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Monitoring compressed air systems energy performance in industrial production: lesson learned from an explorative study in large and energy-intensive industrial firms.

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Abstract

Compressed air is one of the principal means for energy and material transport in today's industries. On average, the incidence of the compressed air systems is around 10% of total energy consumption but in some cases can reach 25%. Nevertheless, there are still no available energy performance benchmarks based on measured industrial data, taking into consideration actual operating conditions, and referred to compressed air production and, most of all, use. In 2015 the Italian transposition of the European Directive 2012/27/EU (i.e. Legislative Decree 102/2014) allowed to require energy audit to large and energy intensive enterprises. First analyses, aimed at developing energy performance indicators, showed some limitations in data collection. For these reasons, a questionnaire has been composed in order to identify the actions to be undertaken, we need to start from "specific" consumption by type of production. In particular, the questionnaire has made possible to identify some necessary actions to develop a rational compressed air production and use management system using measuring systems suitable for monitoring and controlling operations. The survey is aimed at the energetic analysis of the operating conditions of the compressors and their technical characteristics for a sample of companies, selected among those with a compressed air consumption of 5% EE.
The present study aims to define a measurement procedure that will ensure the availability of the necessary data for proper benchmarking of energy performance in production and use of compressed air.

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Keywords: Energy Efficiency; Compressed Air Systems; Directive 2012/27/EU; energy benchmarking.

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1. Introduction

According to Benedetti et al. (2016) compressed air accounts for as much as 10% of industrial electricity consumption in the European Union and in some cases the energy consumption due to the compressed air systems can reach 25% of the total. It is easy to understand the importance of the reduction of energy consumption due to the generation of compressed air for industrial uses.

According to Art. 8 of Legislative (Lgs.) Decree n°102 of the 4th July 2014, Italian transposition of the European Union through Directive 2012/27/EU, the large and energy intensive enterprises must undergo energy audits on their plants at least every four years, starting from the first deadline that was 5 December 2015 (Benedetti et al. (2016)). Energy audit allows to obtain adequate knowledge of the energy consumption profile of an industrial plant. This kind of energy data analysis, carefully lead, has made possible to identify the best opportunities for improvement (Longo et al. (2016)).

Doing continuous evaluations of the products, services and organizations between one site belonging to a firm and another one representing the best practices is a starting point to reach a complete results, that is the benchmark for Festel et al. (2014). Benchmark is recognized to be one of the most important methods to improve energy efficiency. According to Ke et al.(2013) it is the methodology to have a full evaluation of the energy performance of an industrial part or sector against a reference plant o sector. A benchmark analysis can help firms to assess their performances compared to the other enterprises and to increase own performances in term of production and energy efficiency. Making a benchmark oblige the companies to have a lot of data coming from the measuring systems and to use typical indicator to have an assessment of their performances. It needs a certain number of examples to define a range of methods to build the benchmarking model. It is possible to use both very basic single-factor measures, both complex econometric techniques and mathematical programming approaches (Chung (2011)).

In some cases benchmark has been done on entire industrial sectors analysing energy consumption related to CO2 production (Phylipsen et al.(2002)); in other cases only a kind of installation has been considered (Mui et al.(2007), Sahoo et al. (2014), Chung et al. (2006)).

Despite the importance of compressed air generation sector, does not exist a common standard to evaluate compressed air systems performances. Furthermore, there are not many documents and reviews about benchmarking methodologies applied in compressed air production which consider other than nominal conditions (Benedetti et al. (2016)).

Collected data has been used for some considerations about energy consumption of the various sectors and to do simple comparisons using KPIs about energy consumption and tons of final product. Starting from the most common techniques of data analysis, the study presented in this paper wants to define a strategy to measure the energy performance in the right way to make the data available to a benchmark. In particular, this work wants to define which are the variables to be measured and how to do it. To do a benchmark for the compressed air systems it is important to have some characteristic values as the amount of air produced, the system operating pressure, etc.

