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Utilisation of a compressed air test bed to assess the effects of pneumatic parameters on energy consumption

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ABSTRACT

In the manufacturing industry, pneumatic powered components provide a safe and reliable opportunity to automate a production line. However, compressed air systems are notoriously expensive to operate as a result of system losses and inefficiencies. Typical systems have an output efficiency of 10–12%. This offers a significant improvement opportunity to meet sustainable targets concerning energy consumption in industry and lower life cycle energy impacts. Amongst various inefficiencies, leakages and excessive pressures are identified as some of the most common sources of waste. The scope of this study was to make use of a compressed air system which was designed in the form an experimental test bed in order to assess the sustainability impact of various compressed air shortcomings. Simulations were carried out under experimental conditions to measure the additional energy consumption and air volume required for different pneumatic scenarios. Some of the results showed that a noise level of 70 dB is attributable to a leakage of 1.5 mm at the industry standard of 6 bar. Such a single leak could incur more than €470 of additional electrical costs and would result in 1.8 tonnes of additional carbon dioxide emissions within one year of operation, highlighting a significant effect on the life cycle impacts of industrial production.

1. Introduction

With the ever increasing environmental and sustainable concerns regarding the manufacturing industry, governing bodies such as the European Union have been introducing stricter directives and legislations in order to attain an operational shift in corporate attitude through both sustainable consumption and production. Therefore, in a globalized market, manufacturers are seeking alternative methodologies to attain improved efficiency and effectiveness by implementing sustainable manufacturing production systems and technologies.

Compressed Air (CA) is considered as the fourth major industrial utility due to the safe and reliable applicable potential that could be offered across a wide range of industrial sectors (Talbott, 1993). However, Compressed Air Systems (CAS) experience substantial energy losses resulting in a typical output efficiency of 10–12% (Mousavi et al., 2014). For this reason, CAS are considered as the most expensive energy source within an industrial enterprise accounting for 10% of the total European industrial energy consumption (Saidur et al., 2009).

The aim of this study was to simulate and evaluate the impact of various shortcomings that one typically finds in industry such as leakages and excessive system pressures by utilizing a compressed air test bed (CATB) that was developed by Abela et al. (2019). The test bed provided an ideal platform to carry out various pneumatic simulations under experimental conditions and repeats without industrial demands that typically restrict analysing CAS case studies. During this study, an established methodology of detecting leakages by using ultrasonic leakage detectors was used in conjunction with the capabilities of a cyber-physical CATB in order to attain a more holistic understanding of the impact of leakages within CAS from a sustainability standpoint (Abela et al., 2019).

2. Literature review

The manufacturing stage of production plays a major role when evaluating the life cycle assessment of a product. For instance, throughout the life cycle of mobile phones, the manufacturing phase accounts for 50% of the total energy consumption while the use phase only contributes 20% towards the total energy consumption (Yu et al., 2010). Therefore, it is essential that the manufacturing phase is carried out in an efficient and sustainable manner. According to Saidur et al. (2009), throughout the whole life cycle

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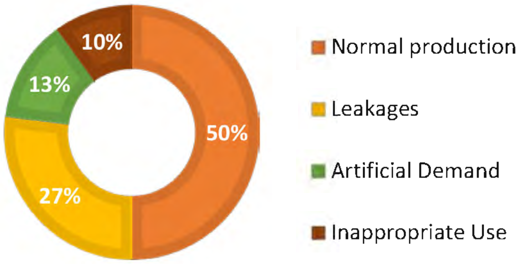

Fig. 1. Energy Losses at the Demand Side of a CAS (Sommers, 2015; Marshall, 2015).

Table 1
Leakage costs within a CAS operating 24 h/day for a whole year with a CA cost of 1.9 cents/Nm^3 (FESTO 2013).

