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SUSTAINABILITY ANALYSIS OF A COMPRESSED AIR SYSTEM

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ABSTRACT: The scope of this study was to conduct a sustainability analysis of compressed air systems in industry. This was accomplished by evaluating the financial aspect, environmental impacts, and societal effects in the working environment of the system and to society as a whole. A literature review was carried out and three different approaches were identified in order to improve the sustainability of a compressed air system. A specific compressed air system at Toly Products Malta Ltd was investigated through power logging of the air compressors and loss analyses through leak identification and quantification exercises. These exercises were carried out using an ultrasonic leak detector and through some minor works, losses were reduced by 32 per cent. This led to the formation of several recommendations with regard to sustainable compressed air production and use and for the implementation of a compressed air monitoring system.

Keywords: Compressed Air Monitoring System, Compressed Air System, Ultrasonic Leak Detector

1 INTRODUCTION

The industrial sector of the economy requires several inputs in order to produce products and services which assist us in everyday life. These produced items lead to the development of man. Such inputs include sources of energy, which are converted into numerous forms to produce a manufacturing operation. An indispensable form of energy used in the manufacturing industry is stored as Compressed Air (CA). The generation, treatment and use of CA consume a large percentage of the electrical energy produced for industry. In fact, this accounts for about 10 per cent of the total energy produced for industry within the European Union. This large consumption is the reason why CA is typically one of the most expensive utilities in an industrial facility [1].

In order for development to be sustainable, the manufacturing systems used to produce products and services must be sustainable in their own right. Sustainable manufacturing (SM) encompasses methods, which utilize materials and processes that minimise negative environmental impacts. This is achieved through the conservation of energy and natural resources. In addition, the safety of employees, communities, and consumers must be safeguarded whilst ensuring economic stability [2]. CA generation, treatment and use contribute significantly to the sustainability of a manufacturing system.

The main objective of this project is to analyse the sustainability of a Compressed Air System (CAS) within a local company (Toly Products Malta Ltd) and through this analysis, suggestions were formulated in order to enhance its sustainability. Hence, the economic, environmental and social aspects of the CAS were investigated.

2 LITERATURE REVIEW

Compressed air is defined as air that has been sourced from the atmosphere around us, which exists in a state of pressure greater than that at which it naturally exists. This elevated state of pressure of air lends itself to numerous applications and is a vital element in the production capabilities of industries. A CAS is composed of three major subsystems. These include the compressor itself, conditioning equipment, and the distribution network [3]. The point-of-use of CA also plays a vital role in determining the sustainability of the CAS since, this determines the demands on the whole CAS.

2.1 Sustainability of Compressed Air Systems

Since CASs are one of the major consumers of electrical energy in an industrial setting, improving the sustainability of the system will result in major benefits. This will not only benefit the industries using CA but also society at large. This is due to financial benefits and a reduced impact on the environment.

2.1.1 Industrial Compressed Air Systems

For most industrial operations, the annual operating costs of air compressors present a large portion of the Life Cycle Cost (LCC) in comparison to the initial investment and maintenance costs [4, 5] as is illustrated in Figure 1. In order to minimise these costs, CA should be considered only if safety enhancements, significant productivity gains, or labour reduction, are achieved through its use. CA is such an expensive form of energy since only around 19 per cent of the electrical energy consumed is translated into CA. CA is then used for several applications within industry, such as those involving the operation of pneumatic equipment, to drive pneumatic motors, spray painting and cleaning [4].

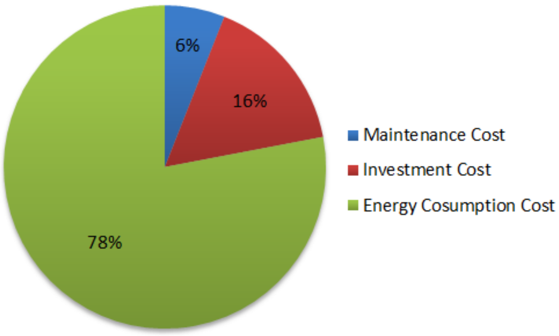

Figure 1: Description of CASs LCCs [4]

2.1.2 Attaining Sustainable Compressed Air Systems

Inefficiencies in CASs are often ignored since the input into the system is the free air in the atmosphere. These inefficiencies are only tackled when pressure losses occur and thus have a direct impact on the production process, such as causing a line stoppage.

