Article

An Integrated Energy Simulation Model of a Compressed Air System for Sustainable Manufacturing: A Time-Discretized Approach

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Abstract: A compressed air system (CAS) is one of the most common and energy-consuming systems in manufacturing. To practice more economically and environmentally sustainable manufacturing, manufacturers need ways to reduce the energy costs and carbon footprint, resulting from a CAS in their production systems. While preliminary energy studies on a CAS and on machining processes are available separately, existing research studies rarely analyze energy costs using a tool that considers both a CAS and production systems. Therefore, in this study, we propose an energy simulation tool that combines a CAS and a production system to evaluate the effects of a CAS and production parameters on energy consumption and costs at a factory level. In particular, we develop a time-discretized algorithm for simulating a CAS to accurately consider the dynamics of CAS parameters such as pressure and flow rate. From 48 simulation case studies, we show that changes in a CAS such as proper HP sizing, a reduction in compressed air leaks, and a decrease in the discharge pressure can increase productivity and reduce energy costs by up to 11%. The simulation analysis from this study suggests a way to help manufacturers and researchers find more sustainable ways to achieve energy-efficient configurations for production systems including a CAS.

Keywords: simulation; compressed air system; production system; energy consumption; energy cost

1. Introduction

The industrial sector accounts for about 32% of the total energy consumption in the United States [1], making it an important factor to consider when analyzing economic and environmental sustainability. Specifically, manufacturers constantly need to analyze the energy consumption in their facilities to reduce energy and resource consumption in order to practice sustainable manufacturing. The monthly electricity cost for manufacturers generally comprises an energy charge (monthly total kWh × USD/kWh) and a demand charge (monthly peak kW × USD/kW). When lowering their kWh consumption or peak kW, manufacturers can reduce not only energy costs but also resource consumption since high demands from consumers require power suppliers to invest additional capital into the building infrastructures related to a power system [2].

A great deal of attention has been paid to sustainable manufacturing, with sustainable manufacturing studies focusing on a variety of aspects of production [3–7]. For example, researchers have investigated the green and sustainability performance of a production system by assessing the applicability of lean manufacturing [8] and Industry 4.0 standards [9,10]. Not many studies, however, have been made of use of a compressed air

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Simulation techniques are often used to create and monitor physical processes. In terms of sustainable manufacturing, the energy simulation technique can identify a variety of opportunities for greater process sustainability, such as improvements in energy consumption. For example, researchers have applied simulation techniques to material removal processes such as milling and turning to evaluate the impacts of various production parameters on energy performances and to estimate the factory level energy costs [2,12]. Additionally, simulation methods have been used to estimate the power required by a CAS by using actual power data [11,13]. The application of simulation techniques to a manufacturing system is valuable in that they can help test and adjust relevant production parameters without applying new production plans for a real system.

While energy simulation studies of a production system and a CAS together would be helpful in studying the energy consumption of a manufacturing system, these systems have only been studied separately. In addition, the production energy simulation studies have not been conducted to see the effects of production parameters and CAS parameters on energy performance, including the energy consumption and relevant costs. Thus, it would be beneficial for improving the manufacturing sustainability with an energy simulation study including both a production system and a CAS to be conducted to see the combined and individual effect of each on the energy performance measures.

2. Literature Review

A typical production setup consists of machines along with various equipment-supporting machining processes. A CAS is one of the most commonly used systems to support the production processes throughout different types of manufacturing industries [14]. A variety of pneumatic systems with tools can be supported by a CAS [15]. In addition, a CAS can be used to provide compressed air for machining operations such as cleaning and air cooling, as well as for energy storage purposes [16–18]. Some applications of compressed air energy storage systems can be the operation of active distribution systems [19] and vehicle transportation [20]. CASs account for approximately 10% of the total electricity consumption in the United States [21]. The energy cost of a compressor during its life cycle is usually 75% or more of the overall operational cost [22]. In terms of energy costs, manufacturers can achieve 20% to 50% energy savings by improving the compressed air systems [23]. Because a CAS is one of the highest electricity consumers, if manufacturers better understand the energy consumption and associated energy costs of a CAS, energy costs can be reduced, and manufacturing sustainability can be improved.

A CAS can be divided into a supply side and a demand side. The supply side of a CAS consists of an air compressor and related components such as an air filter, dryer, and air receiver; the demand side of a CAS includes the various equipment that uses compressed air and the distribution system to provide compressed air [14]. Out of the various compressor types, three of the most commonly used CASs in manufacturing industries are the rotary screw, reciprocating, and centrifugal compressors [11,15]. As the demand for compressed air varies throughout the production process, a CAS is equipped with certain controls to efficiently match the supply and demand. A CAS is generally equipped with one of six control modes: start/stop, load/unload, modulation, dual control, variable displacement, and variable speed controls [24]. A start/stop control strategy turns a driving motor on or off based on the pressure settings. In the load/unload control, the motor runs continuously, and an air compressor unloads when the discharge pressure is adequate. In other words, an air compressor supplies the compressed air until the discharge pressure is met (that is, the loading condition) and supplies no new compressed air until the system pressure
drops to a preset pressure level (that is, the unloading condition). Therefore, a CAS with the load/unload control is usually equipped with an air receiver (that is, an air tank) that maintains a constant supply of pressure during the unloading conditions [14]. In a CAS equipped with modulation controls, the output of the compressor varies based on the flow requirements. The dual control is a modification of load/unload control that allows a compressor to stop after running in the unloaded condition for a certain amount of time. The variable displacement control uses various valves to reduce the compressor displacement without reducing the inlet pressure. The usage of variable speed control allows a compressor to continuously adjust the motor speed within a variable range based on the demand requirements. For our research purposes, a rotary screw air compressor with a load/unload control system is considered since it is the most commonly used CAS [11,13,14].

Usually, the power rating of a CAS is expressed in horsepower (HP) and is provided by a CAS manufacturer. However, the air compressor motor can draw more or less power than the rated power under particular conditions such as full-load and part-load operations. Furthermore, the average (avg.) power (kW) consumed by a CAS can be calculated by converting the HP requirement into kW using available formulas. The avg. power required by a CAS (W_{CAS}) can be defined as the avg. power required to operate a CAS during its operation time. For the load/unload controls, a CAS does not require the maximum rated power or the full-load power throughout the operation time, as the power required varies based on the loading and the unloading conditions of a CAS. Hence, a CAS equipped with a load/unload control system would work on part load and load/unload based on the defined pressure settings on a CAS [11,13]. For the part-load operation of a CAS, W_{CAS} depends on the avg. loading power and avg. unloading power of the air compressor. The loading power can be defined as the power required by a CAS during the loading condition, and the unloading power can be defined as the power required by a CAS during the unloading condition. Generally, for a CAS working on a part-load, W_{CAS} can be calculated as W_{CAS} = (H_{F}) \times (B_{CF}) \times (1/E_{m}) \times [R_{L} + (R_{HF} \times R_{U})], where H_{F} = the HP consumed by the air compressor during the loading condition, B_{CF} = the conversion factor to convert HP to kW = 0.746 kW/HP, E_{m} = the efficiency of the air compressor motor, R_{L} = the proportion of the time a CAS is running in the loading condition, R_{HF} = the proportion of the full-load HP of the air compressor consumed during the unloading condition, and R_{U} = the proportion of time a CAS is running in the unloading condition [14]. Rotary screw air compressors generally draw about 105% to 120% of the rated power at the loading condition and 20% to 60% of the loading power when unloaded [13].

In industries, a common practice to estimate the full-load power is to assume a 15% continuous service factor of a motor and use two-thirds of the service factor. In other words, the full-load power is estimated as 10% above the rated HP of the air compressor (H_{R}) or 110% of H_{R}. Furthermore, 30% of the loading HP can be considered as a good HP consumption estimation for the unloading condition of the rotary screw air compressors [14]. Therefore, the loading and the unloading HP of the rotary screw air compressors can be estimated as 110% of H_{R} and 30% of the loading HP (33% of H_{R}), respectively.

The time duration of the power requirement for the loading and the unloading of a CAS depends on the loading and unloading time of an air compressor. The loading time of a CAS can be defined as the period between the time when a CAS starts to load (supply of compressed air) and the time when a CAS starts to unload (no supply of compressed air). Furthermore, the unloading time of a CAS can be defined as the period between the time when a CAS starts to unload and the time when a CAS starts to load. Since a CAS with the load/unload control system is equipped with an air receiver, the fundamental equation governing the dynamics of the air receiver can be used to estimate the loading and the unloading time of a CAS. The fundamental equation governing the dynamics of the air receiver is given as t_{p} = (V \times |P_{final} - P_{initial}|) / (F_{R} \times P_{b}), where t_{p} = the time to fill or empty the air receiver (minutes (min.)), V = the size of the air receiver (cubic feet (cu ft)), P_{final} = the final air receiver pressure (psig), P_{initial} = the initial pressure inside the air
receiver (psig), \( F_R \) = the compressed air supply or demand flow rate (cubic feet per minute, cfm), and \( P_a \) = the absolute atmospheric pressure (psia) = 14.7 psia [15]. The loading time of a CAS (\( t_L \)) can be considered as the time taken by an air compressor to fill the air receiver until the final air receiver pressure is equal to the discharge pressure. Then, for the estimation of \( t_L \), \( t_p \) can be modified as \( t_L = (V \times (P_U - P_L))/((S - C) \times 14.7) \), where \( P_U \) = the discharge pressure/unloading pressure (psig), \( S \) = the compressed air flow rate (supply) from the air compressor to the air receiver (cfm), and \( C \) = the compressed air flow rate (consumption or demand) from the air receiver to the equipment (cfm). Furthermore, the unloading time of a CAS (\( t_U \)) can be considered as the time taken for the pressure in the air receiver to drop until the pressure at which the air compressor starts to load. Then, for the estimation of \( t_U \), \( t_p \) can be modified as \( t_U = (V \times (P_{U,I} - P_L))/((S - C) \times 14.7) \), where \( P_L \) = the pressure at which the air compressor starts to load/unloading pressure (psig). Hence, the equation can be used as the governing law for a CAS operating on the load/unload control to estimate the loading and the unloading time. We believe that the equations for \( t_L \) and \( t_U \) can be modified to estimate the dynamic change in the air receiver pressure by discretizing the loading and the unloading time of a CAS. Additionally, \( P_U \) has a significant effect on \( S \). Generally, \( S \) at a given \( P_U \) is provided by the manufacturer of the air compressor. For calculation purposes, \( S \) at different values of \( P_U \) can be estimated by using Boyle’s law as \( S = (S_R \times (P_{U,I}/P_U))/P_{U,I} \), where \( S_R \) = the manufacturer-rated compressed air flow rate from the air compressor at the rated discharge pressure (cfm) and \( P_{U,I} = \) the manufacturer rated discharge pressure (psig) [25].