To collect more information about compressed air system besides the requested data, a questionnaire was set up with the aim of obtaining more information about the compressed air measurement system and about the level of management of this.

The already possessed data have been resulted unreliable because of some non-negligible approximations. First of all, it is impossible to know their veracity; in many cases the consumption data come from estimates made on productions of hours or even relying on electric bills. This inconsistency has led to a great difficulty in preparing complete and accurate analysis. Also, more importantly, it was not possible to use a common standard to develop a reliable benchmark methodology.

The results of this study will be the starting point for the development of guidelines for the next energy audit (expected in 2019) and a useful reference for all organizations wishing to evaluate and monitor over time the energy performance of their compressed air systems.

2. Methods

To monitor the degree of potential efficiency gains available for any given system it is important to consider many factors including: leakage rates, system pressure (set point and variation), specific demand (CAS demand per unit of plant output), specific power consumption of compressors, environmental variables (air quality, water quality) (Neale and Kamp (2009)).

To provide a valid benchmark analysis it is important to consider some key performance indicators, defined in terms of energy demand, end use, technology, process and device, and use them to compare the various cases. Physical-based indicators are normally calculated by relating energy consumption to an activity indicator measured in the physical terms (e.g. tons of steel, passenger-kilometres, floor area in square metres, etc.) or to an energy consumption unit (e.g. vehicle, dwelling, etc) (Ang (2006)).

Companies whose data make up the dataset are all part of nine industrial sectors that are: manufacture of basic metals, chemical products, pharmaceutical products, metal products, motor vehicles, plastics products, textiles, food products, paper. Available data include the amount of finished products typical for each industrial sector, the production data of compressed air and the relative energy consumption.

Specifically, the most significant data indicate the total amount of energy used by the company, the amount of energy used for the compressed air production, the amount of the final product and the amount of compressed air produced. Using these first KPIs which has been considered were:

- kWhe CAS/kWhe TOT - The ratio between the amount of energy consumed for the compressed air production and the total electrical consumption;
- kWhe CAS/t - The ratio between the amount of energy consumed for the compressed air production and the production volumes, generally expressed as tons of final product.

The two KPIs used cannot outline an overview of the situation about the efficiency of the compressed air generation system because of the great difference of the production volumes between the various sectors e.g. the importance of compressed air in the production of one ton of paper rather than one ton of metal is very difficult to evaluate. That kind of results can be used to begin a benchmark analysis within the single sectors but are not useful to consider the general performances.

Considering the difficulties to compare different sectors because of their operating services, making a benchmark analysis without considering the differences between the various production is the main idea of the work. To do a benchmark analysis data can be compared using many techniques including: normalization technique, statistical approaches and programming techniques (Longo et al. (2016)). In this work, the normalization technique and the statistical approach are used.

The performance of the system can be robustly monitored in a real-time environment monitoring the flow rate and associated power consumption at a variety of system loads. The use of this KPI on a periodic basis allows the overall system condition assessment. For this reason it has been chosen to use a more objective relationship between energy consumption for compressed air generation and the amount of air produced measured in m3 (kWhe CAS / m3) (O'Driscoll et al.(2013)).

This indicator does not give importance to the final production in fact, only the data on compressed air production are present in the formula.

