoretical and on-field) phase of the framework is of utmost importance because there is a lack of a research studies that consider all the factors coming from the implementation of an EEM for a specific technology. Moreover, without the positive evaluation of this part, each other development on possible applications, is useless. The framework validation was evaluated very positively by all the respondents. The model turned out to be innovative, because of its capability of pointing out all the factors, that usually for lack of capability in identifying them, awareness or subjective importance, are not properly evaluated. There were not specific suggestions for changes in the structure of the framework, being a further prove of how the tool passed the on-field validation.

The application phase, instead, is oriented towards the capability of the eleven firms to report the right implications of the efficiency measures tested, what are the determinant factors, and if they are properly considered (or forecasted) from the available tool. This passage was made to understand if the application of the framework in that specific context can provide a full picture of what are the factors influential for the decision. The comparison with the values attributable to factors (coming from the theoretical part of the validation), resulted useful in understanding which factors lead to a certain decision for the implementation or not of the measure. The indicators of performances to understand what is the practical applicability of the tool are essentially two: effort and user-friendliness. The tool showed its adaptability to the different EEMs and provided evidences of how, if the right factors, with the right level of importance were considered, the decision would be changed in favor of EEM's adoption.

7.2 Limitations and suggestions for future research

The limitations of the study are mainly attributable to the sample heterogeneity: first of all (i) the context under study was only the southern part of the county, that has very different characteristics to the Northern; secondly (ii) the heterogeneity of sectors, since the textile and metal manufacturing are quite important to fully describe the variability of the behavior toward compressed air efficiency measures.

The limitation of the sample to SME may be enlarged to large enterprises, to describe the differences in how their perception about factors changes and, as consequence, to render the framework suitable for all the type of firms. The applicability of the framework to understand the implications can be further extended to the others cross-cutting technologies, because of their wide range of applications, even if should be properly evaluated the potentiality of the instrument for each of the technologies, with the supporting literature studies.

The future outcomes from the application of the study may be directed to other figures that have a crucial role in the decision process; these are mainly revealed to be the technology suppliers. The high involvement of this actors in the decisions was clearer after the on-field evaluation, and some of the comments were about the extension of the tool under that perspective.

The availability of records for all the possible outcomes and factors mainly influencing the adoption of each of the efficiency measures, can provide further benefits, because of shared information. A database like this, can be of utmost importance, since it will be available statistics, suggestions and tips on what are the leader factors for the adoption of each EEM and how should be considered, to increase the capability of understanding which is the role and level of each of them during each phase of the adoption process.

Moreover, from a theoretical perspective, on the one hand, further efforts should be paid in putting together the novel framework here developed with existing taxonomies of barriers and drivers to energy efficiency, so to better understand which are the factors leading to major barriers with respect to specific energy efficiency measures. On the other hand, in this study I have explored EEMs in compressed air systems only. Hence, future work could expand on this framework to better understand the adaptability to different EEMs in other cross-cutting technologies quite relevant in terms of energy consumption and energy efficiency potential such as, e.g, HVAC systems and motor systems.

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Appendix A – References for the theoretical validation of the framework

Energy efficiency measure	Investment cost	Payback time	Energy savings	Pressure	Temperature	Fluid flow rate
Install compressor air intakes in coolest location (48) (128)	L	M	L		X	X
Install adequate dryers on air lines to eliminate blowdown (48) (24)	H	M	N/A		X	X
Upgrade controls on compressors (48) (129) (24)	M	M	M	X	P	X
Install common header on compressors (48) (25)	H	M	N/A	X		X
Use/purchase optimum sized compressor (48) (47) (24)	H	M/L	L	X	X	X
Use compressor air filter (48) (33)	L	M	L	X		
Reduce the pressure of compressed air to the minimum required (48) (25)	L	S	L	X		X
Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products or drying (48) (25)	M	S	H	X		X
Eliminate permanently the use of compressed air (48)	M	S	H			X
Cool compressor air intake with heat exchanger (48) (130) (131)	M	M	L		X	X
Remove or close off unneeded compressed air lines (48)	M	S	N/A			
Eliminate leaks in inert gas and compressed air lines/valves (48) (25) (24)	L	S	H	X		X
Substitute compressed air cooling with water or air cooling (48) (131) (130)	M	S	N/A		X	X
Do not use compressed air for personal cooling (48) (25)	L	S	N/A			X
Recover heat from air compressor (48) (132)	M	M	M		X	X
Recover heat from compressed air dryers (48) (132)	M	M	M		X	X