To identify potential energy-saving opportunities for a CAS, extensive research studies related to the energy consumption of a CAS have been performed. Researchers have found that various factors such as air leakages, the usage of variable speed drives, and reduction in the discharge pressure are critical factors in the reduction of CAS energy costs [21,26]. Furthermore, small modifications in a CAS can result in large energy savings. Some small modifications impacting the energy savings can include reducing leaks, matching supply with demand, reducing the pressure setting if low pressure is adequate, and so on [21]. For example, in an unmaintained manufacturing plant, air leaks can account for about 20% of the total compressed air production capacity, and implementing a regular leak maintenance program can reduce the leaks to be less than 10% of the compressor output [14]. Additional modifications such as a reduction in the air compressor’s inlet temperature and utilizing waste heat from the air compressor can also lead to significant energy savings. Other factors such as motor efficiency and the usage of aftercoolers also impact energy consumption. Moreover, studies have found that the type of compressor control and proper compressor sizing are two of the most important factors influencing the cost of compressed air [13]. The annual operating costs for oversized compressors and the compressors operating in inefficient control modes are extremely high. Therefore, for our research, factors affecting CAS operation such as leak intensity, air compressor sizing, air demand, and pressure setpoints can be considered. Additionally, researchers have simulated CAS power profiles to estimate energy savings based on collected power data [11,13]. We also collect and use CAS power data to validate our model.

For manufacturing processes, the processing rate has been identified as the main component of an energy model based on thermal equilibrium [27]. Energy models for various material removing processes such as milling, turning, and drilling have been developed by researchers to evaluate the machine energy consumption. For example, an empirical model was proposed to predict the energy consumption for a material removal process such as milling or turning based on the material removal rate (MRR) [28]. In addition, empirical models based on production parameters such as cutting speed, feed rate, spindle speed, depth of cut, and so on have been developed for milling [29], turning [30], and drilling processes [31]. Additionally, researchers have experimentally evaluated the mathematical models that consider the impact of various production parameters in optimizing the material removing process and energy consumption [28,32]. To estimate the processing power of processes such as milling and turning, various studies have considered
the machining power as a linear function of the MRR as power \( (kW) \approx b_2 + b_1 \times \text{MRR} \), where \( b_2 \) = the idle power of the machine (W) and \( b_1 \) = the specific energy consumption \( (W \times \text{min/mm}^3) \) [33–35].

Considerable efforts have been made to study the applications of simulation approaches in sustainable manufacturing systems to determine the power demand of machines and energy consumption as a way to estimate electricity costs. For example, one study analyzed production rate using a ratio of processing amounts to processing time to model total utility cost [34]. In another study, simulation models were used to evaluate the demand charge and energy charge [36]. Additionally, a systematic simulation method has also been proposed to estimate the machine-level power demand for various manufacturing processes such as milling, turning, and welding with the help of readily available production parameters [12].

If time-series power data for a CAS is available, the energy consumption of a CAS can be estimated correctly. Usually, it is hard to obtain time-series power data without disrupting real production; this makes the simulation method very useful. No known studies using a simulation approach have yet examined a CAS in conjunction with a production system to identify opportunities to save energy costs. In other words, even though studies related to CAS power consumption and machine-level power consumption are available, an electrical demand simulation tool integrating the power demands of both a CAS and production systems has not been thoroughly investigated. Therefore, there is a need to consider a CAS and machine-level power together to identify and evaluate the resource- or energy-saving opportunities at the factory level to improve manufacturing sustainability. Since a CAS is one of the most vital and energy-consuming systems in any manufacturing facility, we need to build and study energy simulation models integrating the production lines and a CAS to see the combined and individual effects of the production parameters and CAS parameters on energy performances for sustainable manufacturing.

In response to the aforementioned research gap, this study proposes a simulation model integrating a production system and a CAS to investigate the effects of production or CAS parameters on energy consumption, peak kW, and energy costs at a factory level. In particular, we propose a new approach for discretizing simulation time in applying a formula with pressure, air receiver volume, and compressed air flow rate for a CAS. In addition, to accurately simulate the combined system for a CAS and production lines, we connect and apply two simulation techniques: DES and numerical simulation. DES is used to create a variety of production activities including CAS and production machines. Then, the results from the DES are plugged into the numerical simulation to generate time series power from the CAS, machines, and the entire system. Considering a total of 48 cases, we closely examine CAS and production parameters affecting the energy performance of a
combined production system. Since the proposed method aims at reducing resource and energy consumption at manufacturing facilities, this study can be beneficial to industrial as well as academic communities. More specifically, this study will help academic researchers and industrial practitioners learn how to improve productivity and save energy costs by showing the potential opportunities for both CAS operations and production factor adjustments. We especially consider real CAS operation parameters such as air leaks and unregulated compressed air consumption on the machine side. Therefore, manufacturers can test the combination of various CAS and production parameters before applying them to a real system as part of their sustainable manufacturing practice. Additionally, the proposed tool can be useful in generating the time-series power demand at a CAS, machine, or factory level. The time-series power demand data can then be studied by researchers and manufacturers to build a better production schedule to reduce the peak demand and demand charge by shifting power demands. The rest of the paper is organized as follows: In Section 3, an energy simulation model considering a CAS and machines is proposed. In Section 4, the case study results from the proposed simulation model are presented. Section 5 then provides the discussion and conclusion of the findings from this study and suggests future directions for research.

3. Energy Simulation Models

This section provides the energy simulation model of a rotary screw CAS with the load/unload control integrated with the machines to estimate power use at the factory level. After providing the energy simulation technique at a CAS, machine, and factory levels, we present a validation of the proposed model by comparing estimated results with real CAS power data.

3.1. CAS Power Models

A CAS power profile with load/unload control, as shown in Figure 1, can be generated by estimating the following four parameters: (i) power (kW) required by a CAS during the loading condition \( W_L \), (ii) power required by a CAS during the unloading condition \( W_U \), (iii) CAS loading time for each load cycle \( t_L \), \( t_L_1, t_L_2, ..., t_L_M \), and (iv) CAS unloading time for each unload cycle \( t_U \), \( t_U_1, t_U_2, ..., t_U_M \), where \( M \) is the total number of loading/unloading cycles for a CAS.

![Figure 1. CAS power profile estimation for load/unload control system.](image)

To estimate \( W_L \) and \( W_U \), we use the loading HP as 110% of \( H_R \) and the unloading HP as 33% of \( H_R \), and then \( W_L \) and \( W_U \) can be estimated as follows [14]:

\[
W_L = H_R \times B_{CF} \times \left(\frac{1}{E_m}\right) \times 1.10
\]
\[ W_U = H_R \times B_{CF} \times (1/E_m) \times 0.33 \] (2)

t_L and t_U for each load/unload cycle can be estimated from the fundamental equation governing the dynamics of the air receiver provided as follows [15]:

\[ (t_L)_j = \frac{V \times (P_U - P_{\text{initial}})}{(S - C_j) \times 14.7} \] (3)

\[ (t_U)_j = \frac{V \times (P_{\text{initial}} - P_L)}{C_j \times 14.7} \] (4)

where \((t_L)_j\) = CAS loading time for \(j\)th load/unload cycle (min) with \(j = 1, 2, \ldots , M\), \(C_j\) = summation of all the compressed air demand during \(j\)th load/unload cycle (cfm), and \((t_U)_j\) = CAS unloading time for \(j\)th load/unload cycle (min). After a CAS power profile is obtained, \(W_{CAS}\) can be estimated as follows [14]:

\[ W_{CAS} = (W_L \times R_L) + (W_U \times R_U) \] (5)

\(R_L\) and \(R_U\) in Equation (5) can be estimated from a CAS power profile as the ratio of the time that a CAS runs loaded and unloaded, respectively, to the total time a CAS is working. Therefore, if there are a total of \(M\) number of load/unload cycles for a CAS, \(R_L\) and \(R_U\) can be estimated as follows [14]:

\[ R_L = \sum_{j=0}^{M} \left( \frac{(t_L)_j}{(t_L)_j + (t_U)_j} \right) \] (6)

\[ R_U = 1 - R_L = \sum_{j=0}^{M} \left( \frac{(t_U)_j}{(t_L)_j + (t_U)_j} \right), \] (7)