Bar	0.5 mm	1.0 mm	1.5 mm	2.0 mm	2.5 mm	3.0 mm
3	€90	€361	€812	€1444	€2256	€3248
4	€113	€451	€1015	€1805	€2820	€4061
5	€135	€541	€1218	€2166	€3384	€4873
6	€158	€632	€1421	€2527	€3948	€5685
7	€180	€722	€1624	€2888	€4512	€6497
8	€203	€812	€1827	€3248	€5076	€7309

of a CAS, the energy consumption accounts for 78% of the total lifetime costs with the remaining expenses attributable to investments and maintenance costs. For this reason, CAS can account for 10% of the total industrial energy consumption within the European Union (Saidur et al., 2009).

Inefficiencies within CAS arise due to several contributing factors. J. Sommer (Sommers, 2015) and R. Marshall (Marshall, 2015) both stated that as much as half of all produced CA is wasted at the demand side of the system in the form of leakages, artificial demand and inappropriate CA uses as portrayed in Fig. 1. As a result of the major influence that the aforementioned losses have on the total efficiency of a CAS, relatively unpretentious system improvements such as periodic leakage repairs could yield significant financial gains through improved energy consumption (US Department of Energy; Abdelaziz et al., 2011; Boehm and Joerg, 2017). As can be observed in Table 1, a case study by FESTO (FESTO, 2013) concluded that the surveyed CAS could potentially save more than €7000 per year in electrical costs due to leakage elimination.

In practice, several methodologies exist to help identify losses. For instance, excessive system pressure along the distribution system can be easily identified by using monitoring equipment such as pressure gauges and pressure transducers amongst others. One of the most conventional practices that is employed in industry is the use of energy and air audits whereby dedicated personnel carry out investigations along the distribution network of a CAS in order to identify losses (Shanghai and McKane, 2008; Neale and Kamp, 2009). During an energy and air audit case study, Caruana (2017) concluded that the projected saving potential within a whole plant amounted to approximately €4900 per year. Similarly, Shanghai and McKane (2008) concluded that on average energy audits result in the potential saving of 10–50% of the total energy consumption. Despite this significant saving potential, energy audits are easily overlooked. Neale and Kamp (2009) stated that only 53% of industrial manufacturers carried out energy and air audits in New Zealand irrespective of the fact that such audits offered payback periods of less than eighteen months.

One of the most fundamental operations carried out during an energy audit is the detection and correction of several leakages that are commonly incorporated along a complex distribution line of a CAS. Due to the relatively noisy environment that one typically finds within factory shop floors, persistent "hissing" sounds originating from leaking CA orifices are easily overlooked. Therefore, ultrasonic leak detectors provide a convenient option to aid in detecting leaks that emit sounds outside the human audible range (SDT North America 2009; Dudić et al., 2012).

As established by the SDT Leak Survey Handbook (SDT North America, 2009), ultrasonic leak detectors (ULDs) grant a versatile and reliable methodology for detecting leakages. If the methodology is applied consistently, ULDs have the potential of saving as much as $45,000 in annual electrical costs within a 29m^3/min CAS. Moreover, Dudić et al. (2012) not only confirmed the possible gains that one could achieve with the use of ULDs but also highlighted a correlation between the air flow rate being emitted from the orifice of a leak and the decibel level measurements recorded by the ULDs. The results showed that an exponential relationship exists between an increase in air flow rate and decibel reading. However, due to the methodology adopted for their experimentation, Dudić et al. (2012) concluded that the results were attained with some "relatively imprecise measurement equipment". Moreover, during the experimentation phase, leakages were replicated using elastic materials such as ABS pipes. As a result of the elastic nature of the material, smooth-walled orifices were difficult to achieve and therefore, Dudić et al. (2012) observed that the generated ultrasound due to the flow of air from the leak source was profoundly intensified.

It is apparent that from the reviewed literature, there are no studies which collect and analyse real time data from the demand side applications, since the main scope of such applications remains focused on the supply side. The scope of this study was therefore to make use of a cyber physical pneumatic system which was designed in the form an experimental test bed in order to assess the sustainability impact of various compressed air shortcomings. Consequently, in this paper an established experimental methodology in relation to ULDs was applied together with the capabilities of the test bed in order to attain a holistic understanding of how easily leaks can be detected in industry while also considering the impact of leakages on the sustainability of industrial CAS.