There are several approaches to improving the sustainability of the system such as by focusing on specific components and technologies, through the management of the system or through implementation of standards and regulations. Generally, a blend of these different approaches is required [5].

Throughout this study, the sustainability of the specific CAS has been assessed and improved by using a power logger and an Ultrasonic Leak Detector (ULD). These technologies were used to monitor the CAS in order to establish a baseline with regard to its sustainability. Losses were also identified and rectified in order to improve its sustainability. These tasks are outlined in ISO 14001 and 50001 and were applied to managing a CAS.

3 METHODOLOGY

The methodology used in the ISO 14001 Environment Management Standards and the ISO 50001 and ISO 50002 Energy Management System Standards has been adopted for this study.

The ISO 14000 family of standards provides a set of tools for all types of organizations in order to manage their respective environmental responsibilities. Specifically, the ISO 14001 standard focuses on achieving the environmental responsibilities of the organisation through the development of a complete environmental management system rather than specific tools such as labelling and life cycle analysis. This standard provides a framework for the implementation of a successful environmental management system [6]. Apart from the direct environmental and financial benefits achieved through the implementation of this standard due to the reduced consumption of resources, benefits through increased competitive advantage and trust of stakeholders are also achieved.

The ISO 50001 Energy Management standard helps organizations to use energy more efficiently through the development and implementation of an Energy Management System. The model described in these standards is based on the same principles as those used in other continual improvement standards such as ISO 9001. This is essential in providing organizations with a system that can easily be integrated with other systems present within the organization.

The methodology used in the ISO 14001 and 50001 standards is the same. This is principally based on the Plan, Do, Check, Act (PDCA) Cycle. This cycle is a continuous process used by organizations to control and continually improve processes and products [7]. When the PDCA cycle is applied to CASs, the first step involves the monitoring of CA consumption and thus energy costs. This is achieved through the installation of specifically designed monitoring equipment, such as flow meters, which feed information into a centralized monitoring system. The second step of the cycle (the "DO" step) involves the localization of CA losses such as leaks. In order to do this, first the major consumers of CA must be identified. Instruments such as Ultrasonic Leak Detectors are then used to identify and categorize the leaks so that appropriate repairs and maintenance can take place. Losses within the CAS result in a reduction of line pressure. A reduction of 1 bar of pressure drop (due to friction and losses) can save approximately 8 per cent of energy [8].

Once the baseline for the specific CAS has been established using leak detection technology and/or system, a training and information distribution program is formulated. This is to improve the system through better education of the employees.

Since the employees are a functional component of the entire production system, the education of the employees is a powerful tool in achieving a sustainable system. The transfer of knowledge is primarily intended to be applied to the production system within the organization but this information also finds its way into the daily lives of the employees.

The third step of the PDCA cycle in the ISO 50001 standard involves the monitoring of the CAS in order to confirm the benefits gained from the previous steps. This will allow for the ideal design of the system when planning and expanding the CAS. In order to verify the success of the implementation of this management system, the optimizations that have taken place must be continually monitored. The final step of the PDCA cycle applied specifically to CASs involves the cross-fertilization of the improvements across the entire CAS [9].

Since the methodology presented in the ISO 50001 standard only deals with management, a second methodology presented in the ASTM E 2986-15 Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes, was also applied to this project. This standard provided guidance in the identification of the major consumers of CA, boundary conditions for the analysis and the determination of the indicators to be used. This standard provided the guidelines necessary in order to assess the sustainability of the system.

These methodologies were selected as a result of the literature review since together they provide the necessary structure to produce a complete and accurate feasibility study on the sustainability of the CAS case study identified.

4 CALCULATIONS

The equipment and processes related to CA at Toly Products Malta Ltd were investigated in order to assess the sustainability of the specific CAS. Firstly, equipment to be assessed was identified. Then, investigation and preliminary calculations regarding the equipment chosen were carried out.

4.1 Power Logging of Compressors

The scope of this section of this study was to collect the necessary energy data from the operation of the compressors supplying CA to the facility at Toly. In order to obtain accurate data which was representative of the true consumption of energy, the power loggers were connected to individual compressors for an extended period of time. In order to collect the required data, two Kyoritsu KEW 6305 data loggers were used.