To simulate power demand for a CAS, we need a simulation algorithm to reflect the dynamic change of CAS parameters, such as pressure over time. For that, we developed a CAS simulation algorithm based on the change in the pressure level inside the air receiver by discretizing the simulation time into small units (0.01 min). In other words, we discretize the simulation time into “\(N\)” fixed time intervals (see Figure 2) and update the pressure after each time interval “\(t\)” (\(t = 0.01\) min) based on the loading and the unloading condition of a CAS. The fundamental equation governing the dynamics of the air receiver is applied for each discrete time interval to dynamically update the pressure in the air receiver for the loading and the unloading condition of a CAS. More specifically, we discretize the loading and the unloading time of a CAS and fix \(t_L\) and \(t_U\) in the Equations (3) and (4) as “\(t\)” to consider the change in pressure inside the air receiver for the loading and unloading conditions after a specified discrete time interval of “\(t\)” as follows [15]:

\[ \Delta P_L = (P_U - P_i) = \frac{(S - C_i) \times t \times 14.7}{V} \] (8)

\[ \Delta P_U = (P_i - P_L) = \frac{C_i \times t \times 14.7}{V}, \] (9)

where \(\Delta P_L\) = pressure change during the loading condition, \(P_i\) = pressure inside the air receiver at an \(i\)th time interval (psig) with \(i = 1, 2, \ldots , N\), \(C_i\) = summation of all the compressed air demand at an \(i\)th time interval (cfm) (total compressed air demand of machines + total intensity of compressed air leakages at \(i\)th time interval), \(t\) = time interval after which the pressure inside the air receiver will be updated = 0.01 min, and \(\Delta P_U\) = pressure change during the unloading condition.
In Equations (8) and (9), we can fix \( V, S, \) and \( t \) as given information. In addition, we can also determine all the machine-level compressed air demands (\( C_{M_i} \)) and the total intensity of compressed air leakages (\( L \)) to obtain \( C_i \). As we have a specific value of \( C_i \) in Equations (8) and (9) along with \( V, S, \) and \( t \), a CAS simulation model is regulated based on the defined pressure setpoints (\( P_U \) and \( P_L \)). This algorithm is further detailed in Figure 3.

As shown in Figure 3, the CAS simulation model is divided into two parts: the loading and unloading conditions. The simulation model identifies the loading and the unloading condition of a CAS, and the pressure inside the air receiver is updated after a defined discrete time interval “\( t \)”. For the loading condition, the pressure inside the air receiver increases after each time interval “\( t \)” based on \( V, S, \) and \( C_i \) until \( P_i \) reaches \( P_U \), and the pressure after each time interval “\( t \)” is updated as follows [15]:

\[
P_{i+1} = P_i + \frac{(S - C_i) \times t \times P_a}{V}, \quad \text{(when CAS is loading)}
\]

where \( P_{i-1} \) = pressure inside the air receiver at \((i - 1)^{th}\) time interval (psig). For the unloading condition, the pressure decreases in the air receiver after each time interval “\( t \)” based on \( V \) and \( C_i \) until \( P_i \) reaches \( P_L \), and the pressure after each time interval “\( t \)” is updated as follows [15]:

\[
P_i = P_{i-1} - \frac{C_i \times t \times P_a}{V}. \quad \text{(when CAS is unloading)}
\]

3.2. Machine-Level Power Models

Machine-level power (\( W \)) can be determined using various production parameters. For material cutting processes, MRR, which is defined as the volume of material removed per unit time, can determine \( W \) based on the production parameters. \( W \) can be estimated...
as a linear function of MRR: \( W \approx b_2 + b_1 \times \text{MRR} \). In other words, MRR is a processing rate (processing amount/processing time), and \( W \) can then be estimated as follows \([34,35]\):

\[
W \approx b_2 + b_1 \times \frac{A}{T},
\]

where \( A = \text{processing amount (mm}^3\)\) and \( T = \text{processing time (min)}\). For our research purposes, we consider milling machines and use Equation (12) to estimate the power required for milling for a particular material. The milling parameters for various materials, such as \( b_2 \), \( b_1 \), avg. \( A \), and avg. \( T \), are provided in a table presented in a previous study \([2]\).

### 3.3. Factor-Level Power Models

To simulate the factory-level power demand, we developed a time-discretized energy simulation model by connecting DES and numerical simulation techniques. In the DES model, a production system comprising a CAS and machines is designed and simulated. The air supply side (that is, CAS) generates compressed air, and the air demand side (that is, machines and leaks) consumes the compressed air over time. In DES, all simulated activities of a CAS and machines are tagged with a timestamp, and this time information is used in numerical simulation to generate time series power at the equipment level. To estimate the factory-level power demand at a given time, we aggregate all the CAS and machine-level power demand for the same timestamp. Then the time-series power data at the factory level can be used to estimate the peak kW and total kWh consumption. Subsequently, energy cost for a factory can be calculated as peak kW \( \times \) USD/kW + total kWh consumption \( \times \) USD/kWh. Figure 4 illustrates the proposed method.

![Figure 4. Energy cost estimation of a manufacturing system.](image)

### 3.4. Validation of the Energy Simulation Model

To validate and verify our proposed approach, we validated our model by comparing real CAS power data with the simulated CAS power data. We collected real CAS power time-series data from a 40 HP rotary screw CAS working on a load/unload control; its operating parameters are provided in Table 1. Then we simulated the power of a CAS with the actual operational parameters using our proposed method. As shown in Table 2, the simulated results are very close to the observed data, with less than a 0.02% margin of error in terms of peak kW values, avg. power, and total energy consumption. To validate the proposed simulation model with machines, we also made and ran a simulation model with a CAS and a machine using a variety of parameters. We checked the simulated results very thoroughly by comparing the results with manual calculations and could not find any issue.
Table 1. Actual CAS operation parameters.

| Factors |
|---------|
| $H_R$ HP | $E_m$ | $P_U$ psig | $P_L$ psig | $C_i$ cfm | $V$ cu ft (gals) |
| 40 | 0.924 | 125 | 105 | 105 | 53.47 (400) |

Table 2. Comparison of observed and simulated CAS power data.

| Peak Value of 2-min MA of CAS Power Demand | Peak Value of 15-min MA of CAS Power Demand | Avg. Power Consumed by the CAS ($W_{CAS}$) | Total Energy Consumption |
|------------------------------------------|------------------------------------------|------------------------------------------|--------------------------|
| Actual Observed Data                      | Simulated Data                           | Absolute Percentage Error                |                          |
| kW                                       | kW                                       | kW                                       | kWh                      |
| 28.42                                    | 28.92                                    | 0.02%                                    | 85.35                    |
| 26.68                                    | 26.49                                    | 0.01%                                    | 86.01                    |
| 26.13                                    | 26.37                                    | 0.01%                                    | 0.01%                    |

4. Illustrative Examples and Results

This section provides the application of the proposed method to show the effects of various CAS and machine parameters on the peak demand, energy consumption, and productivity in a factory setting. More specifically, we consider the parameters $V$, $L$, $P_L$, $C_M$, $H_R$, sudden compressed air demand ($C_S$), and interarrival time (IAT) of parts for a CAS and production system to see their effects on energy performance at a factory level.

4.1. Electricity Rate Structure

We used the existing electricity rate for demand charge (USD/kW) and kWh consumption charge (USD/kWh) from previous studies to estimate the energy costs for the simulation examples [36]. We chose electricity rates from the four U.S. states of Nebraska (NE), Missouri (MO), Hawaii (HI), and Washington (WA), as shown in Table 3.

Table 3. Electricity rate structures.

| Electricity Rate | NE   | MO   | HI   | WA   |
|------------------|------|------|------|------|
| USD/kW           | 19.95| 1.71 | 19.5 | 4.2  |
| USD/kWh          | 0.0891| 0.0944| 0.2617| 0.074 |

4.2. Case Study and Results

To simulate a production system, we assume a job shop with 10 milling machines processing aluminum alloy parts and having 3 different part flows and a rotary screw CAS providing compressed air for production purposes, as shown in Figure 5. The part arrivals have an exponentially distributed interarrival time (IAT) with an avg. of 10 min or 8 min. $T$ for all the machines is normally distributed with a coefficient of variation (CV) = 0.2. Except for machine #2 (MC #2) and MC #4, all of the machines have a normally distributed $T$, with mean = 5 min and standard deviation = 1 min. MC #2 and MC #4 process more parts than other machines and hence, they have a shorter $T$ following a normal distribution, with mean = 2.5 min and standard deviation = 0.5 min. For aluminum alloys, $A$ is assumed to be fixed for all the machines as 1,069,521 mm$^3$, and $b_2$ and $b_1$ are 2005 W and 0.0163 W min/mm$^3$, respectively [2]. The focus of this study is to estimate the monthly peak kW and total kWh, and therefore, we simulate this system for 45,000 min to represent a month (31 days $\times$ 24 h $\times$ 60 min $\approx$ 45,000 min).
We simulate a total of 48 scenarios (6 sets × 8 cases) to check the effect of the following factors: \( V \), IAT of parts, \( L \), \( P_L \), \( P_U \), \( C_M \), \( H_R \), and \( C_S \). Each of the factors except IAT is varied in each simulation scenario to check the individual effect of each factor on various performance measures. The performance measures include the peak value of the MA for a 2-min power demand \((PD_2)\), the peak value of the MA for a 15-min power demand \((PD_{15})\), and the total kWh consumed by the CAS and the machines at the factory level. Additionally, for the CAS performance measures, we consider \( W_{CAS} \), \( R_L \), and \( R_U \), and for the machine-level performance measure, the total number of parts produced \((Q_T)\) is considered. For our energy cost calculation, we use \( PD_{15} \) and kWh consumption at the factory level for the simulated time of one month and consider the rate structure provided in Section 4.1. To reduce the effects of outliers and to report more reliable results, we replicated each scenario three times and used the avg. value in this study for all performance measures.

