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Pneumatic Control for Sustainable Compressed Air Systems: Multi-criteria Optimisation for Energy Efficient Production

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Abstract

Compressed air is widely utilised in manufacturing processes across all industries due to numerous advantages associated with its use. However, the energy efficiency of compressed air generation is often very low, making pneumatic systems one of the most expensive processes in a manufacturing facility. Additionally, compressed air leakages further artificially increase the demand and decrease their efficiency and productivity. This study focused on identifying the effects of pressure and flowrate regulation on the energy efficiency and productivity of a pneumatic automation system. By combining these two control strategies, a reduction in air consumption was achieved while also maintaining the system's cycle time in order to minimise productivity loss. The assessed system included various leaks of different sizes at different locations. When implementing pressure regulation, a reduction in air consumption of up to 22 per cent was achieved. As expected, this also resulted in an increase in cycle time of up to 19 per cent, which was then reduced to 7 per cent by regulating the system's flowrate at the end of use. Multi-criteria optimisation was subsequently employed to identify the optimal control parameters for a balanced effect on both air consumption and cycle time, affecting energy efficiency and productivity, respectively.

Keywords: air consumption; compressed air; control; cycle time; energy efficiency; optimisation; sustainable systems

1. Introduction

The industrial sector is regarded as a major consumer of energy and natural resources, accounting for 38 per cent of the world's final energy use in 2021 [1]. The International Energy Agency states that the growth in the industrial sector's energy use must be restricted to less than 0.5 per cent per year to reach the Net Zero Scenario milestones set by the agency [1]. These milestones aim to reach net zero energy-related carbon dioxide emissions by 2050. To achieve this goal, the industrial sector must adopt a holistic approach with regards to improving the energy efficiency of all the systems and utilities used.

Compressed air (CA) is one such utility that has in recent years grown significantly in popularity within the industrial sector. In fact, the use of CA accounts to 10 per cent of the industrial energy consumption in the European Union [2]. This high percentage in energy consumption is caused by the fact that compressed air systems (CASs) are severely inefficient, with an average energy output of 10 to 12 per cent, as reported by several studies [3]. This has created a growing field of research and innovation, both from within the academic and the commercial sectors. This research focuses on increasing the energy efficiency of industrial CASs through different approaches, as several studies have documented that energy savings of 20 to 50 per cent can be achieved [2].

The goal of this study was to identify the effects of pressure and flowrate regulation on a typical pneumatic automation system operating with faults on the demand side, with the aim

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of reducing compressed air consumption while also maintaining the system's productivity. By employing multi-criteria optimisation, the energy efficiency of the pneumatic system could be increased whilst minimising any significant loss of productivity. As a result, energy savings could be realised by an industrial facility employing these control methods, without sacrificing production yield.

2. Literature Review

CA is considered as a significant power source in the manufacturing industry since it is safe to handle, clean, readily available and easily produced. It is regarded as the fourth utility after natural gas, electricity and water [2-4] as it is used to perform a wide variety of tasks, such as operating equipment driven by pneumatic components, cleaning machines and parts, and testing of finished products. A typical CAS contains several components, each belonging to one of two major subsystems: the Supply Side and the Demand Side. The Supply Side subsystem comprises equipment that carries out the generation and conditioning of CA while the Demand Side subsystem comprises the distribution and end use of the generated CA through pipes and end effectors [4].

2.1. Compressed Air System Inefficiencies - Leakages

Losses in a CAS are quite substantial due to the considerable number of components required to convert electricity into compressed air, leaving merely 5-10 per cent as an effective output [5]. Significant improvements can be achieved on the demand side of the CAS, where potentially half of the CA produced is wasted in the form of different inefficiencies [6]. Leakages in pneumatic distribution systems consume around 20 to 30 per cent of the produced CA, making them the main source of energy loss [6-8]. According to Saidur et al [9], this energy loss can also increase significantly due to poor maintenance, where leaks can consume as much as 50 per cent of the compressor output. Leaks can occur in several pneumatic constituents, including valves, hoses, filters and joints.