Energy efficiency measure	Activity type	Expertise required	Independency from other components/EEMs	Change in maintenance effort	Accessibility
Install compressor air intakes in coolest location (84) (128) (33) (24)	R	H/L	L	N/A	I
Install adequate dryers on air lines to eliminate blowdown (84) (133) (24) (134) (135) (136)	R	M	L	T	N/A
Upgrade controls on compressors (84) (137) (25)	R/N	H/L	L	T	N/A
Install common header on compressors (84) (117)	N	M	L	+	-
Use/purchase optimum sized compressor (84) (138) (19) (81)	N	H	L	+	I
Use compressor air filter (33) (84)	O	L	H	-	I
Reduce the pressure of compressed air to the minimum required (25) (84) (117) (139)	O	M	L +	-	-
Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products or drying (84) (140) (141)	O	H	L(N/A)	-(T)	I
Eliminate permanently the use of compressed air (84) (139)	O	L	H(N/A)	0	-
Cool compressor air intake with heat exchanger (33) (84) (118) (142)	N	L	H	-(N/A)	-
Remove or close off unneeded compressed air lines (84) (139)	O	L	H (N/A)	0(N/A)	-
Eliminate leaks in inert gas and compressed air lines/valves (25) (84)	Rec	M	L	-(N/A)	-
Substitute compressed air cooling with water or air cooling (130) (84) (74) (143) (118)	N	M	L	-	-
Do not use compressed air for personal cooling (25) (84)	O	L	M	0	-
Recover heat from air compressor (25) (84) (21)	R	H	L	-	-
Recover heat from compressed air dryers (25) (84) (21)	R	H	L	-	-

Energy efficiency measure	Technological	Presence of different pressure loads	Adaptability to different conditions	Synergy with other activities	Distance from electric service	Presence of different thermal loads
Install compressor air intakes in coolest location (128) (33)	H	No	H	H	0	0
Install adequate dryers on air lines to eliminate blowdown (133) (24)	H	No	0	H;-D (N/A)	-	0
Upgrade controls on compressors (129) (25)	H	No	++	H (N/A)	0	0
Install common header on compressors (117) (144)	H	-	+	H;-D	0	0
Use/purchase optimum sized compressor (48) (19) (144) (81) (25)	H	H	+	H; +D	0	0
Use compressor air filters (33)	L	No	0	+M (N/A)	0	0
Reduce the pressure of compressed air to the minimum required	0	H (N/A)	0	H (N/A)	0	0
Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products or drying (25) (145)	H	T	-	L;-D (N/A)	-	0
Eliminate permanently the use of compressed air (25) (145)	0	No	0	H(N/A)	0	0
Cool compressor air intake with heat exchanger (130) (128)	0	No	0	H; +M (N/A)	0	0
Remove or close off unneeded compressed air lines (25) (145)	0	No	0	H (N/A)	0	0
Eliminate leaks in inert gas and compressed air lines/valves	0	L	0 (N/A)	H; -D (N/A)	0	0
Substitute compressed air cooling with water or air cooling (145) (77)	M	No	0	H; +M	0	0
Do not use compressed air for personal cooling	0	No	0	H (N/A)	-(N/A)	0
Recover heat from air compressor (25) (132)	M	+	-	M(N/A)	0	+
Recover heat from compressed air dryers (25) (34)	M	+	-	M(N/A)	0	+

Energy efficiency measure	Safety	Noise	Air Quality	Wear and Tear	Artificial demand
Install compressor air intakes in coolest location (33) (128) (118) (142)	0	+	I	+	0
Install adequate dryers on air lines to eliminate blowdown (25) (24) (146)	0	-	++	+; -	0
Upgrade controls on compressors (25) (24) (118)	-	+	0	+	+
Install common header on compressors (117)	0	0	0	+(N/A)	0
Use/purchase optimum sized compressor (25) (118)	0	I	0	I	0
Use compressor air filter (25) (33) (118)	+	+	++	+	0
Reduce the pressure of compressed air to the minimum required (24)	+ (N/A)	+	I (N/A)	+ (N/A)	++ (N/A)
Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products or drying (140)	+	+	I (N/A)	+ (N/A)	+
Eliminate permanently the use of compressed air	0	+	0	0	+
Cool compressor air intake with heat exchanger (118)	0	0	0	0	0
Remove or close off unneeded compressed air lines	-	0	0	+ (N/A)	+ (N/A)
Eliminate leaks in inert gas and compressed air lines/valves (25) (24)	+	+	0	+	++ (N/A)
Substitute compressed air cooling with water or air cooling (118) (147)	0	I	0	0	0
Do not use compressed air for personal cooling (25) (118)	++	- (N/A)	+	0	+
Recover heat from air compressor (77)	0	0	+	+	0
Recover heat from compressed air dryers (77)	0	0	+	+	0

Appendix B - Model for characterization of energy efficiency measures

Macro-categories: Economic-energetic parameters | Operative parameters | Contextual parameters

Axes (Contextual parameters): Complexity | Compatibility | Observability

Factors

Economic-energetic parameters	Operative parameters	Complexity	Compatibility	Observability
Implementation cost[1]	Pression	Activity type[2]	Technological[3]	Safety[4]
Payback[1]	Temperature	Expertise required[2]	Presence of different pressure loads	Air Quality[5]
Energy expenditure	Flow-rate	Independency from other components/EEMs[6]	Adaptability to different conditions[7]	Noise[8]
		Change in maintenance effort[9]	Synergy with other activities[10]	Wear and Tear[11]
		Accessibility	Distance to the electric service[12]	Artificial demand[13]
			Presence of thermal loads	

[1] (83), (104), (84)
[2] (83), (84)
[3] (101), (112)
[4] (97), (94), (118)
[5] (97), (94), (92)
[6] (83), (109), (110)
[7] (25)
[8] (95), (93), (94), (24)
[9] (95), (97)
[10] (114), (102)
[11] (95), (97), (92)
[12] (115)
[13] (25), (19)