Table 4 shows the simulation parameters for Set 1, and the summary of simulation results from Set 1 is presented in Table 5. We define Set 1 as our baseline set. We also designate Case 1-1 (C1-1) as the baseline case of Set 1. The other cases are counterparts of the baseline case, with each case having one parameter different from C1-1. C1-1 represents a realistic CAS setup with reasonable CAS parameters. \( V \) (in gals, 1 gal = 0.134 cu ft) is set as 5 times the estimated maximum air demand, and \( L \) is reasonably estimated to be 15 cfm. Furthermore, we assume that the minimum system pressure requirement is 90 psig, and to avoid sudden pressure drops, we also assume \( P_U \) and \( P_L \) to be 120 psig and 100 psig, respectively. The milling machines are assumed to consume a total of 12 cfm of compressed air per machine \((C_M = 12 \text{ cfm})\) for air cooling and cleaning purposes. We chose \( H_R \) as 40 HP with \( E_m = 0.941 \) and a manufacturer’s rating of 175 cfm at 150 psig based on the maximum possible air demand. For different \( H_R \) and discharge pressure settings, we will modify \( S \) based on Boyle’s law, as shown in Table 6 [25].

From Tables 4 and 5 for Set 1, we can check the effects of the different factors on the various performance measures. From C1-1 to C1-2, we reduced \( V \) from 660 gals to 400 gals; this change is observed to have a limited impact on the performance measures since the CAS would still have to work for a similar amount of time as the total air demand remains unchanged. Since we do not observe any significant differences in the performance measures due to the change in \( V \), we see that the air receiver size does not have much impact on energy performances and costs in these setups. For C1-3, we reduced \( L \) by 50% from C1-1. The total kWh consumed by the CAS is reduced from C1-1 to C1-3, and subsequently, the total kWh (factory) is reduced. As \( L \) decreases, the total compressed air consumption for the system also decreases; hence, \( t_L \) is lower and \( t_U \) is higher as compared
to C1-1. Subsequently, $R_L$ is lower and $R_U$ is higher, and hence, $W_{CAS}$ is lower. As a result, the total kWh (CAS) and total kWh (factory) are reduced by approximately 4% and 1%, respectively, as compared to C1-1. In addition, the avg. kW (CAS) over a given time frame for C1-3 is lowered due to reduced $L$. Therefore, $PD_2$ (CAS) and $PD_{15}$ (CAS and factory) are slightly lower than C1-1, but $PD_2$ for the factory is similar to C1-1. As the difference between $L$ in C1-1 and C1-3 is not large enough to show significant changes, we see a limited impact on $PD_2$ (factory). For C1-3, the energy costs are lower as well, due to a reduction in total kWh (factory) and $PD_{15}$. Given the lower unloading pressure ($P_U = 110$ psig) in C1-4, $L$ is reduced since $S$ is higher for reduced pressure (see Table 6), and the CAS works less in C1-4 as compared to C1-1. Therefore, for C1-4, the total kWh for a CAS and a factory is lower (4% and 1% reduction for CAS and factory, respectively) in comparison to C1-1. As $R_L$ is lower and $R_U$ is higher as compared to C1-1, the MA for the CAS power is lowered, the result of which can be explained by Equation (5). Then, $PD_2$ and $PD_{15}$ for the CAS and factory are lower than those for C1-1. As a result, the energy costs for C1-4 are reduced.

**Table 4.** Simulation parameters for Set 1.

| Case | $V$ cu ft (gals) | IAT min | $L$ cfm | $P_U$ psig | $P_L$ psig | $C_M$ cfm | $H_R$ HP | $C_S$ cfm |
|------|----------------|---------|---------|------------|------------|----------|--------|----------|
| C1-1 | 88.23 (660)    | 10      | 15      | 120        | 100        | 12       | 40     | -        |
| C1-2 | 53.47 (400)    | 10      | 15      | 120        | 100        | 12       | 40     | -        |
| C1-3 | 88.23 (660)    | 10      | 7.5     | 120        | 100        | 12       | 40     | -        |
| C1-4 | 88.23 (660)    | 10      | 15      | 110        | 100        | 12       | 40     | -        |
| C1-5 | 88.23 (660)    | 10      | 15      | 120        | 90         | 12       | 40     | -        |
| C1-6 | 88.23 (660)    | 10      | 15      | 120        | 100        | 6        | 40     | -        |
| C1-7 | 88.23 (660)    | 10      | 15      | 120        | 100        | 12       | 25     | -        |
| C1-8 | 88.23 (660)    | 10      | 15      | 120        | 100        | 12       | 40     | 60       |

**Table 5.** Simulation results from Set 1.

| Case | Results | Energy Costs (USD/Month) |
|------|---------|--------------------------|
|      | CAS     | Machine                  | Factory                  | NE | MO | HI | WA |
|      | $R_L$ % | $R_U$ % | $W_{CAS}$ kWh | $PD_2$ kWh | $PD_{15}$ kWh | kWh | $Q_t$ | $PD_2$ kWh | $PD_{15}$ kWh | kWh | $R_L$ HP | $R_U$ HP | $C_S$ cfm |
| C1-1 | 37      | 63     | 20     | 28     | 25     | 14,657 | 13,568 | 73 | 60 | 33,499 | 97 | 84 | 48,155 | 5962 | 4689 | 14,236 | 3915 |
| C1-2 | 37      | 63     | 20     | 28     | 24     | 14,657 | 13,569 | 73 | 61 | 33,506 | 97 | 85 | 48,163 | 5988 | 4692 | 14,263 | 3921 |
| C1-3 | 34      | 66     | 19     | 25     | 24     | 14,025 | 13,569 | 71 | 60 | 33,500 | 95 | 84 | 47,526 | 5905 | 4630 | 14,071 | 3869 |
| C1-4 | 34      | 66     | 19     | 25     | 24     | 14,089 | 13,569 | 71 | 60 | 33,497 | 94 | 83 | 47,586 | 5905 | 4635 | 14,081 | 3872 |
| C1-5 | 37      | 63     | 20     | 35     | 26     | 14,089 | 13,570 | 70 | 60 | 33,507 | 102 | 85 | 46,163 | 5994 | 4693 | 14,268 | 3922 |
| C1-6 | 22      | 78     | 16     | 21     | 18     | 11,877 | 13,569 | 72 | 60 | 33,507 | 92 | 78 | 45,384 | 5595 | 4417 | 13,393 | 3685 |
| C1-7 | 61      | 39     | 16     | 22     | 19     | 11,984 | 12,631 | 74 | 51 | 32,705 | 90 | 69 | 44,689 | 5352 | 4336 | 13,034 | 3595 |
| C1-8 | 37      | 63     | 20     | 30     | 25     | 14,658 | 13,569 | 73 | 61 | 33,503 | 96 | 85 | 46,161 | 5996 | 4692 | 14,270 | 3923 |

**Table 6.** $S$ for different discharge pressure.

| $H_R$ | Manufacturer’s Rating | $P_U$ | $S$ |
|-------|-----------------------|-------|-----|
| 25 HP | 102.3 cfm ($S_R$) at 150 psig ($P_U$) |
|       | 150 psig               | 120 psig | (150 psig $\times$ 102.3 cfm)/150 psig $\approx$ 102.3 cfm |
| 40 HP | 175 cfm ($S_R$) at 150 psig ($P_U$) |
|       | 150 psig               | 140 psig | (150 psig $\times$ 175 cfm)/150 psig $= 175$ cfm |
|       | 120 psig               | 110 psig | (150 psig $\times$ 175 cfm)/120 psig $\approx$ 191 cfm |
| 60 HP | 249.2 cfm ($S_R$) at 150 psig ($P_U$) |
|       | 140 psig               | 120 psig | (150 psig $\times$ 249.2 cfm)/140 psig $\approx$ 267 cfm |
|       | 110 psig               | 110 psig | (150 psig $\times$ 249.2 cfm)/110 psig $\approx$ 340 cfm |
For C1-5, when $P_L$ is reduced to 90 psig from 100 psig, we observe a limited impact on the total kWh. This shows that, in a comparison with C1-1, the total work performed by the CAS in C1-5 would be similar since $P_U$ and the total compressed air demand for the system are the same as C1-1. Therefore, over the simulation runs, the compressor will work for a similar amount of time, but the time-frequency to load and unload will differ from C1-1. In addition, $PD_2$ in a CAS and factory for C1-5 is higher than that in C1-1; this result can be explained by Equation (5). As $P_L$ is lower than C1-1, the CAS with C1-5 is in a loading state for a longer time to reach $P_U$ once it is in a loading state, and therefore, MA for the CAS power for a small duration is higher than C1-1. For a longer duration of time, the peak value of the MA power demand ($PD_{15}$) for the CAS and factory is observed to be similar since the total working time of a CAS between C1-1 and C1-5 is similar. In C1-6, given a 50% reduction in $C_M$ ($C_M = 6$ cfm), the total compressed air demand of the system is reduced as compared to C1-1 (see Figure 6). As a result, the CAS takes more time to unload and less time to load than the baseline case (C1-1), and hence, the CAS works less. As a result, the total kWh consumed by the CAS, $R_L$, and $W_{CAS}$ are lower, and $R_U$ is higher as compared to C1-1. Thus, the total kWh at a factory level is lower (6% reduction). We can see from Figure 7 that the unloading period for C1-6 is longer than that of C1-1, as shown in the time duration for the lower limit of the lines representing C1-1 and C1-6. Since $R_U$ is higher, the avg. kW of a CAS over a given time frame is lower. Hence, $PD_2$ and $PD_{15}$ are lower (see Figure 8), and the energy costs are reduced by 6%.