The power loggers were connected to the compressors using a 3-phase 3-wire configuration (3P3W3A) as illustrated in Figure 2. In order to establish an accurate understanding of the power consumption of the compressors the power loggers were set to record at an interval of every minute as this was also the minimum interval possible with the memory available within the power loggers to conduct the logging over a number of days.

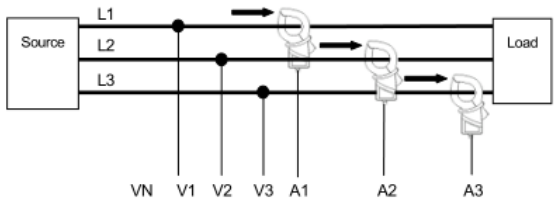

Figure 2: Schematic Diagram of Power Logger Connection [10]

4.2 Process Identification and Investigation

The production system at Toly consists of injection moulding machines in the ‘Machine Area’ and automated assembly machines in the ‘Assembly area’. Once the separate components are moulded prior to assembly, the parts have their surface altered through a spraying process in the mixed UV varnishing lines.

The equipment, which was to be analysed, was chosen together with the engineers at Toly under the criteria of being the major consumers of CA and significant representatives of all the equipment which function using CA in the facility. The equipment chosen consisted of a (i) linear, (ii) a rotary automated assembly machine, and (iii) a mixed UV varnishing line.

The first step in assessing the losses in the equipment was to list all the components that consume CA present in the equipment. Once the components were identified, the relevant technical literature for each specific component was acquired and studied in order to obtain the required information to calculate the volume of the particular line. In addition, the lengths and inner diameters of the CA piping were determined in order to calculate the total volume. The results of the investigation that was carried on the rotary automated assembly line are illustrated in Table 1.

This method of investigation was also undertaken for the linear automated assembly line.

With regard to the mixed UV varnishing line, the volumes and consumptions of CA for the different sections of the UV line were obtained from literature [11].

Table 1: Volume of components of Rotary Automated Assembly Line

Station	Items	**Volume (l)**
Main Supply	Piping	0.038
	Components	0.028
Station 1	Piping	0.009
	Components	0.392
Station 2	Piping	0.033
	Components	0.686
Station 3	Piping	0.018
	Components	0.392
Station 4	Piping	0.083
	Components	0.246
Station 5	Piping	0.111
	Components	0.442
Robot 1 (Platform SCARA Robot)	Piping	0.109
	Components	0.196
Robot 2 (Base SCARA Robot)	Piping	0.180
	Components	7.200
	Total	**10.163**

4.3 Loss Quantification

Equation (1) was used to quantify the amount of CA being lost due to leaks. This formula translates the pressure loss in the system to a volume of CA being lost in a specified period of time.

$$Air\ Flow = \frac{\left(\frac{Pressure\ Loss}{1\ Atmosphere}\right) \times Volume\ of\ System}{Specified\ Period\ of\ Time} \quad (1)$$

Equation (1) is derived from the combination of Boyle’s Law, Charles’ Law, and Gay-Lussac’s Law thus achieving the Combined Gas Law or General Gas Equation [12].

The volumes of the systems were calculated as in section (4.2). The pressure loss was measured using a pressure gauge connected to the system. Once the system was pressurized, the supply of CA to the system was shut-off using a specifically installed ball valve downstream to the drop from the main distribution network. While the supply was being shut-off, a timer was started simultaneously. The amount of time elapsed for a predetermined pressure drop was recorded.

Initially a baseline for the equipment was calculated, and then any leaks in the equipment were identified using the ultrasonic leak detector. The leaks which could be fixed with the available resources, were fixed and the test was carried out once again. These tests were repeated three times in order to obtain an average value.

4.4 Leak Identification and Quantification

The test procedure for the identification and quantification of leaks was carried out using ASTM E 1002 Standard Test Method for Leaks Using Ultrasonics. This standard emphasises the importance of reducing the interference caused by background noise that can result from other equipment consuming CA causing air movement and equipment vibration. In order to reduce the interference of background noise, all testing was carried during the weekend when production was at a minimum and only 10 to 20 per cent of the total production capacity at Toly was operational.