3. Results and discussion

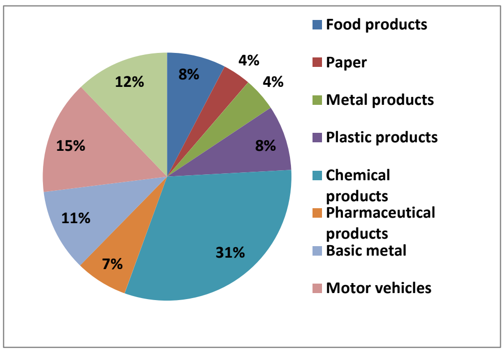

Fig.1. Incidence % of compressed air on national electricity consumption

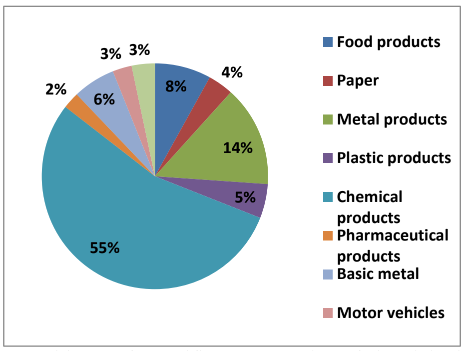

Fig.2. Incidence of "specific" consumption of electricity by sector

Results coming from the data collection campaign show that, within the sample, the sectors whose energy consumption is larger are: Chemical products (about 31%) and Motor vehicles (about 15%). In Fig. 1 has been represented the incidence of "specific" electricity consumption in comparison with the corresponding total national total consumption. The Fig. 2 represents the incidence of the compressed air system consumption within the total energy consumption sector by sector.

By comparing the energy consumption in kWhe CAS/m^3 it is assumed that the working conditions do not vary significantly between all the enterprises, hence restricting the applications of this approach (Longo et al. (2016)).

From these data analysis, it is difficult to find clear indications to have a good benchmark. The data are little significant and apart from outliers, previously removed, there is a typical trend for each sector that differs a bit from the general average. In Fig. 3 the histograms of collected data have been represented.

The situation gets better if we also add a correlation analysis between energy consumption and production data.

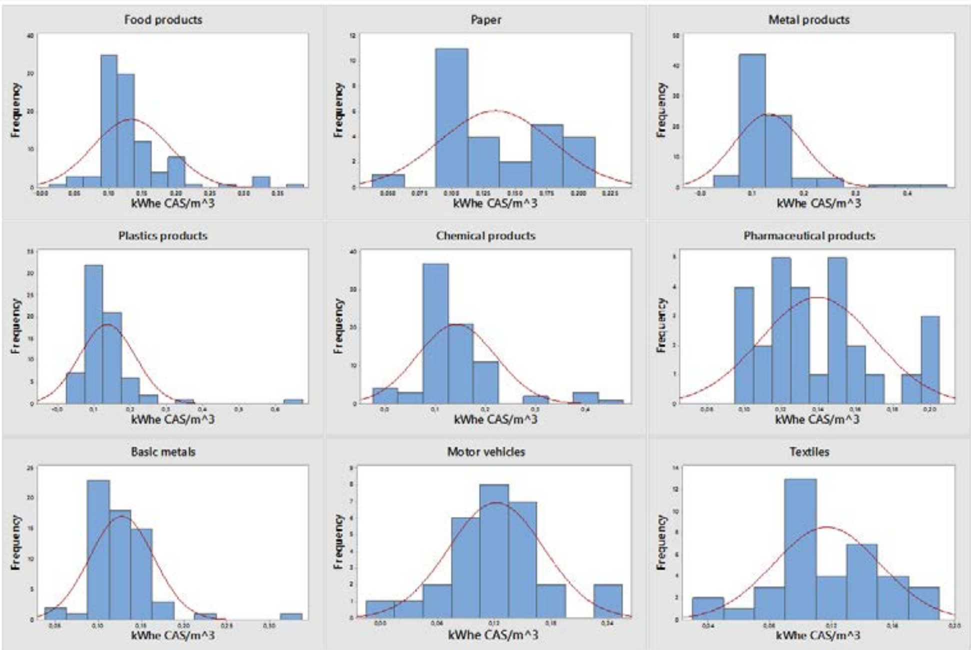

Fig. 3. Histograms of data sorted by sector.

As it can be seen from the Table 1 (left side), the correlation between all the input and output data is not homogeneous for all the sectors. Furthermore, the firms which have not measured the compressed air production might have estimated their data starting from some assumption coming from literature; that kind of data would falsify the analysis.