![Figure 6. Compressed air demand comparison for C1-1 and C1-6.](image1)

![Figure 7. CAS power comparison for C1-1 and C1-6.](image2)
For C1-7, we simulate the case with an undersized CAS \((H_R = 25 \text{ HP}, \text{ manufacturer rating } = 102.3 \text{ cfm at } 150 \text{ psig}, \text{ and } E_m = 93.6\%)\). As seen in Table 5, all the performance measures are lower except for \(R_L\). For C1-7, we assume for our simulation purposes that the parts have to wait until the air receiver is full and has adequate pressure. In other words, the parts cannot be processed on the machine until the pressure inside the air receiver has reached \(P_U\). Therefore, more parts have to wait to be processed as compared to C1-1, and the CAS is loaded for more time to keep the desired pressure as \(S\) at the same pressure is lower for a lower \(H_R\) (see Table 6). Hence, \(Q_T\) is lower as compared to C1-1 (13,569 to 12,631). Since \(H_R\) is lower, the CAS consumes less power, and \(PD_2\), \(PD_{15}\), and the total kWh (CAS, machine, and factory) and energy costs are lower as well. For C1-8, three sudden air demands \((C_S = 60 \text{ cfm})\) are introduced in the simulation to examine their impact on the performance measures. We can see from the results that \(C_S\) has a limited impact on the performance measure and energy costs as compared to C1-1, and the air receiver size is adequate to compensate for the sudden air demand. Furthermore, due to the sudden increase in demand, the CAS is unloaded faster for the duration of increased demand, and the unloading time is reduced, thereby increasing the MA of power demand over a small time interval. This can explain higher \(PD_2\) for the CAS, with a 6\% increase.

The simulation cases with IATs shorter than the baseline scenario (IAT = 8 min) are given in Table 7 (Set 2). Table 8 presents the simulation results from Set 2. These show the effects of increased part production on various performance measures. The input parameters for the rows in Table 7 (Set 2) are similar to the input parameters in Table 4 (Set 1), but with IAT= 8 min rather than 10. For Set 2, the machines are idle for a shorter duration of time as compared to Set 1 due to an increase in part production. As a result, the CAS and machines have to work more. Therefore, the total kWh (CAS, machine, and factory), \(R_L\), and \(W_{CAS}\) are higher, and \(R_U\) is lower as compared to Set 1. Furthermore, we can see from Figures 9 and 10 that the 2-min MA power demand (CAS) for C1-1 is close to that of C2-1, and therefore, higher machine utilization has a limited impact on \(PD_2\). However, \(PD_{15}\) for the CAS, machines, and factory are higher than those for Set 1, with a 1\% to 4\% increase for the factory. This shows a clear increase in the demand for the shorter IAT cases in Set 2. For other cases in Set 2 (C2-2 to C2-8), similar observations can be made as those for Set 1.
Table 7. Simulation parameters for Set 2.

| Case  | Factors |  
|-------|---------|
|       | V cu ft (gals) | IAT min | L cfm | P_U psig | P_L psig | C_M cfm | H_R HP | C_S cfm |
| C2-1 | 88.23 (660) | 8 | 15 | 120 | 100 | 12 | 40 | - |
| C2-2 | 53.47 (400) | 8 | 15 | 120 | 100 | 12 | 40 | - |
| C2-3 | 88.23 (660) | 8 | 7.5 | 120 | 100 | 12 | 40 | - |
| C2-4 | 88.23 (660) | 8 | 15 | 110 | 100 | 12 | 40 | - |
| C2-5 | 88.23 (660) | 8 | 15 | 120 | 90 | 12 | 40 | - |
| C2-6 | 88.23 (660) | 8 | 15 | 120 | 100 | 6 | 40 | - |
| C2-7 | 88.23 (660) | 8 | 15 | 120 | 100 | 12 | 25 | - |
| C2-8 | 88.23 (660) | 8 | 15 | 120 | 100 | 12 | 40 | 60 |

Table 8. Simulation results from Set 2.

| Case  | Results |  
|-------|---------|
|       | CAS Machine Factory Energy Costs (USD/Month) |  
|       | CAS | Machine | Factory | Energy Costs (USD/Month) |  
|       | W_CAS kW | P_D2 kW | P_D15 kW | kWh | Q_T | P_D2 kW | P_D15 kW | kWh | PD2 kW | PD15 kW | kWh | NE | MO | HI | WA |  
| C2-1 | 45 | 55 | 21 | 28 | 25 | 16,000 | 16,864 | 74 | 61 | 37,940 | 98 | 86 | 53,940 | 6527 | 5239 | 15,798 | 4354 |  
| C2-2 | 45 | 55 | 21 | 28 | 25 | 16,003 | 16,864 | 72 | 62 | 37,946 | 98 | 87 | 53,949 | 6537 | 5241 | 15,809 | 4356 |  
| C2-3 | 41 | 59 | 20 | 27 | 25 | 15,373 | 16,864 | 73 | 61 | 37,950 | 97 | 85 | 53,233 | 6455 | 5180 | 15,620 | 4305 |  
| C2-4 | 41 | 59 | 20 | 27 | 25 | 15,324 | 16,863 | 70 | 62 | 37,944 | 95 | 86 | 53,268 | 6457 | 5175 | 15,613 | 4302 |  
| C2-5 | 45 | 55 | 21 | 35 | 26 | 15,997 | 16,863 | 72 | 63 | 37,949 | 105 | 88 | 53,946 | 6553 | 5242 | 15,825 | 4360 |  
| C2-6 | 26 | 74 | 17 | 21 | 19 | 12,550 | 16,863 | 72 | 62 | 37,950 | 92 | 80 | 50,500 | 6095 | 4904 | 14,776 | 4073 |  
| C2-7 | 66 | 34 | 17 | 22 | 19 | 12,463 | 12,463 | 77 | 52 | 33,794 | 94 | 69 | 46,257 | 5551 | 4885 | 13,454 | 3713 |  
| C2-8 | 45 | 55 | 21 | 30 | 26 | 16,003 | 16,863 | 84 | 62 | 37,948 | 110 | 87 | 53,951 | 6550 | 5242 | 15,822 | 4359 |  

Figure 9. CAS power comparison for C1-1 and C2-1.

Figure 10. Two-minute MA CAS power comparison for C1-1 and C2-1.
For Set 3 (Table 9), we almost doubled $V$ as compared to the simulation parameters in Set 1 (Table 4). The results from the simulation run for the cases in Set 3 are shown in Table 10. We observe that increasing $V$ has a limited impact on the total kWh since the CAS still has to work a similar amount of time as compared to Set 1. Since $V$ is significantly larger than in the baseline cases, the CAS stays longer in the unloading (or loading) condition once it starts to unload (or load) until the preset loading or unloading pressure is reached. This phenomenon can be observed in Figure 11 as the time duration for upper and lower limits of the power profile for C3-1. Therefore, $PD_2$ for the CAS is increased as compared to Set 1; this result can be seen in Figure 12 where the peaks of the 2-min MA power demand for C3-1 are higher than those of C1-1. However, for a longer duration of time, we see a limited impact of the peak value of the MA of power demand as $PD_{15}$ values for the CAS and factory are similar to that of Set 1. Thus, we see a limited impact on energy costs. C3-2 to C3-8 show similar results to those of Set 1.

### Table 9. Simulation parameters for Set 3.

| Case | $V$ (cu ft (gals)) | IAT (min) | $L$ (cfm) | $P_U$ (psig) | $P_L$ (psig) | $C_M$ (cfm) | $H_R$ (HP) | $C_S$ (cfm) |
|------|-------------------|----------|-----------|-------------|-------------|-------------|-----------|-------------|
| C3-1 | 141.7 (1060)      | 10       | 15        | 120         | 100         | 12          | 40        | -           |
| C3-2 | 88.23 (660)       | 10       | 15        | 120         | 100         | 12          | 40        | -           |
| C3-3 | 141.7 (1060)      | 10       | 7.5       | 120         | 100         | 12          | 40        | -           |
| C3-4 | 141.7 (1060)      | 10       | 15        | 110         | 100         | 12          | 40        | -           |
| C3-5 | 141.7 (1060)      | 10       | 15        | 120         | 90          | 12          | 40        | -           |
| C3-6 | 141.7 (1060)      | 10       | 15        | 120         | 100         | 6           | 40        | -           |
| C3-7 | 141.7 (1060)      | 10       | 15        | 120         | 100         | 12          | 25        | -           |
| C3-8 | 141.7 (1060)      | 10       | 15        | 120         | 100         | 12          | 40        | 60          |

### Table 10. Simulation results from Set 3.

| Case | Results |
|------|---------|
|      | CAS     | Machine | Factory | Energy Costs (USD/Month) |
|      | $R_L$ % | $R_U$ % | $W_{CAS}$ kW | $PD_2$ kW | $PD_{15}$ kW | $P_D$ kW | $PD_{15}$ kW | kWh | $P_D$ kW | $PD_{15}$ kW | kWh | NE | MO | HI | WA |
| C3-1 | 45     | 55     | 21    | 28    | 25    | 16,000 | 13,567 | 70 | 60 | 33,502 | 102 | 84 | 48,157 | 5965 | 4690 | 14,239 | 3916 |
| C3-2 | 45     | 55     | 21    | 28    | 25    | 16,003 | 13,568 | 73 | 60 | 33,499 | 97  | 84 | 48,155 | 5962 | 4689 | 14,236 | 3915 |
| C3-3 | 41     | 59     | 20    | 27    | 25    | 16,973 | 13,569 | 70 | 60 | 33,496 | 103 | 84 | 48,153 | 5971 | 4690 | 14,244 | 3917 |
| C3-4 | 41     | 59     | 20    | 25    | 24    | 15,324 | 13,569 | 70 | 60 | 33,505 | 95  | 82 | 47,599 | 5885 | 4634 | 14,064 | 3868 |
| C3-5 | 45     | 55     | 21    | 35    | 26    | 15,997 | 13,569 | 70 | 60 | 33,507 | 96  | 79 | 45,386 | 5616 | 4419 | 13,414 | 3690 |
| C3-6 | 26     | 74     | 17    | 21    | 19    | 12,550 | 13,569 | 70 | 60 | 33,507 | 96  | 79 | 45,386 | 5616 | 4419 | 13,414 | 3690 |
| C3-7 | 66     | 34     | 17    | 22    | 19    | 12,463 | 8835  | 67 | 47 | 28,890 | 81  | 64 | 39,813 | 419 | 3867 | 11,662 | 3214 |
| C3-8 | 45     | 55     | 21    | 30    | 26    | 16,003 | 13,569 | 72 | 60 | 33,510 | 105 | 84 | 48,164 | 5960 | 4690 | 14,235 | 3915 |