The method of detecting and locating the leaks dictated by this standard is as follows: Firstly, the sensitivity of the Ultrasonic leak detector was set to a maximum. The detector was used to scan the equipment by pointing the probe towards the test area. The sensitivity was reduced as the leak was approached. The focusing probes provided with the detector were used in order to isolate the leak from competing ultrasound as the focusing probes increase the directional response characteristics of the detector. The ultrasound reading and “rushing” sound in the headset were followed to the loudest point. In order to confirm a leak, the scanning probe was placed at the suspected leak site and the probe was moved slightly back and forth, up and down. If a leak was present, the reading both increased and decreased in intensity with the movements.

5 RESULTS AND DISCUSSION

The results of the data collection tests described in Section 4 are presented in this section. These results and some social aspects of CASs are also discussed.

5.1 Power Logging of Compressors

Power logging of the individual compressors was undertaken over a 17-day span including three weekends. Firstly, the two compressors in Compressor Room 1 were assessed using two power loggers. The number of production lines that were in operation each day was also noted. Once the logging of the first compressor room was completed, power logging of the four compressors in Compressor Room 2 could commence.

The percentage average energy consumption was calculated by relating the actual value of the average consumption for the particular shift with the maximum consumption of the air compressor. If any of the compressors were to run at their maximum power rating of 63 kW, which was achieved from the power logging data, for the entire shift (amounting to eight hours) the maximum consumption would be of 504 kWh. This is equivalent to 796 kVAh for an average power factor of 0.63 as achieved from the power logging data. This power factor was obtained by averaging the power factor values for all the logging periods. All six compressors present in the two compressor rooms at the Toly facility are of the same power rating.

These values were then compared to the number of injection moulding machines, which were running from the total 48 machines, during the same shift as the power logging of the specific compressor. The energy consumption of the mixed UV varnishing line was also taken into consideration since it is a major consumer of CA at the Toly plant with a total consumption of 19 per cent of the maximum CA capacity [11]. This value was calculated through information obtained from the technical file of the mixed UV varnishing line. The mixed UV varnishing line was only in operation on weekdays and not on Saturdays and Sundays.

The control system in place for the air compressors consists of individual threshold pressure values for each compressor at 0.2 bar apart. Thus, the compressor out of the six that is set to come in last has its threshold value set at 1 bar greater than that of the compressor which has the highest priority to come online when the system pressure is lower than the threshold value. This is classified as a cascade set point network control system [13].

As can be seen in Figure 3 (where P2 signifies plant room 2 and C1 signifies compressor 1) when the quantity of production taking place was below 10 per cent, the compressor was still operating at approximately 65 per cent of its full capacity. This was the case for five out of the six compressors. The period where the compressors were not consuming any energy signifies the time when all the compressors were turned off on a weekly basis.

The only compressor which did not follow this trend was compressor 2 in plant room 2. In this case, the maximum percentage use of the compressor throughout the logging period was below 12 per cent. This compressor was set to have its threshold pressure to come online the furthest away from the air compressor with the highest priority. The reason for having the lowest priority was due to the model being older than the other compressors and the newer compressors were favoured due to increased reliability.

This data signifies that although there was little demand from production, the compressor still had to perform a considerable amount of work. This is due to losses in the CAS, thus, the compressors must continue to perform work to maintain the system pressure in order to compensate for these losses.

The data obtained from the power logging of the compressors illustrated that there were several instances where the compressors were continually being engaged and disengaged for several hours. This indicates that the demand on the CAS could not be exactly matched by the supply produced by the existing control system and compressors. The implementation of a variable speed drive compressor would benefit this scenario. This is due to the ability to match the demand on the CAS more accurately. This would increase the efficiency of the system and would lengthen the operating life of the equipment due to the ability to have a smooth start-up at low speeds reducing current and torque peaks, which in turn reduces mechanical wear.

The data obtained provided the motivation for the next set of tests, which consisted of the Air Loss Quantification exercises.