Doing a linear regression with the data relative to the measured quantities has allowed to analyze the P-Value and the significance (right side). From the results, if all the available data are considered, the P-Value is under 0.05 for all the linear regression inclines. If only the measured data have been considered, for some sectors, the regression loses its significance. This result can be due to the differences between the various firms analyzed; to have a relation between the electric consumption and the air production it is assumed that it is possible to scale linearly inputs and outputs, i.e. it is assumed constant return to scale. This heterogeneity is also effective due to the differences with which companies have estimated their consumption. The measurement difficulties are also considerable and are given by the paucity of information on the operating pressure of the compressors, the type of compressors installed and the plant characteristics. Furthermore, of all the companies for which data were available, 17% have measured their consumption related to the production of compressed air in a continuous or periodic, 69% calculated the consumption through bills while the remainder did not state the data; the way the data was calculated based on the energy bills is not known. Even if the data are derived from direct measurements not all companies are equipped with the necessary tools and there is not a unique procedure that can determine the power consumption for the compressor park.

From this first analysis, it is easy to note that the percentage of companies that provide a certain datum of their consumption (albeit with possible errors) is low, for this reason some corrective actions are necessary.

Table 1. Correlation and Linear regression results

Sector	Correlation			Linear regression			
				Overall		Measured	
	Overall	Measured	Estimated	Intercept	Incline	Intercept	Incline
Food products	0,970	0,992	0,882	0,582	9,60E-68	0,439	1,28E-15
Paper	0,963	0,986	0,961	0,002	1,07E-15	0,646	0,106
Metal products	0,123	0,261	0,072	0,214	0,270	0,865	0,281
Plastic products	0,969	0,998	0,955	0,899	2,64E-45	0,027	5,27E-06
Chemical products	0,996	0,997	0,978	0,017	4,47E-84	0,119	1,36E-16
Pharmaceutical products	0,865	0,821	0,821	0,811	7,15E-10	0,935	0,179
Basic metal	0,974	0,978	0,974	0,248	2,67E-44	0,726	5,07E-06
Motor vehicles	0,949	0,999	0,955	0,049	1,69E-14	0,288	0,027
Textiles	0,997	1,000	0,999	0,142	1,30E-42	-	-

4. Lesson learned on monitoring of compressed air system

Used data about produced compressed air and consumed energy make the benchmarking not completely significant for all the sectors taken into account because of the low reliability of the most data available.

Starting from this assumption a 12 wide-ranging questions survey were submitted to a sample of companies. The questions are collected in table 2.

Table 2. List of the questions

Q1. What about an energy efficiency program of the compressed air system serving the production processes within the company?	Q7. What about the compressors control system (on/off, inverter)?
Q2. Systematic diagnoses of the compressed air system, to find out energy saving opportunities carried out including measurement campaigns and energy audits.	Q8. What about the pressure drops in distribution system?
Q3. What about the improper use of compressed air?	Q9. What about the positioning of the intake air inlet?
Q4. What about measurement systems with which determine the amount of compressed air produced and/or used (definition of a measurement plan able to determine the variables to be measured, the measurement frequency and the measuring instruments)?	Q10. What about the evaluation of compressed air delivery pressure?
Q5. What about the analysis of compressed air demand profile?	Q11. What about the analysis of the compressed air leaks in the distribution network?
Q6. What about the scheduling maintenance of compressors?	Q12. What about the analysis of the cost and energy consumption data of the compressed air system?

Questionnaire

In order to have meaningful results, only companies whose electric consumption related to compressed air system is major than 5% of the total are considered in the questionnaire. The Fig. 4 shows the percentage distribution of the sample. The most numerous sample is represented by chemical sector which is also the more energy intensive.