3. Experimental approach

To ensure experimental repeatability while also minimizing external impacts (such as production outputs that are typically associated with industrial CAS case studies), a CATB developed by Abela et al. (2019) was utilized for this study as shown in Fig. 2. The various capabilities of the CATB, which were discussed in detail by Abela et al. (2019), established a complete cyber physical pneumatic system in order to gather continuous and accurate information in relation to energy and CA consumption.

The devised methodology towards this study, was intended to display the abilities of the developed CATB while also determining the effectiveness of quantifying leakage diameters with the use of ultrasonic leak detectors. To carry out the intended experiment, the experimental set-up displayed in Fig. 3 was setup on the testbed. Additionally, a UE Systems Inc. Ultraprobe 100 (UE Systems Inc. 2011) was utilized throughout the testing period to measure the decibel reading of each experimental scenario.

To carry out each experimental condition the following procedure was adopted (refer to Fig. 3);

- The compressor was set to supply regulated compressed air to the receiver tank by means of a hysteresis pressure regulator at a pressure between 6.5 and 8 bar.
- A regulator was utilized to regulate the pressure from the receiver between 3 and 6 bar. This pressure was measured accurately and in real time using 'Pressure Transducer 2′,
- 'Air Flow Sensor 1′ is used to measure continuously the total air flow rate that is being supplied to the CAS,

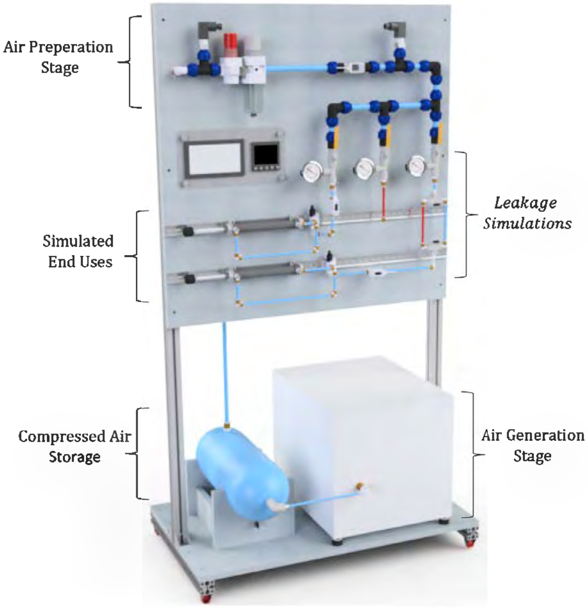

Fig. 2. Major Elements that form part of the CATB (Abela et al., 2019).

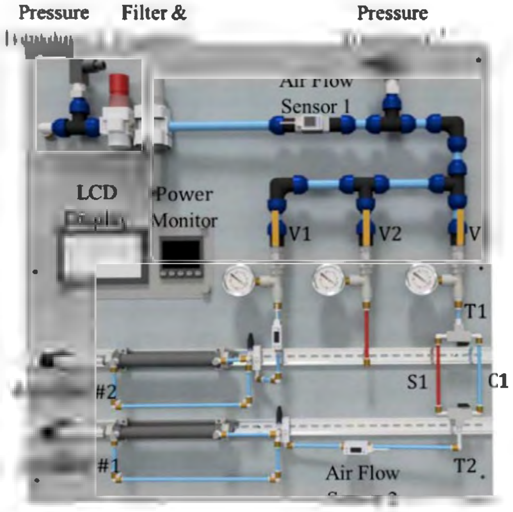

Fig. 3. Experimental Set-up of the CATB.

- By opening valve 'V3' the CA would flow through a red ABS pipe, at point 'S1', comprising a leak of known diameter between 0.5 – 1.5 mm,
- CA flow rate was also measured again using 'Air Flow Sensor 2′ downstream of the leak. The intended end use 'Actuator #1′ was fitted with a double acting cylinder.

Each test was ten minutes long whereby the functional units of the double acting cylinder 'Actuator #1′ was set-up to reach 600 actuations per test amounting to 1 actuation per second. The controllable input factors for each experimental condition were manipulated as follows;

- Pressure: varied between 3 – 6 bar in increments of 1 bar,
- Leakage Diameter: varied between 0.5 – 1.5 mm in increments of 0.5 mm.