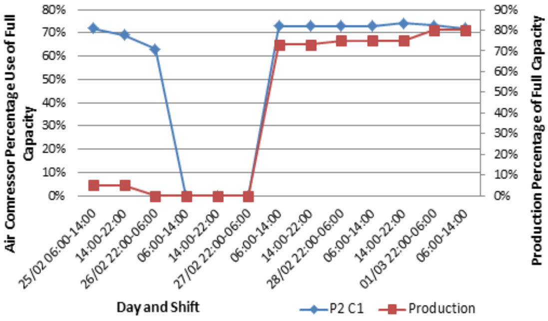

Figure 3: Graph of Compressor P2 C1 Percentage Use of Full Capacity and Production Percentage of Full Capacity for the logging period

5.2 Air Loss Quantification

The volume of CA loss attributed to each piece of equipment investigated was quantified and translated into a financial loss. The tariff rate in kVAh for non-residential establishments rated above 100 amperes obtained from Enemalta plc which applies to Toly is of €0.1170 per kVAh.

The cost of the quantified loss of CA was calculated by converting this known volume of air to energy consumption by the air compressors. This was achieved through knowledge of the rate at which a specific volume of air can be produced by the compressors when in operation. This is the output capacity of one of the air compressors. Each compressor is capable of producing a maximum volume of $9.51 m^3 min^{-1}$ of CA.

In the following calculations, it was assumed that the equipment under test was in operation for three eight-hour shifts a day between Monday and Friday and operated for two shifts on a Saturday. This equates to 136 hours of operation a week. It was also assumed that the equipment operates for 48 weeks out of 52 per year due to shut down periods. Finally, it was assumed that the losses investigated during the testing would be constant for the projected period.

The process described in sections 4.3 and 4.4 were used to achieve the required results for the selected equipment. An uncertainty analyses was also carried out for the air loss calculations. These uncertainties are tabulated in Table 2.

The results from the leak detection process using the ULD on the rotary automated assembly line before repairs were carried out are illustrated in Table 2.

Table 2: Rotary automated assembly test results before leak repairs

Test Number	Start Pressure (± 0.315 bar)	End Pressure (± 0.315 bar)	Time (± 0.23 s)	Airflow (±0.331 ls^{-1})
1	7.1	4	13.84	2.25
2	7.1	4	13.34	2.86
3	7.1	4	14.15	2.20
Average	**7.1**	**4**	**13.78**	**2.26**

The test to achieve the results in Table 2 was repeated once the leaks from the equipment were identified using the ultrasonic leak detector and when leaks which could be repaired were repaired. The components that were identified as possessing leaks were retested for leaks once fixed using the ultrasonic leak detector under the same conditions. No leaks were registered on the detector.

The yearly loss of CA, power consumed to produce this lost CA, the financial cost and environmental impact for the rotary automated assembly line before and after the leak testing exercise was carried out is illustrated in Table 3.

Table 3: Yearly Total Financial Losses and Total Environmental Impact for the Linear and Rotary Automated Assembly Line and the Application Cabin of the Mixed UV Varnishing Line

	Prior to Leak Test	Post Leak Test	Savings
Volume of Air Lost (m^3)	140,371	95,461	44,910
Power Consumed (kVAh)	24,476	16,645	7,831
Financial (€)	2,863	1,948	915
Environmental (CO_2 Equivalent - kg)	10,120	6,882	3,238

The uncertainty in the percentage savings described in Table 3 is very low. This is because the uncertainty of the percentage savings is a ratio of the time measurements. This value is small in comparison to the percentage uncertainty of the airflow values because the uncertainty in the time measurement is low.

The CO_2 emissions released due to the generation of electricity are dependent on the method through which the electricity is produced. The main sources of electrical energy in Malta are the power plant in Delimara, the Electrogas power plant also situated in Delimara and the Malta-Sicily interconnector. Due to the unavailability of information regarding the energy mix at the time of writing, the energy mix of the year 2015 was used. The unavailability of information is due to the major changes which occurred to Malta's energy mix at the time. In 2015, Malta consumed 2,257,218 MWh of electricity. An additional 103,540 MWh were obtained from renewable energy sources. The Malta-Sicily interconnector supplied 47 per cent of this consumption. The emission rating for the Malta-Sicily interconnector is unknown, as the source of the energy could not be traced. At the time of testing it was assumed nil. The remaining 53 per cent of the supply was generated in Malta. This production of electrical energy was responsible for the release of 854 million kg of CO_2 into the environment in 2015. This equates to an emission rating of 653g/kWh of CO_2 during the year of 2015 [15]. This CO_2 emission rating was used in order to describe the Global Warming Potential (GWP). The value of the CO_2 emissions is used as a benchmark for all other gasses associated with the GWP.