Such a developed questionnaire helps to understand what kind of actions are needed get a better dataset with more information useful to get a good benchmark analysis. In this way, it is possible to cluster the enterprises based on their answers in order to have groupings not based on their performances neither on their features, that could go against the feature of generality described above.

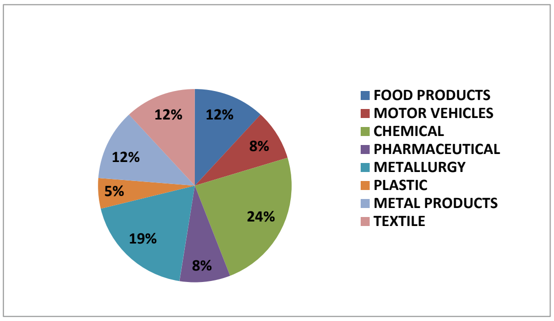

Fig. 4. Percentage of answers sorted by sectors.

Table 3. Question matrix

		Classes		
		1	2	3
N° Choices	3	Q12	Q4	--
	4	Q1, Q9	Q11	Q10
	5	Q2, Q6	Q8	Q3, Q5, Q7

This type of action has been made necessary by the feature of current dataset which is composed mainly by estimated values. Using the results, it is possible to assess the quality of analysed data and suggest some corrective actions.

Questions have been collected in Table 3. The rows indicate the number of choices (from 3 to 5). The columns indicate the class of the questions. The first column collects general questions about energy efficiency of CAS, the second column groups the questions about measurement systems and in the third column there are questions about working conditions. Answers are organized according to the growing level of development of management and operation procedures. One of the most simple and powerful way to reduce energy consumption is to install a measurement system capable of continuous monitoring and any anomalies detection. For this reason, the analysis focused on class 2 (about measurement system).

Table 4. Possible answers to questions 4, 8 and 11

Q4	1.	They have never been considered;
	2.	They have been considered and used sporadically (indicate the frequency of the measurements, the unit of measurement of the amount of compressed air measured and the measuring point);
	3.	They have been considered and used regularly (indicate the frequency of the measurements, the unit of measurement of the amount of compressed air measured and the measuring point).
Q8	1.	They have never been measured;
	2.	The magnitude of pressure drops is known and some more immediate and cost-effective corrective actions have been planned (regular maintenance of filters, replacement of other welding connections, etc.);
	3.	The magnitude of pressure drops is known and almost all the most immediate and low-cost correction work was done and some of the most important interventions planned (check the correct size of the pipes and replace them, purchase pressure gauges on condition Filters, correcting the shape of the net to avoid curves);
	4.	All the most important interventions have been planned and some have been implemented;
	5.	The network is optimized for minimizing pressure losses.
Q11	1.	An assessment of their size has never been carried out;
	2.	It has been estimated on the basis of on-board ignition / shutdown tests of stationary compressors and is considering taking action to improve it;
	3.	Surveys were carried out following which the most significant losses have been removed and at least the planned introduction of solenoid valves on the ducts to the user equipment has been planned;
	4.	Minor losses were also eliminated or reduced.

The results of questions 4, 8 and 11 are collected in table 5. The answers to question 4 show that most of the companies surveyed do not have a measuring system, corresponding to 52% of the sample. From the analysis of the answers to question 8, it is noted that, adding the percentages of response 1 and 2, most of the sample has not yet set up a system for monitoring pressure drops. Therefore, there is the possibility that some of them produce compressed air at a pressure higher than that required by the user, and may increase the consumption considerably. From question 11 on the note that only 15% of the sample has never undertaken actions aimed at assessing leakage of compressed air. Very positive result indicating a certain sensitivity to the energy data.

Table 5. Answers percentage to questions 4, 8 and 11

Answers	1	2	3	4	5
Q4	52,54%	11,86%	35,59%	/	/
Q8	37,29%	15,25%	16,95%	10,17%	22,23%
Q11	15,25%	30,51%	32,20%	23,73%	/

Measurement system

Starting with the questionnaire, it is necessary to define a standard for surveys, which makes possible to compare different companies also belonging to completely different industrial sectors.