2.2. Energy Saving Measures – Pressure Reduction

Due to the importance of CA in industry, several energy saving measures have been researched and developed to mitigate the effects of leakages and other commonly occurring inefficiencies. These measures also aim to optimise the system's energy efficiency, since any potential savings in energy consumption directly improve the company's financial pillar [2].

One such energy saving measure commonly identified in studies is that CASs should always operate at the lowest functional pressure, since at higher operating pressures, more CA volume is provided to the end-use and ensuing leaks. In a study carried out at a company producing automotive interior components, Barringer et al. [10] highlighted that one of the main ways to reduce energy consumption of CASs was to decrease the overall system pressure to the lowest possible amount. As it is challenging to implement such change it was recommended that the system pressure is reduced in minor increments while equipment performance is checked over a one-week operation period. By doing so, the lowest functional system pressure can be identified. A CAS auditing software tool was then used to estimate that potential energy savings of around 22 per cent, equivalent to around €19,000/year could be accomplished by reducing the system pressure from 8.6 to 6.6 bar in this study.

2.3. Current Market Options

Manufacturers of pneumatic equipment such as FESTO, Aventics and SMC have also focused on developing CA monitoring and management systems. The FESTO MSE6 series Energy Efficiency Modules [11] allows for parameter monitoring and automatic control of the CA supply. This set-up recognises whether the system is in operation or at idle thus, being able to shut off CA supply. Similarly, SMC developed an Air Management System series of products [12], which carry out similar control functions. Aventics produces a Smart Pneumatics Monitor [13] that makes use of proprietary fieldbus equipment to collect data. This product is able to detect air leakages during different processes by continuously monitoring CA and energy consumption and identifying any increases in flowrate beyond specified limits. This information, can also be utilised to extract additional system details, including component wear and system energy efficiency.

2.4. Multi-criteria Optimisation

When the optimisation of a CAS is being considered, two main conflicting criteria arise, where satisfying either one comes at the expense of the other. These criteria are air consumption and cycle time. As air consumption decreases, less air is available to provide energy to the components. Hence, individual motions take longer, and the cycle time increases. On the other hand, if the cycle time increases, more air is consumed due to the longer period of operation. Similar scenarios of multiple conflicting criteria are common in most optimisation problems, thus multi-criteria optimisation methods have been developed to provide a mathematical framework to arrive at the decision maker's optimal solution. Some of the commonly used methods include the Weighted Sum Model (WSM), Lexicographic Order, ε-Constraint, and Physical Programming [14]. Such multi-criteria optimisation methods have been employed in many studies involving conflicting criteria, but as of the time of writing, no research has been discovered with regards to the use of these methods in the optimisation of CAS. By utilising these methods, specific parameters can be identified which provide a significant reduction in air consumption without severely affecting the system cycle time. The effect on cycle time must be respected since its increase would result in a lower production output, which in industrial operations would result in additional costs.

2.5. Identification of Research Gap

While reviewing the available literature it was observed that a research gap exists with regards to demand side control strategies that primarily utilise the system's parameters.

Researchers have focused on increasing the efficiency of CASs by monitoring and modifying both the supply and demand sides [4-9]. Research has also been conducted on the effects of reducing the system's pressure, which resulted in an increase in energy efficiency [10]. This suggests that potential reductions in air consumption could be realised by varying system parameters while inefficiencies are present during operation, whilst also minimising the effect on cycle time.

3. Methodology

The aim of this study was to methodically generate and evaluate control functions that utilise pressure and flowrate regulation which are suitable for pneumatic systems that are operating with an inefficiency present. By doing so, the energy efficiency and productivity of the CAS could be increased by mitigating the fault's effects, thus increasing the sustainable performance. A control function was designed to be implemented in such a pneumatic system where a source of inefficiency was introduced during operation. Thus, by implementing the control function, reductions in air consumption could be achieved while the system continued operating with an inefficiency present, until the required maintenance could be carried out.