The measurable output responses were measured in terms of;

- The average decibel reading 1 m away from the leakage source with the use of the Ultraprobe 100,
- The total energy consumption for each experimental condition by using a power monitor connected to the compressor,
- The total air volume for each experimental condition by subtracting the air volume measured by 'Air Flow Sensor 2′ from the total system air volume measured by 'Air Flow Sensor 1′ (Fig. 3).

Table 2
Uncertainty analysis of the measurable output responses during a control experiment with no leakages at 3 bar pressure.

Measurable Output	Reading	Accuracy	Percentage
Energy Consumption	33 Wh	±0.49 Wh	±1.5%
Air Volume 'Air Flow Sensor 1′	171 litres	±8.7 litres	±5.1%
Air Volume 'Air Flow Sensor 2′	172 litres	±3.5 litres	±2%
Pressure 'Pressure Transducer 2′	3.1 bar	±0.1 bar	±3.2%

A comparison was also carried to establish the difference between smooth walled orifice sounds originating from leakages within 8 mm aluminium pipes and irregular shaped orifices that originate within 8 mm ABS plastic piping due to the elastic nature of the material. However, for the duration of the experiments, irregular shaped leakages in ABS pipes were utilized since most leaks occur at the demand side of a CAS which usually contains ABS pipes for ease of system modulation and flexibility.

4. Results and analysis

4.1. Uncertainty analysis

To ensure the validity of the results and to determine the unavoidable errors associated with the measuring instruments used, an uncertainty analysis was first conducted on the measured output parameters. Through preliminary testing it was determined that the highest uncertainty attributable to the instrumentation was at the lowest measurable output responses established in Section 3 i.e. during optimal CA conditions with no leakages and a system pressure of 3 bar. Table 2 shows the readings measured under the aforementioned conditions along with their respective accuracies.

Since the experimental condition shown in Table 2 comprised no leakages, 'Air Flow Sensor 1′ and 'Air Flow Sensor 2′ measured similar air flow rates and resulted in the same air volume reading within a ten-minute experiment. In addition to the sensor accuracies displayed in Table 2 at the worst-case scenario, the uncertainty of the handheld Ultraprobe 100 was specified as ±3db. The aforementioned conditions tabulated in Table 2 were considered throughout the duration of this study.

4.2. Results

As a result of the elastic nature associated with the ABS pipes that were installed at point S1 in Fig. 3, the purposely drilled orifices of 0.5 mm, 1.0 mm and 1.5 mm resulted into relatively irregular shaped orifices (Willoughby, 2001). After comparing the irregular shaped orifices drilled in ABS plastic piping to smooth-walled orifices that were drilled within aluminium pipes it was observed that leakage sounds from the ABS plastic pipe were muffled when measured using the ULD. Therefore, it was concluded that the irregular shape of the ABS orifice restricted the flow of CA exiting the leak which caused diminished CA volume losses and as a result a lower measurable sound level measured by Ultraprobe 100.

The measured decibel readings attributable to each specific leak at a particular system pressure are plotted in Fig. 4. This technique provides a simple estimation tool for manufacturers to approximate the size of relatively large leakages between 0.5 mm and

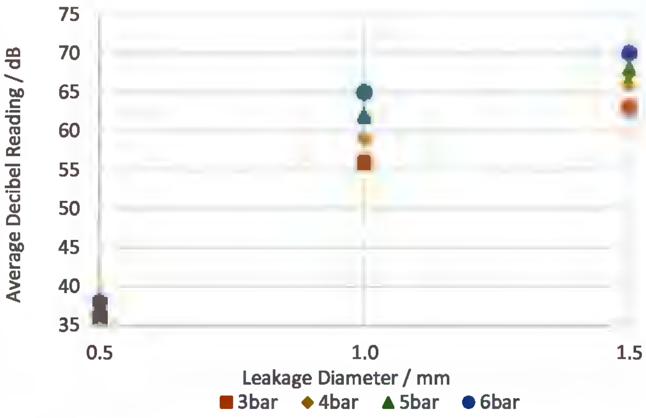

Fig. 4. Average Decibel Reading attributable to each experimental condition.