**Figure 11.** CAS power comparison for C1-1 and C3-1.
We define Set 4 (Table 11) by increasing $L$ 50% from each of the simulation cases in Set 1 (Table 4). The simulation results for Set 4 are given in Table 12. The compressed air leakages can be considered as an additional compressed air demand, and as $L$ increases, the CAS has to work more to keep the desired pressure in the air receiver. Hence, the CAS stays in the loading condition for a longer time as compared to the cases in Set 1. Therefore, the total kWh consumption of a CAS and a factory in Set 4 is higher than those of Set 1, with an increase of 1% to 3% for the factory. Figure 13 shows that the CAS in C4-1 takes more time to load and less time to unload as compared to C1-1. In other words, the duration of the time that the CAS is in the loading condition and the unloading condition is higher and lower, respectively, than in C1-1, and as a result, $W_{CAS}$ and total kWh consumption are higher for C4-1. Also, the peaks of 2-min MA power demand (CAS) for C4-1 are slightly higher than those of C1-1 (see Figure 14). This suggests that for higher $L$, the $PD_2$ of a CAS and a factory is increased. Additionally, $PD_{15}$ of a CAS and factory is also higher for most of the cases, and the energy costs are higher as well, with 1% to 3% increase over those for Set 1. Other cases in Set 4 show similar results to those in Set 1.

Table 11. Simulation parameters for Set 4.

| Case | Factors | V_{cu ft (gals)} | IAT min | $L_{cfm}$ | $P_U_{psig}$ | $P_L_{psig}$ | $C_M_{cfm}$ | $H_R_{HP}$ | $C_S_{cfm}$ |
|------|---------|----------------|---------|----------|-------------|-------------|-------------|-----------|-------------|
| C4-1 | 88.23 (660) | 10 | 30 | 120 | 100 | 12 | 40 | - |
| C4-2 | 53.47 (400) | 10 | 30 | 120 | 100 | 12 | 40 | - |
| C4-3 | 88.23 (660) | 10 | 15 | 120 | 100 | 12 | 40 | - |
| C4-4 | 88.23 (660) | 10 | 30 | 110 | 100 | 12 | 40 | - |
| C4-5 | 88.23 (660) | 10 | 30 | 120 | 90 | 12 | 40 | - |
| C4-6 | 88.23 (660) | 10 | 30 | 120 | 100 | 6 | 40 | - |
| C4-7 | 88.23 (660) | 10 | 30 | 120 | 100 | 12 | 25 | - |
| C4-8 | 88.23 (660) | 10 | 30 | 120 | 100 | 12 | 40 | 60 |

Table 12. Simulation results from Set 4.

| Case | Results | CAS | Machine | Factory | Energy Costs (USD/Month) |
|------|---------|-----|---------|---------|---------------------------|
| C4-1 | 44 56 21 32 26 | 15,905 13,569 71 61 | 33,500 98 | 49,405 6136 4812 | 14,624 4021 |
| C4-2 | 44 57 21 29 26 | 15,912 13,569 71 60 | 33,503 98 | 49,415 6116 4812 | 14,607 4017 |
| C4-3 | 37 63 20 28 25 | 14,657 13,568 73 60 | 33,499 97 | 48,155 5962 4689 | 14,236 3915 |
| C4-4 | 40 60 20 27 25 | 15,243 13,568 97 79 | 33,515 118 | 48,759 6372 4777 | 14,742 4035 |
| C4-5 | 44 56 21 35 26 | 15,910 13,569 71 60 | 33,503 103 | 49,412 6117 4811 | 14,607 4017 |
| C4-6 | 29 71 18 22 21 | 13,132 13,569 71 60 | 33,504 90 | 46,636 5757 4540 | 13,771 3788 |
| C4-7 | 71 29 17 22 20 | 13,061 11,621 65 49 | 31,647 83 | 44,708 5316 4235 | 13,003 3589 |
| C4-8 | 44 56 21 35 26 | 15,903 13,569 71 61 | 33,503 101 | 49,406 6134 4812 | 14,623 4021 |
For Set 5, the simulation cases have pressure setpoints \((P_U, P_L)\) higher than the cases in the baseline scenario, as shown in Table 13, while the rest of the input parameters is kept similar to the input parameters in Table 4 (Set 1). Table 14 presents the simulation results from each of the cases in Set 5. We observe that when the pressure setpoints are increased, the \(PD_2, PD_{15}\), and the total kWh consumption increases in comparison to Set 1. The energy costs also increase 2% to 4% as compared to Set 1. The CAS takes more time to load than in the baseline set as \(S\) is lower for higher discharge pressure based on Boyle’s law (see Table 6), and hence, the CAS works more. For instance, it can be seen Figure 15 that the loading duration for C5-1 is longer than C1-1. Figure 16 shows that the CAS takes more time to reach the discharge pressure of 150 psig compared to a discharge pressure of 120 psig (as in Set 1). Therefore, the total kWh of a CAS and a factory is higher than that for Set 1, with a 2% to 4% increase for the factory. Since the CAS is loaded longer in C5-1, \(R_L\) is higher, and \(W_{CAS}\) is higher than in the baseline cases. Therefore, \(PD_2\) and \(PD_{15}\) for Set 5 are much higher than in Set 1. Figure 17 shows that the peaks of 2-min MA power demand for C5-1 are higher than those for C1-1. Other cases in Set 5 show similar results from what is provided within Set 1.
Table 13. Simulation parameters for Set 5.

| Case  | $V$ cu ft (gals) | IAT min | $L$ cfm | $P_U$ psig | $P_L$ psig | $C_M$ cfm | $H_R$ HP | $C_S$ cfm |
|-------|------------------|---------|---------|------------|------------|-----------|---------|-----------|
| C5-1  | 88.23 (660)      | 10      | 15      | 150        | 130        | 12        | 40      | -         |
| C5-2  | 53.47 (400)      | 10      | 15      | 150        | 130        | 12        | 40      | -         |
| C5-3  | 88.23 (660)      | 10      | 7.5     | 140        | 130        | 12        | 40      | -         |
| C5-4  | 88.23 (660)      | 10      | 15      | 150        | 130        | 12        | 40      | -         |
| C5-5  | 88.23 (660)      | 10      | 15      | 150        | 130        | 12        | 40      | -         |
| C5-6  | 88.23 (660)      | 10      | 15      | 150        | 130        | 6         | 40      | -         |
| C5-7  | 88.23 (660)      | 10      | 15      | 150        | 130        | 12        | 25      | -         |
| C5-8  | 88.23 (660)      | 10      | 15      | 150        | 130        | 12        | 40      | 60        |

Table 14. Simulation results from Set 5.

| Case  | Results | CAS Machine Factory Energy Costs (USD/Month) |
|-------|---------|---------------------------------------------|
|       | $R_L$ % | $R_H$ % | $W_{CAS}$ kW | $P_{D2}$ kW | $P_{D3}$ kW | $P_{D4}$ kW | $P_{D5}$ kW | $Q_T$ | $P_{D1}$ kW | $P_{D2}$ kW | $P_{D3}$ kW | $P_{D4}$ kW | $P_{D5}$ kW | $kWh$ | $NE$ | $MO$ | $HI$ | $WA$ |
|-------|---------|---------|---------------|-------------|-------------|-------------|-------------|-------|-------------|-------------|-------------|-------------|-------------|=======|------|------|------|------|
| C5-1  | 47      | 53      | 22            | 35          | 29          | 16,362      | 13,569      | 69    | 59          | 33,504      | 102         | 88          | 49,866      | 6196  | 4858 | 14,763 | 4059 |
| C5-2  | 47      | 53      | 22            | 33          | 28          | 16,359      | 13,569      | 70    | 60          | 33,493      | 100         | 88          | 49,853      | 6193  | 4856 | 14,758 | 4058 |
| C5-3  | 42      | 58      | 21            | 35          | 27          | 15,576      | 13,568      | 69    | 60          | 33,497      | 101         | 87          | 49,073      | 6108  | 4781 | 14,539 | 3997 |
| C5-4  | 43      | 57      | 21            | 29          | 27          | 15,792      | 13,568      | 72    | 60          | 33,504      | 100         | 86          | 49,295      | 6112  | 4803 | 14,582 | 4010 |
| C5-5  | 47      | 53      | 22            | 35          | 27          | 16,358      | 13,570      | 73    | 60          | 33,501      | 107         | 87          | 49,860      | 6185  | 4856 | 14,751 | 4056 |
| C5-6  | 28      | 72      | 17            | 25          | 21          | 12,889      | 13,570      | 71    | 60          | 33,505      | 93          | 80          | 46,394      | 5727  | 4516 | 12,594 | 3769 |
| C5-7  | 69      | 31      | 17            | 22          | 20          | 12,879      | 10,167      | 86    | 49          | 30,180      | 101         | 68          | 43,039      | 5193  | 4181 | 12,594 | 3769 |
| C5-8  | 47      | 53      | 22            | 35          | 28          | 16,359      | 13,569      | 71    | 59          | 33,503      | 102         | 87          | 49,862      | 6187  | 4857 | 14,754 | 4057 |

Figure 15. CAS power comparison for C1-1 and C5-1.