To do a complete benchmark analysis can be used two types of indicator using different type of data. The first kind of indicator serves to calculate the performance of the different systems according to (Cesarotti et al.(2006)).

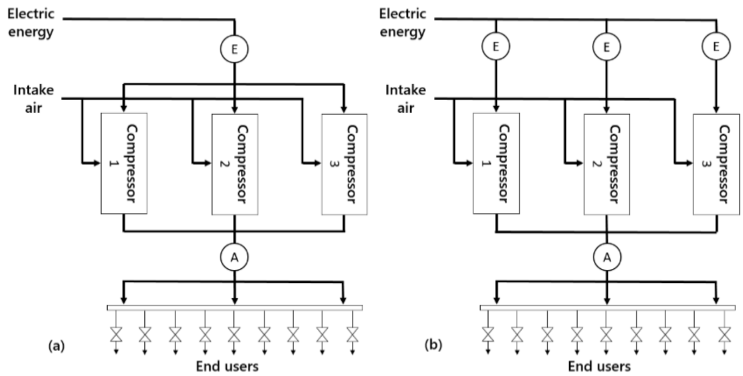

Fig. 5. (a) minimum configuration of measurement system; (b) ideal configuration.

To calculate other performances indicators it is necessary to have:

- Greater availability of data from measurements; could be defined a minimum measurement system in order to measure the amount of energy used by all the compressor park including the cooling system's pumps and the compressed air produced by all the compressors (Fig. 5). In this way, it is possible to calculate the ratio between compressed and energy consumption and the total consumption or the air production (kWhe CAS/kWhe TOT, kWh CAS/m3).
- Some further information about the pressure of compressed air generated. In the event that the system has multiple pressure levels it would be useful to develop a statistical analysis system that considers the effect of pressure and develop different benchmarks based on the pressure level. A further path could be the development of a more complex benchmark system capable of different pressure levels.
- More information about compressor parks: e.g. compressor size, compressor type, modulation type (presence of inverter or not, presence or not of an electronic control unit for the ignition and shutdown of individual compressors). If it is possible, it is useful to know the percentage of consumption and of total compressed air of each compressor or, at least, an estimate of the annual operating hours of the individual compressor. An indication of the variability of air demand over time it could be useful, but more complex. In this way, it would be possible to compare the performance of the different systems, provide information on the most efficient systems and the savings that can be gained from using these systems.
- More information about the system management. It can be useful to know some information about the maintenance scheduling, about the cost analysis and, above all, about any possibility of energy efficiency.

The second kind of indicator wants to investigate and compare various features of compressed air such as: type of use, quality and pressure. Data coming from firms could be used for a preliminary clustering and later perform the analysis cluster by cluster.

Using data from surveys, it is possible to estimate the potential for energy savings and a general assessment of the company's level of performance over time.

The introduction of a performance-oriented measurement system is the first step to developing an energy performance management and information system based on an energy management system (Introna et al. (2014)).

Each company can also develop a baseline for internal performance benchmarking, monitor them through the use of control charts and improve them. The regression method using measured data can help firms to analyze their electric consumption and thanks to control charts and CUSUM they can have a real-time monitoring system.

This kind of procedure allows to have alarm signals about malfunctions and excessive consumptions ensuring significant savings (Cesarotti et al. (2014)).

5. Conclusions

Starting from the lesson learned by Benedetti et al. (2016), some further indication to make a complete benchmark analysis are given. The available data have made necessary a definition of indicators and procedures to collect more data in order to perform a complete benchmarking of compressed air generation systems for energy-intensive industrial firms. The indicator kWh CAS/m^3 is considered the most important and the only on which allow to compare firms belonging to different industrial sectors.