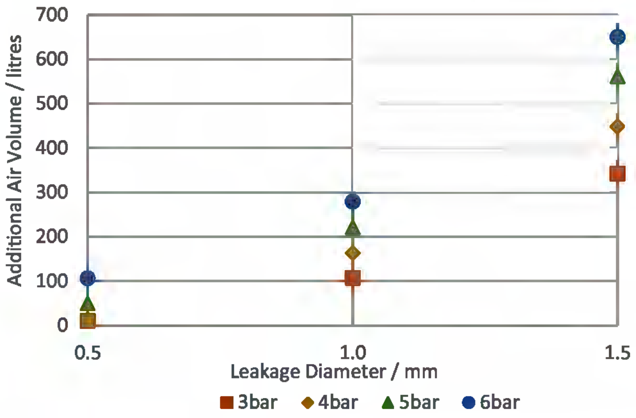

Fig. 6. Additional CA volume utilised per testing condition.

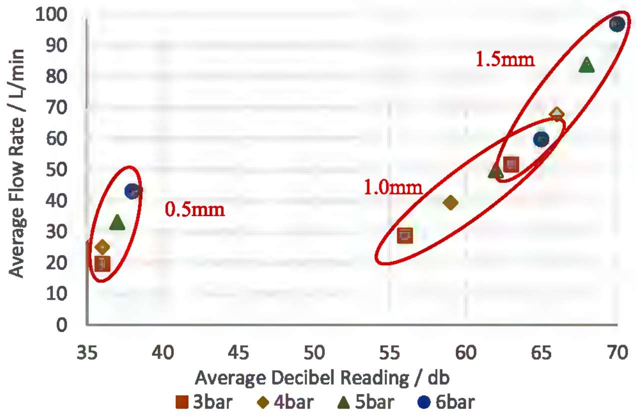

Fig. 5. Correlation between acoustic reading and air volume used per test.

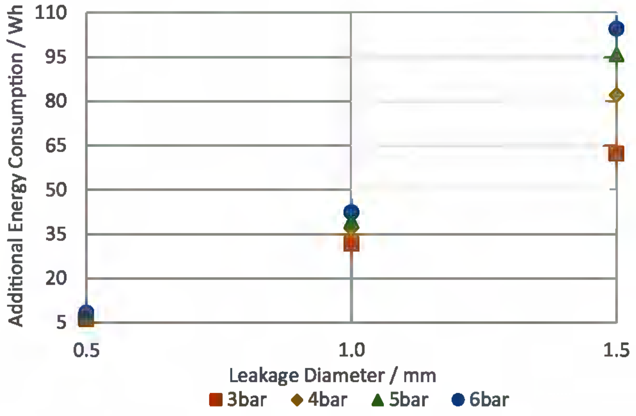

Fig. 7. Additional energy utilised per testing condition.

1.5 mm by measuring the decibel levels. Such detections could easily be carried out simply by holding the detector 1 m away from the leakage sources during operating down times or before manufacturing start-ups. Through consistent monitoring of either energy usage or air consumption, manufacturers could than compare and contrast the losses associated with a detected leak.

As a result of the holistic interpretation that could be achieved with the use of the CATB, additional information attributable to each leakage such as the correlation between acoustic readings and air flow rate were also measured and analysed as can be observed in Fig. 5. As expected, it is quite evident that the CA leak rate increases exponentially with an increase in decibel reading. This observation was also recorded by Dudić et al. (2012). Moreover, the correlation in Fig. 5 also shows that leakage diameters can be isolated by comparing the acoustic reading from the ultrasonic leak detector with the air flow rate and average system pressure. The additional air volume per ten-minute test required due to each testing condition resulting from the inclusion of a specific leakage diameter is shown in Fig. 6. As a result of the additional CA consumption required to overcome a leakage, the total energy consumption consumed by the compressor installed on the test bed witnessed a direct impact as portrayed in Fig. 7.