The simulation cases and results with an oversized CAS ($H_R = 60$ HP and manufacturer rating = 249.2 cfm at 150 psig) with $E_m = 95\%$ are presented in Tables 15 and 16, respectively as Set 6. For each of the cases within Table 15, all the input parameters except for $H_R$ are unchanged as compared to Set 1. For the higher $H_R$, $t_L$ is reduced since $S$ at the same discharge pressure is higher for higher $H_R$ (see Table 6). Hence, $R_L$ is lower, and $R_U$ is higher as compared to Set 1. Also, $W_{U}$ and $W_{L}$ are higher for the cases in Set 6 than those of Set 1 as determined in Equations (1) and (2). Therefore, $W_{CAS}$ is higher for the same operation time. For example, for C1-1, $R_L = 37\%$, $R_U = 63\%$, $H_R = 40$ HP and $E_m = 94.1\%$: then $W_{CAS}$ can be calculated from Equation (5) as $W_{CAS} = (40 \text{ HP} \times 0.746 \text{ kW/HP} \times (1/0.941) \times 1.10 \times 0.37) + (40 \text{ HP} \times 0.746 \text{ kW/HP} \times (1/0.941) \times 0.33 \times 0.63) \approx 20 \text{ kW}$. For C6-1, $R_L = 26\%$, $R_U = 74\%$, $H_R = 60$ HP and $E_m = 95\%$: then $W_{CAS}$ can be calculated from Equation (5) as $W_{CAS} = (60 \text{ HP} \times 0.746 \text{ kW/HP} \times (1/0.95) \times 1.10 \times 0.26) + (60 \text{ HP} \times 0.746 \text{ kW/HP} \times (1/0.95) \times 0.33 \times 0.74) \approx 25 \text{ kW}$. Hence, $W_{CAS}$ for Set 6 is higher than...
that of Set 1 as seen in Figure 18. As a result, $PD_2$ and $PD_{15}$ are also higher than those of the cases in Set 1 as provided in Figure 19. Further, the total kWh consumed by the CAS in Set 6 is higher as $W_{CAS}$ in Set 6 is higher as compared to Set 1. Thus, the total kWh consumed at the factory level is also approximately 9% higher than that of Set 1. This can be seen in Figure 20. Therefore, choosing an oversized air compressor can lead to additional power demands and energy consumption, which increases the energy costs, in this comparison, with a 7% to 11% increase over Set 1.

Figure 16. CAS pressure profile comparison for C1-1 and C5-1.

Figure 17. MA CAS power comparison for C1-1 and C5-1.
Table 15. Simulation parameters for Set 6.

| Case | Factors | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | V cu ft (gals) | IAT min | L cfm | P_U psig | P_L psig | C_M cfm | H_R HP | C_S cfm | |
| C6-1 | 88.23 (660) | 10 | 15 | 120 | 100 | 12 | 60 | - | |
| C6-2 | 53.47 (400) | 10 | 15 | 120 | 100 | 12 | 60 | - | |
| C6-3 | 88.23 (660) | 10 | 7.5 | 120 | 100 | 12 | 60 | - | |
| C6-4 | 88.23 (660) | 10 | 15 | 110 | 100 | 12 | 60 | - | |
| C6-5 | 88.23 (660) | 10 | 15 | 120 | 90 | 12 | 60 | - | |
| C6-6 | 88.23 (660) | 10 | 15 | 120 | 100 | 6 | 60 | - | |
| C6-7 | 88.23 (660) | 10 | 15 | 120 | 100 | 12 | 40 | - | |
| C6-8 | 88.23 (660) | 10 | 15 | 120 | 100 | 12 | 60 | 60 | |

Table 16. Simulation results from Set 6.

| Case | Results | Machine Factory Energy Costs (USD/Month) | |
|---|---|---|---|---|---|---|---|---|
| | CAS | Machine | Energy Costs (USD/Month) | |
| | | | | | | NE | MO | HI | WA | |
| C6-1 | 26 | 74 | 25 | 36 | 30 | 18,767 | 13,570 | 80 | 60 | 33,510 | 107 | 90 | 52,277 | 6445 | 5088 | 15,427 | 4245 |
| C6-2 | 26 | 74 | 25 | 32 | 30 | 18,763 | 13,570 | 75 | 59 | 33,498 | 103 | 89 | 52,261 | 6423 | 5085 | 15,403 | 4239 |
| C6-3 | 24 | 76 | 24 | 35 | 29 | 18,113 | 13,569 | 76 | 65 | 33,506 | 107 | 92 | 51,618 | 6433 | 5030 | 15,301 | 4206 |
| C6-4 | 24 | 76 | 24 | 32 | 29 | 18,175 | 13,569 | 71 | 60 | 33,504 | 101 | 89 | 51,679 | 6382 | 5031 | 15,262 | 4199 |
| C6-5 | 26 | 74 | 25 | 34 | 31 | 18,760 | 13,569 | 71 | 61 | 33,502 | 102 | 90 | 52,262 | 6461 | 5088 | 15,441 | 4247 |
| C6-6 | 15 | 85 | 21 | 25 | 24 | 15,865 | 13,569 | 69 | 60 | 33,506 | 94 | 84 | 49,372 | 6072 | 4804 | 14,555 | 4006 |
| C6-7 | 37 | 63 | 20 | 28 | 25 | 14,657 | 13,568 | 73 | 60 | 33,499 | 97 | 84 | 48,155 | 5962 | 4689 | 14,236 | 3915 |
| C6-8 | 26 | 74 | 25 | 38 | 30 | 18,763 | 13,569 | 71 | 61 | 33,494 | 102 | 90 | 52,257 | 6439 | 5088 | 15,438 | 4247 |

Figure 18. CAS power comparison for C1-1 and C6-1.

Figure 19. Two-minute MA CAS power comparison for C1-1 and C6-1.
Table 17 shows a summary of the case comparison by taking the ratios of the simulation case results in Set 1 (Table 5), Set 2 (Table 8), and Set 3 (Table 10) with the simulation case results in Set 1. For C1-1 to C1-8, we compare the cases to the baseline case C1-1, and for the rest of the cases, we compare each of the cases to their respective baseline case. The first eight sets of ratios present that the total kWh (CAS and factory), \( PD_2 \) and energy costs are reduced when \( L, P_{U}, H_{R}, \) and \( C_{M} \) are reduced (ratios less than 1). The second set of ratios compares the cases between Set 2 and Set 1. We can observe that all the ratios for total kWh (factory), \( PD_{15} \) (factory), and energy costs are higher than 1, and therefore, machine utilization is a significant factor for energy performance. The comparison of C2-7/C1-7 shows that \( Q_T \) is lower in C2-7 even though the machine utilization and total kWh (factory) consumption are higher for C2-7 as compared to C1-7. This can be explained as some parts might have been in one of the production machines and have not been finished, and therefore, the total kWh consumption is higher in C2-7 but \( Q_T \) is lower. Therefore, undersized CAS for production capability has a significant impact on the productivity of a manufacturing system. The third set of ratios compares Set 3 and Set 1. Ratios show that the change in \( V \) (Set 3) has a limited impact on the total kWh (CAS, machine, and factory) and \( PD_{15} \) (ratios close to 1). For C3-7/C1-7, results show a reduction in \( Q_T \) for C3-7 as compared to C1-7, and this result can be explained by using Equation (3). As \( V \) is increased in C3-7, the CAS will take more time to reach \( P_{U} \) as compared to C1-7, and hence, more parts have to wait to get processed.

The comparison of cases from Set 4, Set 5, and Set 6 with Set 1 are presented in Table 18. The first and second set of ratios in Table 18 shows the comparison of Set 4 and Set 5 with Set 1, respectively. For most of the case comparisons in the first and second set, the ratios are greater than 1 for the total kWh (CAS, machine, and factory), \( PD_2, PD_{15} \), and energy costs. Therefore, an increase in \( L \) (Set 4) and pressure setpoints (Set 5) have a significant impact on the total kWh, the peak value of the MA for power demand, and energy costs. Also, for case comparisons C4-7/C1-7 and C5-7/C1-7, \( Q_T \) is lower as compared to C1-7 (ratio less than 1). This result can be explained as the CAS takes more time to provide adequate pressure for processing parts due to higher leak intensity and pressure setpoints, respectively. These case comparisons also suggest that undersized CAS has a significant impact on the productivity of a manufacturing system. The third set of ratios compares the cases between Set 6 and Set 1. All the ratios for the total kWh consumption, \( PD_2 \), and \( PD_{15} \) for the CAS and factory are greater than 1 for higher \( H_R \). This suggests that an oversized CAS has a significant impact on the total kWh consumption, the peak value of the MA for power demand, and energy costs. Overall, machine utilization (Set 2), \( L \) (Set 4), \( P_{U} \) (Set 5), and \( H_R \) (Set 6) are significant factors that affect the peak kW, total kWh, energy costs, and productivity of a manufacturing system. Figure 21 shows that the energy cost increases.

![Figure 20. Factory level power comparison for C1-1 and C6-1.](image-url)
when there is an increase in machine utilization (C2-1), \( L \) (C4-1), \( P \) (C5-1), and \( H \) (C6-1), using electricity rates from the four U.S. states. C3-1 in Figure 21 shows lower energy costs than other cases (C2-1, C4-1, C5-1, and C6-1). We observe this cost reduction in C3-1 as an increase in \( V \) has a limited impact on energy costs while other factors have larger impacts. More specifically, the results of C3-1 are lower than those of C2-1 (more parts production), C4-1 (more air leakages), C5-1 (higher pressure setpoints), and C6-1 (higher \( H \)) since C2-1, C4-1, C5-1, and C6-1 show higher energy costs for a respective reason.