Since several sources of inefficiencies on the demand side of pneumatic systems have been discussed in literature [2-7], this study focused on leaks as the main source of inefficiency. A multi actuator system was used to simulate a simple industrial CAS. The goal of this setup was to allow for the implementation of the control function in similar systems in industry, so that comparable results could be achieved.

3.1. Experimental Setup

To investigate leak effects, two specific locations were designated to induce faults during the experiments. As shown in Fig. 1, the leak locations allowed for the leak to be generated either upstream to the pick-and-place system or within the pick-and-place itself. The second leak location (Leak location 2) created an intermittent leak, since CA would only flow through the leak during the retraction stroke of the vertical cylinder. By utilising these two leak locations, the effect of the control function on leaks situated in different parts of a CAS could be evaluated. These locations also simulated two types of leaks commonly found in industry, as discussed by Kosturkov et al. [15]: leaks in pipes and actuator specific leaks. Two leak diameters were also determined: 0.5 and 1.0 mm. These two diameters were chosen since leaks of a diameter larger than 1.0 mm would cause the system to fail due to the loss in flowrate, whilst leaks smaller than 0.5 mm would not have a significant enough effect on the system's performance. The setup included several sensors to collect data from a pick-and-place system, as shown in Fig. 1. Two pressure sensors and one flowrate sensor were used to monitor the pressure and flowrate at different locations. The first pressure sensor (i.e. P1) monitored the upstream pressure, whereas the second pressure sensor (i.e. P2) monitored the pressure downstream to the fault and this made it possible to monitor pressure drops caused by leaks at different locations. Both pressure measurements were made using a Wika S-20 transducer. As discussed by Borg et al. [16], accuracy has a significant effect on the performance of the monitoring system. Thus, the Wika S-20 pressure sensor was used due to its higher accuracy. Flowrate readings were taken using sensor F which was an SMC PFMB7201 flowrate sensor.

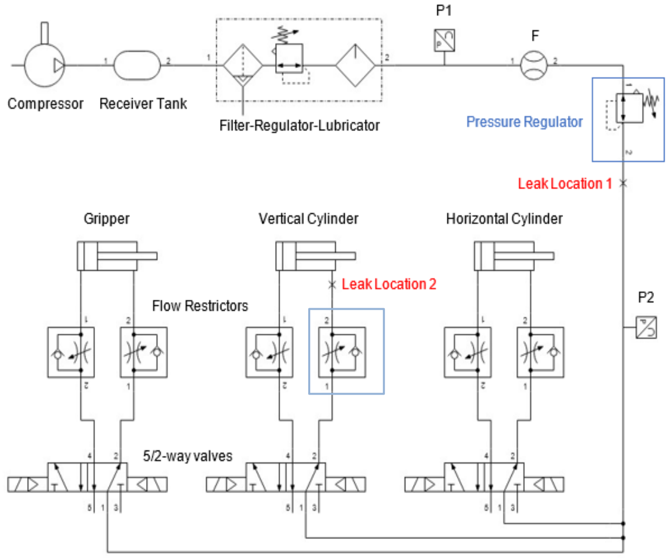

Fig. 1. The pneumatic control schematic.

The pick-and-place system simulated an industrial operation as illustrated in Fig. 2. The system incorporated a two jaw gripper, a vertical compact rod guided cylinder (SMC MGPM12-80Z) and a horizontal rod less cylinder (SMC EMY1C25G-800), both double-acting cylinders. Each cylinder was equipped with two reed switches to monitor the positions of each cylinder, i.e. whether the cylinder was retraced or extended.