References

[1] Benedetti, Miriam, Ilaria Bertini, Francesca Bonfà, Silvia Ferrari, Vito Introna, Domenico Santino and Stefano Ubertini. (2016) "Assessing and improving Compressed Air Systems' energy efficiency in production and use: findings from an explorative study in large and energy-intensive industrial firms." ICAE2016 Oct 8-11, Beijing, China.

[2] Longo, Stefano, Benedetto Mirko d'Antoni, Michael Bongards, Antonio Chaparro, Andreas Cronrath, Francesco Fatone, Juan M. Lema, Miguel Mauricio-Iglesias, Ana Soares and Almudena Hospido. (2016). "Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement." *Applied Energy* 179 (2016): 1251–1268.

[3] Festel, Gunter and Martin Würmseher. (2014). "Benchmarking of energy and utility infrastructures in industrial parks." *Journal of Cleaner Production* 70 (2014): 15-26.

[4] Ke, Jing, Lynn Price, Michael McNeil, Nina Zheng Khanna and Nan Zhou. (2013). "Analysis and practices of energy benchmarking for industry from the perspective of systems engineering." *Energy* 54 (2013): 32-44.

[5] Chung, William. (2011). "Review of building energy-use performance benchmarking methodologies." *Applied Energy* 88 (2011): 1470–1479.

[6] Phylipsen, Dian, Kornelis Blok, Ernst Worrell and Jeroen de Beer1. (2002). "Benchmarking the energy efficiency of Dutch industry: an assessment of the expected effect on energy consumption and CO2 emissions." *Energy Policy* 30 (2002): 663–679.

[7] Mui, K.W., L.T. Wong, L.Y. Law. (2007) "An energy benchmarking model for ventilation systems of air-conditioned offices in subtropical climates." *Applied Energy* 84 (2007) 89–98.

[8] Sahoo, Lalit Kumar, Santanu Bandyopadhyay and Rangan Banerjee. (2014). "Benchmarking energy consumption for dump trucks in mines" *Applied Energy* 113 (2014): 1382–1396.

[9] Chung, William, Y.V. Hui and Y. Miu Lam. (2006). "Benchmarking the energy efficiency of commercial buildings." *Applied Energy* 83 (2006): 1–14.

[10] Neale, James R. and Peter J.J. Kamp. (2009). "Compressed air system best practice programmes: What needs to change to secure long-term energy savings for New Zealand?" *Energy Policy* 37 (2009): 3400–3408.

[11] Ang, B.W. (2006). "Monitoring changes in economy-wide energy efficiency: From energy–GDP ratio to composite efficiency index." *Energy Policy* 34 (2006): 574–582.

[12] O'Driscoll, Eoin, Donal O´g Cusack and Garret E. O'Donnell. (2013). "The development of energy performance indicators within a complex manufacturing facility." *Int J Adv Manuf Technol* (2013) 68:2205–2214 DOI 10.1007/s00170-013-4818-z.

[13] Cesarotti, Vittorio, Bruna Di Silvio and Vito Introna. (2006). "Plant energy consumption reduction through monitoring and control system based on quality management concepts and tools." MITIP2006, 11-12 September, Budapest.

[14] Introna, Vito, Vittorio Cesarotti, Miriam Benedetti, Sonia Biagiotti and Raffaele Rotunno. (2014). "Energy Management Maturity Model: an organizational tool to foster the continuous reduction of energy consumption in companies." *Journal of Cleaner Production* 83 (2014): 108-117.

[15] Cesarotti, Vittorio, Simone Deli Orazi and Vito Introna. (2010). "Improve Energy Efficiency in Manufacturing Plants through Consumption Forecasting and Real Time Control: Case Study from Pharmaceutical Sector." Proceedings of International Conference on Advances in Production Management Systems (APMS 2010), ISBN 9788864930077, 11-13 October 2010, Cernobbio, Como, Italy.