By taking into consideration the three pieces of equipment that were analysed, the total yearly financial loss due to air leaks was projected to be of €2,864. Concerning the environmental pillar of sustainability, the total emission of CO_2 attributed to the losses quantified in the linear and rotary automated assembly lines and the Application Cabin of the mixed UV varnishing line, a total of 10.12 tonnes of CO_2 is projected to be released into the atmosphere on a yearly basis. Leak identification and quantification exercises were carried out and any leaks that could be fixed were fixed. This resulted in a yearly financial and environmental impact improvement of 32 per cent.

At the time of the testing 14 automated assembly lines were in operation at the Toly plant. Six linear and eight rotary automated assembly lines. It was assumed that the respective linear and rotary automated assembly lines were of similar volume and comprised of similar components. In addition, it was assumed that the losses attributed to each type of automated assembly line were constant throughout all the automated assembly lines. In order to calculate the losses attributed to all the mixed UV varnishing line it was assumed that the losses within the different sections of the mixed UV varnishing line were equal to those in the section assessed. The resulting yearly financial losses are illustrated in Figure 4. The percentage reduction in financial losses and environmental impact is also presented. This would result in a total yearly financial saving of €3,984 and a reduction in CO_2 emissions of 14.17 tonnes.

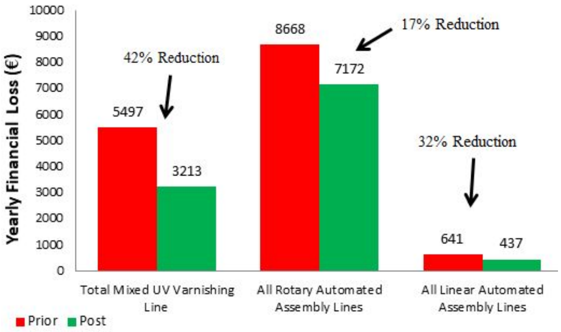

Figure 4: Yearly financial loss and percentage reduction applied to all the major consumers of CA

The average percentage reduction in CA losses due to the leak testing exercise applied to the six linear and eight automated assembly lines and to all of the mixed UV varnishing line is 27 per cent. This percentage is consistent with savings quantified in published literature.

Through the improvement of the sustainability of CASs several social benefits are achieved. Through the consumption of less electrical energy, less impact on the environment is being made. In this project, the health hazards to the employees related to CA were also investigated. One such hazard is the noise generated by the use of CA. The high levels of noise and leaks observed at the facility may cause hearing impairment to the employees but it may also cause discomfort which can reduce the productivity of the employees, thus having an effect on the production efficiency of the facility. This led to the conclusion that increased awareness and education concerning the risks involved with the use of CA should be undertaken in order to decrease the eventuality of any of the employees being injured.

6 CONCLUSION

An essential part of reducing losses to a minimum is to constantly acquire and analyse data concerning the production and consumption of CA within the facility. A means to acquire, analyse and transfer this information is through the use of a CA monitoring system which includes power loggers, sub meters and air flow meters used to measure the energy consumption of the compressors and the CA consumption of particular equipment in the system. This data allows the accurate identification of areas or equipment with large losses. This knowledge provides opportunities for significant energy savings and reductions in operating costs. The monitoring and loss rectification exercises conducted at Toly Products Malta Ltd reduced CA losses on the analysed equipment by 32 per cent. This is not saying that all CA losses were rectified. Therefore, it is suggested for Toly to implement a CA monitoring system, possibly including the investment in an ULD.

7 FUTURE WORK

From an academic perspective, future projects could be dedicated to focusing on specific equipment and not on the entire CAS. This study has concluded that there is a definite reason to investigate the CA use and losses in specific equipment.

From an industrial perspective for future work, the implementation of a CA monitoring system will allow a more in-depth study of the specific CAS. This will also allow the analysis of the implementation of energy efficient technologies, such as variable speed drives, and the overall system design.

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