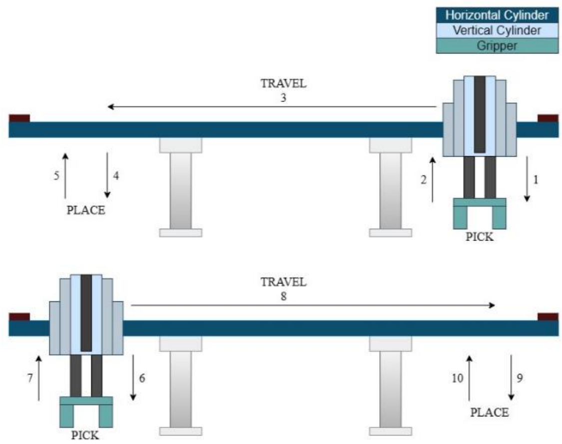

Fig. 2. The pick-and-place cycle; top: cycle steps 1-5, bottom: cycle steps 6-10

3.2. Formulation of the Control Function

To mitigate fault effects whilst minimally affecting the cycle time, a combination of two control strategies was explored in the form of pressure and flowrate adjustments. The first strategy revolved around regulating the system pressure using a pressure regulator. The second control strategy made use of a flow restrictor, adjusting flow through the meter-out connection of the vertical actuator, making it possible to regulate flow along the fault. The control parameters chosen allowed for changes to be made in the performance of the system without the need of any major modifications. By utilising components that are present in most industrial pneumatic systems: pressure regulators and flow restrictors, similar control strategies could also be easily applied in industry.

3.3. Design of Experiments

Throughout this study, a Design of Experiment approach was taken to appropriately plan the structure of the experiments. To monitor the system response, the CA flowrate, the downstream pressure P2 and the total cycle time of each pick-and-place sequence, were considered. These variables were chosen to evaluate the effectiveness of different control parameters, comparing the effects on each variable. Several variables were kept constant during the experiments including the travel distances of the actuators, the mass of the part picked and the supply pressure. The latter was kept constant at 6 bar. The parameters varied during the tests are shown in Table 1. The flow restrictor settings represent the level of restriction imposed on the component's flowrate, where setting 11 signifies no restriction (restrictor fully open) while setting 6 restricts the flowrate downstream to the restrictor by around half the upstream amount.

Table 1: Experimental variables and levels

Parameter	Levels
Pressure Regulator Setting	4, 6 bar
Flow Restrictor Setting	6, 11 (11 = fully open)
Leak Diameter	0.5, 1.0 mm
Leak Location	1, 2

Since several factors with different levels were required, a full factorial design was chosen so that all possible combinations could be evaluated. The experimental schedule was generated, where the runs were split into four groups depending on the leak scenario, as shown in Table 2. Each run comprised ten cycles of the pick-and-place operation, which was repeated three times. An initial run (Run 0) was carried out without any leaks present, in order to produce a benchmark to which the experimental runs could be compared. In this run, the pressure regulator was set to 6 bar and the flow restrictor was set to 11, so that the system operated with the highest operating pressure and without restrictions. By doing so, the effects caused by the leaks and the control functions could be measured. The first run of each leak scenario group was considered as the fault run (Runs 1, 5, 9, 13), where the system operated with the respective leak present, without any control functions applied. This made it possible to quantify the fault effects whilst better comprehending the system response. Three experimental metrics were utilised to analyse the results:

(1) cycle time which represented the time taken by the system to complete one cycle of the operation,
(2) air consumption which represented the air consumption of the CAS for each run,
(3) the operating pressure taken directly from reading P2.

Table 2: Experimental schedule

Run	Leak Location	Leak Diameter (mm)	Pressure Regulator Setting (bar)	Flow Restrictor Setting (11=open)
0	/	/	6	11
1	1	0.5	6	11
2				6
3			4	11
4				6
5	1	1.0	6	11
6				6
7			4	11
8				6
9	2	0.5	6	11
10				6
11			4	11
12				6
13	2	1.0	6	11
14				6
15			4	11
16				6