4.3. Results analysis

To analyse the effects of the results in terms of the financial and environmental impact of the CAS, the measured energy consumption for each 10-minute test were considered over a period of a whole year to acquire more realistic values. To do so, the CATB was assumed to operate for 6240 h per year.

Table 3
Additional cost (€) across one whole year of operation.

Leakage diameter	3 bar	4 bar	5 bar	6 bar
Control (0 mm)	149.52	192.08	229.85	285.00
0.5mm	+ 28.30	+ 29.62	+ 33.69	+ 37.29
1.0mm	+ 142.32	+ 167.02	+ 176.85	+ 190.76
1.5mm	+ 279.73	+ 369.05	+ 430.44	+ 469.53

To determine the incurred expenses associated with the financial pillar of sustainability, the average electrical tariff rate of the Maltese Islands for non-residential buildings that utilizes 5 million kWh of electricity a year was calculated to be 0.1199 €/kWh (Regulator For Energy & Water Services 2015). Table 3 highlights the additional costs incurred due to each leak at a specific pressure when compared to the benchmark (ideal) costs of the control experiment i.e. when the CAS was operated with no leakages.

The procedure was repeated to determine the additional grams of carbon dioxide equivalent (gCO_2e) that would otherwise be emitted into the atmosphere under each condition in order to analyse the effects on the environmental pillar of sustainability. The emissions rate associated to the electricity generated within the Maltese Islands was calculated to be 452 gCO_2e/kWh (;)ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, 2015, National Statistics Office - Malta, 2017, Regulator For Energy & Water Services, 2015; Willoughby, 2001). The resulting values are portrayed in Table 4.

The results depicted in Tables 3 and 4 highlighted the detrimental repercussions imposed on the financial and environmental pillars of sustainability. As a result of the quadratic increase in the energy consumption of the compressor due to leakages, the in-

Table 4
Additional $kgCO_2e$ emissions released over a period of a year.

Leakage diameter	3 bar	4 bar	5 bar	6 bar
Control (0 mm)	564	724	866	1074
0.5 mm	+ 107	+ 112	+ 127	+ 141
1.0 mm	+ 537	+ 630	+ 667	+ 719
1.5 mm	+ 1055	+ 1391	+ 1623	+ 1770

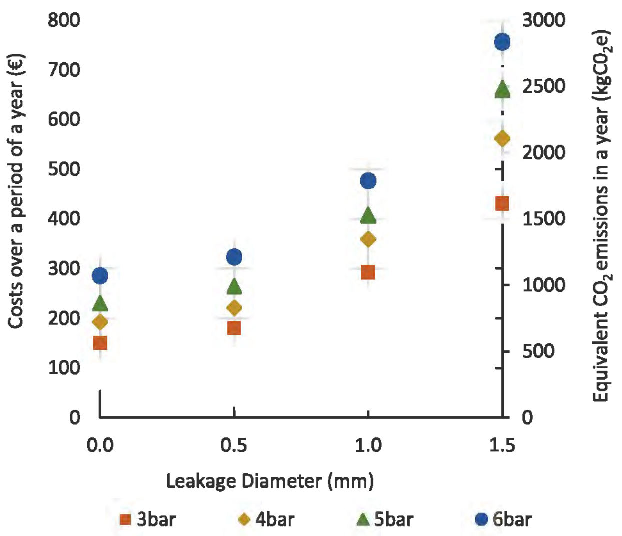

Fig. 8. Graphical representation of the detrimental impact of leakages on the environmental and financial pillar to operate a CAS for 6240 h per year.

creased costs and emissions also reflected this relationship as portrayed in Fig. 8.

Fig. 8 depicts that if the system was running under ideal conditions for a whole year, at the typical industry pressure standard of 6 bar, the incurred costs would amount to a total of €285 in electrical charges while also emitting approximately 1.1 tons of CO_2e to operate a typical double acting cylinder as used in this study. However, if a 1.5 mm leak is retained for a whole year at 6 bar, the cost of electricity surges to €755 while the emissions reach 2.8 tons of CO_2e. This result amounts to an increase of 165% in electrical costs and carbon emissions, per additional leak.