3.4. Multi-criteria Optimisation Method

From the multi-criteria optimisation methods mentioned in Section 2.4, the WSM is most commonly used when the optimal solution maximises a desirable response whilst minimising an undesirable objective [17-19]. This method removes most of the complexity that surrounds other optimisation methods, is computationally simple and thus can be easily applied to a diverse range of problems [14]. Since this study was concerned with the optimisation of air consumption whilst minimising the increase in cycle time, it was determined that the WSM was best suited to identify the optimal solutions. The model combines different criteria with corresponding weight factors, resulting in a single score for each scenario. The WSM formula was adapted to suit this study as shown in Equation (1). By dividing the cycle time and air consumption results of each run by the results of each respective benchmark, the differences between each run and the benchmark run could be determined as dimensionless values. These values would then be multiplied by the criteria weights, resulting in a score between 0 and 1. The optimal solution would be the run with the score closest to 1, that is the run with the results closest to the benchmark run.

$$A_{WSM-score} = \left(w_1 \times \frac{CT}{CT_0}\right) + \left(w_2 \times \frac{AC}{AC_0}\right) \quad (1)$$

w_1, w_2 *are the criteria weights* $(0 < w_i < 1)$ $(w_1 + w_2 = 1)$,
CT *is the cycle time of the specific run,*
CT_0 *is the cycle time of the benchmark* (21.70 s),
AC *is the air consumption of the specific run,*
AC_0 *is the air consumption of the benchmark* (10.65 NL)

To achieve the desired results, the criteria weights were both set to 0.5 so that equal importance was given to both air consumption and cycle time. Different combinations of criteria weights could be evaluated depending on the desired result, such as 0.75 for cycle time and 0.25 for air consumption in the case of an industrial system where productivity is of higher importance. In such a scenario, a higher importance would be given to the effect on cycle time since this criterion has the higher weighting, whilst the effect on air consumption is still taken into consideration due to the 0.25 weighting.

4. Results and Discussion

Once all the experimental runs were concluded, the results were analysed according to the experimental metrics. The Weighted Sum Model was then employed to identify the optimal parameters to increase the system's performance from both CA consumption and productivity perspectives.

4.1. Analysis of Results

Fig. 3 shows the results for the total cycle time and air consumption of each run. Each run was compared to the benchmark as shown using the percentage difference values. Runs 14 and 16 were inconclusive since the pick-and-place system did not have enough pressure (and hence flow) to execute the pick-and-place operation due to the respective control parameters in these two runs.

When analysing the results, it was observed that runs 1 to 8 had very similar increases in cycle time. These runs belonged to the first two leak scenarios, with a common leak location (1). Although runs 5 to 8 were exposed to the larger leak diameter of 1.0 mm, the increase in cycle time was identical to the previous runs (0.5 mm diameter). It can be concluded that since the leak was located further upstream, the system had enough pressure to execute the runs in identical cycle times for both diameters and only excess pressure was 'consumed' by the leak. When comparing the air consumption results for the same runs, it was also observed that the runs with the larger leak diameter had significantly higher increases. This further supported the conclusion that the pick-and-place system was operating at a higher pressure than required, and thus the excess pressure was being exhausted through the leak.

Similar comparisons could not be reliably made for the other two leak scenarios due to the inconclusive results, but a higher increase in cycle time was still observed, as compared to the first two scenarios. This increase was due to the second leak location resulting in an intermittent leak that caused a pressure drop directly to the vertical cylinder. Thus, during the cylinder's retraction stroke, a significant portion of CA was consumed by the leak, resulting in less pressure available for the cylinder. Since the leak was located upstream to a single component, rather than induced upstream to the entire system, the change in air consumption of each run was significantly less than those reported prior, as CA was only flowing through the leak during the retraction stroke.

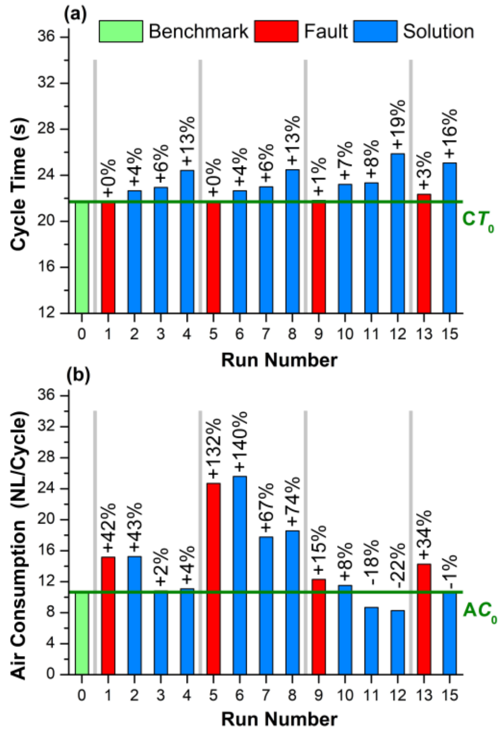

Fig. 3. (a) Cycle time results; (b) Air consumption results.

4.2. Multi-criteria Optimisation Results

The WSM was employed to identify the runs with the most balanced effect on both cycle time and air consumption. These runs would provide a significant decrease in air consumption without significantly increasing the cycle time. The optimal run in each leak scenario was achieved when the resulting score was closest to 1. These were: Run 3, Run 7, Run 12, and Run 15. The WSM scores for each run are shown in Fig. 4, where the optimal score of 1 is marked. By referring to the experimental schedule shown in Table 2, the control parameters of the optimal runs were identified. In all four runs, the pressure regulator was set to 4 bar, thus resulting in a significant decrease in air consumption. This correlates to the results of several studies found in literature [14], as discussed in Section 2.2. This reduction in air consumption resulted in an increase in total cycle time since less pressure was available to the system. The increase in cycle time was then mitigated by regulating the flowrate, where the flow restrictor upstream to the vertical cylinder was set to setting 11 (fully open) in three out of the four runs. This increase in flowrate allowed the vertical cylinder to execute the retraction stroke quicker, resulting in a reduced total cycle time. In Run 12, the flow restrictor was set to setting 6, which resulted in a significant increase in cycle time.

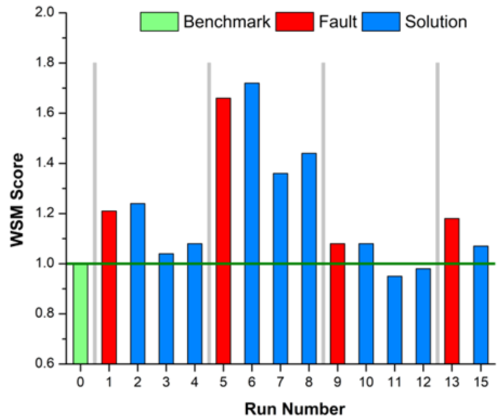

Fig. 4. WSM scores for each test performed.

Since equal weighting was given in the WSM for both air consumption and cycle time, the increase in cycle time in Run 12 was compensated by the high decrease in air consumption. This resulted in a WSM score very close to 1, even though it had the highest cycle time from all the runs. This scenario can be avoided by setting different criteria weights as discussed in Section 3.4.

5. Conclusion

In this study, a research gap was identified pertaining to the effects of varying system parameters on air consumption and cycle time whilst a CAS is operating with inefficiencies. To answer this gap, the effects of pressure and flowrate regulation on a CAS operating with faults were evaluated. A multi-criteria optimisation method was employed to identify the optimal control parameters that resulted in considerable savings in air consumption without having a significantly detrimental effect on cycle time. From the obtained results, the highest reductions in air consumption were achieved when the system was operating at a pressure of 4 bar, resulting in CA savings of up to 22 per cent. This reduction in air consumption resulted in an increase of 19 per cent in cycle time, which would significantly impact the productivity of an industrial CAS. By regulating the flowrate of a single element in the system, the increase in cycle time was reduced significantly for each leak scenario.

This study shows that a CAS operating with leaks at different locations can be controlled by employing multi-criteria optimisation to identify the optimal control parameters. These control parameters allow for reductions in air consumption to be achieved whilst the system's productivity is not jeopardised. This work aims to contribute towards a greener and more financially sustainable industry by demonstrating that the energy consumption of CASs in industry can be reduced by optimising system parameters, without sacrificing productivity of the system.

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