The total energy consumption required to supply CA to a leakage of 1.5 mm at 6 bar amounted to 3900 kWh of energy per year over 6240 h. According to Apap (University of Malta, 2016), the average energy output of 12 photovoltaic panels in Malta amounts to 4800 kWh of energy per year (3000 h of sunlight). Therefore, a single leak of 1.5 mm at 6 bar of pressure within the CATB consumes the equivalent energy consumption as the total energy generated by ten photovoltaic panels in Malta.

As a result of the relatively small 1.1 kW compressor utilized during the experiments, the energy results depicted in this paper were undervalued. According to the power consumption of the compressor installed within the test bed and the Maltese electrical tariff rates explained in the beginning of this section, it was calculated that the cost of CA for the CATB amounted to 1.93 €/m^3. This is equivalent to the cost of CA recorded in Table 1 by FESTO. However, FESTO (FESTO, 2013) carried out their case study within a plant air CAS which utilize compressors with a large power output to meet the CA demands of a whole factory. According to Dornfeld and Lee (2007) and Yuan (Yuan et al., 2006), plant air systems deliver the most inefficient form of CA within an industrial facility. When comparing plant air to point-of-use CAS (such as the CATB), Yuan et al. (2006) concluded that the two systems required 115 and 97 Wh/m^3 respectively.

This discrepancy between the two was also portrayed within this experiment whereby, it was calculated that the operational costs due to a leak of 1.5 mm at 6 bar increased by €470 in 6240-hours. On the other hand Table 1 shows that within a 24 h plant air CAS, the operational costs due to a 1.5 mm leak at 6 bar, surged by €1421 during 8760 h in one year. By adjusting the total operational time to 6240 h per year, which was adopted throughout this experiment, the plant air system analysed by FESTO (2013) incurred €1012 which is more than double the surges in electrical costs witnessed by this CATB (€470). This discrepancy is the result of several contributing factors which include; the scaling differences of the CAS, efficiency of compressors and the specific energy consumption amongst others.

This study also showed that an ULD can be used on the developed test bed to detect and quantify the impacts of CAS on sustainability. As an example, a 70 dB detection at 6 bar indicates that there is a leak of around 1.5mmin diameter which could potentially result in 1.8 tonnes of CO2 emissions and a further €470 in operational costs per year.

5. Conclusion

In conclusion, an effective understanding to adequately identify and approximate the size of leakages by using ULDs was gained. Moreover, the results showed that by successfully repairing one leak of 1.5 mm in diameter operating at 6 bar, this approach could potentially save more than 3900 kWh of electrical energy within one year. This amounts to €470 of additional electrical costs and 1.8 tons of carbon dioxide emissions according to tariff and emissions rates within the Maltese Islands. Such waste could easily offset the benefits gained from implementing sustainable energy sources. It was shown that a 1.5 mm leak could offset, 3900 kWh of energy which is equivalent to the total electrical energy generated by ten photovoltaic panels installed in Malta per year. A large CAS could easily include tens of unnoticed leakages along its distribution system which would ultimately have a direct effect on both the life cycle of production systems as well as products.

CAS are widely adopted due to the safety and reliability in the production and handling of CA. However, such attributes have caused an upsurge of CA applications without giving due consideration to the implications on sustainable manufacturing. Very often, an objective could be achieved more efficiently through alternate utilities. This study attempted to highlight these implications by presenting quantitative and qualitative results. These conclusions are aimed towards educating academia and business organisations by carrying out an assessment of financial and environmental CA implications.

6. Future work

Through the correct application of this experiment, future work will involve the application and repeatability of the methodology presented in this work within an industrial setting. Another interesting investigation would be to build on the results of this research work by analysing the CAS with the use of a dynamic model. Other future work opportunities will include the investigation of more energy saving opportunities within the CAS, such as identifying optimal compressor running periods and/or establishing the correct size of receiver tank for each system.

CRediT authorship contribution statement

Kyle Abela: Data curation, Formal analysis, Software, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Emmanuel Francalanza:** Conceptualization, Formal analysis, Software, Funding acquisition, Methodology, Resources, Supervision, Writing - review & editing. **Paul Refalo:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing - review & editing.

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