![Figure 21. Energy cost comparison for cases 1-1 through 6-1.](image)

**Table 17.** Summary of comparison of results from Set 1, Set 2 and Set 3 to baseline cases.

| Case    | CAS Machine Factory Energy Costs |
|---------|----------------------------------|
| W\(_{CAS}\) | \( P_{D2} \) | \( P_{D15} \) kWh | \( Q_T \) | \( P_{D2} \) | \( P_{D15} \) kWh | \( P_{D2} \) | \( P_{D15} \) kWh | NE | MO | HI | WA |
| C1-1/C1-1 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| C1-2/C1-1 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.02 | 1.00 | 1.02 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| C1-3/C1-1 | 0.96 | 0.95 | 0.98 | 0.96 | 1.00 | 0.97 | 1.01 | 1.00 | 0.98 | 1.00 | 0.99 | 0.99 | 0.99 | 0.99 |
| C1-4/C1-1 | 0.96 | 0.89 | 0.96 | 0.96 | 1.00 | 0.98 | 1.00 | 0.96 | 1.00 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| C1-5/C1-1 | 1.00 | 1.24 | 1.04 | 1.00 | 0.96 | 1.00 | 1.00 | 1.05 | 1.02 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 |
| C1-6/C1-1 | 0.81 | 0.74 | 0.75 | 0.81 | 1.00 | 0.99 | 1.00 | 0.94 | 0.93 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 |
| C1-7/C1-1 | 0.82 | 0.78 | 0.76 | 0.82 | 0.93 | 1.01 | 0.85 | 0.98 | 0.93 | 0.82 | 0.93 | 0.90 | 0.92 | 0.92 |
| C1-8/C1-1 | 1.00 | 1.06 | 1.02 | 1.00 | 1.00 | 1.01 | 1.00 | 0.99 | 1.02 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 |
| C2-1/C1-1 | 1.09 | 1.00 | 1.00 | 1.09 | 1.24 | 1.02 | 1.02 | 1.13 | 1.01 | 1.03 | 1.12 | 1.09 | 1.12 | 1.11 |
| C2-2/C1-2 | 1.09 | 1.00 | 1.03 | 1.09 | 1.24 | 0.99 | 1.02 | 1.13 | 1.02 | 1.02 | 1.12 | 1.09 | 1.12 | 1.11 |
| C2-3/C1-3 | 1.10 | 1.00 | 1.02 | 1.10 | 1.24 | 1.03 | 1.01 | 1.13 | 1.02 | 1.02 | 1.12 | 1.09 | 1.12 | 1.11 |
| C2-4/C1-4 | 1.09 | 1.00 | 1.02 | 1.09 | 1.24 | 0.99 | 1.04 | 1.13 | 1.01 | 1.03 | 1.12 | 1.09 | 1.12 | 1.11 |
| C2-5/C1-5 | 1.09 | 1.00 | 1.09 | 1.09 | 1.24 | 1.02 | 1.04 | 1.13 | 1.04 | 1.03 | 1.12 | 1.09 | 1.12 | 1.11 |
| C2-6/C1-6 | 1.06 | 1.00 | 1.01 | 1.06 | 1.24 | 1.01 | 1.03 | 1.13 | 1.00 | 1.03 | 1.11 | 1.09 | 1.11 | 1.11 |
| C2-7/C1-7 | 1.04 | 1.00 | 1.01 | 1.04 | 0.99 | 1.04 | 1.02 | 1.03 | 1.04 | 1.01 | 1.04 | 1.03 | 1.03 | 1.03 |
| C2-8/C1-8 | 1.09 | 0.99 | 1.03 | 1.09 | 1.24 | 1.16 | 1.02 | 1.13 | 1.14 | 1.02 | 1.12 | 1.09 | 1.12 | 1.11 |
| C3-1/C1-1 | 1.00 | 1.24 | 1.00 | 1.00 | 1.00 | 0.96 | 0.99 | 1.00 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| C3-2/C1-2 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 0.98 | 1.00 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 |
| C3-3/C1-3 | 1.00 | 1.30 | 1.01 | 1.00 | 1.00 | 1.06 | 0.99 | 0.99 | 1.06 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 |
| C3-4/C1-4 | 1.00 | 1.04 | 0.98 | 1.00 | 1.00 | 0.99 | 0.99 | 1.00 | 1.01 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 |
| C3-5/C1-5 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 | 1.00 | 1.01 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 |
| C3-6/C1-6 | 1.00 | 1.29 | 1.03 | 1.00 | 1.00 | 0.97 | 1.01 | 1.00 | 1.04 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 |
| C3-7/C1-7 | 0.91 | 1.00 | 0.98 | 0.91 | 0.70 | 0.91 | 0.92 | 0.88 | 0.89 | 0.93 | 0.89 | 0.90 | 0.89 | 0.89 |
| C3-8/C1-8 | 1.00 | 1.17 | 0.99 | 1.00 | 1.00 | 0.99 | 0.98 | 1.00 | 1.09 | 0.98 | 1.00 | 0.99 | 1.00 | 1.00 |
Table 18. Summary of comparison of results from Set 4, Set 5 and Set 6 to baseline cases.

| Case     | CAS Ratios | Machine Ratios | Factory Ratios | Energy Costs |
|----------|------------|----------------|----------------|--------------|
|          | $W_{CAS}$ | $PD_2$ | $PD_{15}$ | kWh | $Q_T$ | $PD_2$ | $PD_{15}$ | kWh | $PD_2$ | $PD_{15}$ | kWh | NE | MO | HI | WA |
| C4-1/C1-1 | 1.09      | 1.14 | 1.07 | 1.09 | 1.00 | 0.97 | 1.02 | 1.00 | 1.01 | 1.04 | 1.03 | 1.03 | 1.03 | 1.03 |
| C4-2/C1-1 | 1.09      | 1.03 | 1.07 | 1.09 | 1.00 | 0.98 | 0.99 | 1.00 | 1.01 | 1.01 | 1.03 | 1.02 | 1.03 | 1.02 |
| C4-3/C1-3 | 1.04      | 1.05 | 1.03 | 1.05 | 1.00 | 1.03 | 0.99 | 1.00 | 1.02 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 |
| C4-4/C1-4 | 1.08      | 1.09 | 1.05 | 1.08 | 1.00 | 1.36 | 1.32 | 1.00 | 1.26 | 1.22 | 1.02 | 1.03 | 1.05 | 1.04 |
| C5-1/C1-1 | 1.11      | 1.06 | 1.12 | 1.11 | 1.00 | 0.98 | 1.01 | 1.00 | 0.99 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 |
| C5-2/C1-1 | 1.09      | 1.00 | 1.03 | 1.09 | 1.00 | 1.01 | 1.00 | 1.00 | 1.02 | 1.01 | 1.03 | 1.02 | 1.03 | 1.02 |
| C5-3/C1-3 | 1.12      | 1.22 | 1.12 | 1.11 | 1.00 | 0.98 | 1.00 | 1.00 | 1.05 | 1.02 | 1.04 | 1.03 | 1.03 | 1.03 |
| C5-4/C1-4 | 1.08      | 1.16 | 1.05 | 1.07 | 1.09 | 0.92 | 0.88 | 0.95 | 0.92 | 0.97 | 1.00 | 0.99 | 1.00 | 1.00 |
| C5-5/C1-5 | 1.09      | 1.24 | 1.16 | 1.12 | 1.00 | 0.94 | 0.99 | 1.00 | 1.05 | 1.05 | 1.04 | 1.04 | 1.04 | 1.04 |
| C5-6/C1-6 | 1.12      | 1.17 | 1.14 | 1.12 | 1.00 | 1.01 | 1.00 | 1.00 | 1.07 | 1.03 | 1.04 | 1.04 | 1.04 | 1.04 |
| C5-7/C1-7 | 1.11      | 1.30 | 1.13 | 1.11 | 1.00 | 0.98 | 0.99 | 1.00 | 1.06 | 1.04 | 1.03 | 1.03 | 1.03 | 1.03 |
| C5-8/C1-8 | 1.12      | 1.17 | 1.14 | 1.12 | 1.00 | 0.98 | 0.99 | 1.00 | 1.06 | 1.02 | 1.03 | 1.03 | 1.03 | 1.03 |
| C6-1/C1-1 | 1.28      | 1.27 | 1.23 | 1.28 | 1.00 | 1.11 | 1.00 | 1.00 | 1.10 | 1.07 | 1.09 | 1.08 | 1.08 | 1.08 |
| C6-2/C1-2 | 1.28      | 1.14 | 1.12 | 1.28 | 1.00 | 1.03 | 0.97 | 1.00 | 1.07 | 1.04 | 1.09 | 1.07 | 1.08 | 1.08 |
| C6-3/C1-3 | 1.29      | 1.29 | 1.22 | 1.29 | 1.00 | 1.08 | 1.07 | 1.00 | 1.13 | 1.10 | 1.09 | 1.09 | 1.09 | 1.09 |
| C6-4/C1-4 | 1.29      | 1.27 | 1.23 | 1.29 | 1.00 | 0.99 | 1.01 | 1.00 | 1.08 | 1.07 | 1.09 | 1.08 | 1.08 | 1.08 |
| C6-5/C1-5 | 1.28      | 1.19 | 1.28 | 1.10 | 1.00 | 0.98 | 1.01 | 1.00 | 1.00 | 1.06 | 1.09 | 1.08 | 1.08 | 1.08 |
| C6-6/C1-6 | 1.34      | 1.20 | 1.31 | 1.34 | 1.00 | 0.96 | 1.01 | 1.00 | 1.03 | 1.08 | 1.09 | 1.09 | 1.09 | 1.09 |
| C6-7/C1-7 | 1.22      | 1.29 | 1.32 | 1.22 | 1.07 | 0.99 | 1.17 | 1.02 | 1.08 | 1.22 | 1.08 | 1.11 | 1.08 | 1.09 |
| C6-8/C1-8 | 1.28      | 1.26 | 1.21 | 1.28 | 1.00 | 0.97 | 1.00 | 1.00 | 1.07 | 1.06 | 1.09 | 1.08 | 1.08 | 1.08 |

5. Discussion and Conclusions

In this paper, we proposed a time-discretized energy simulation model for a rotary screw CAS with the load/unload controls integrated with milling machines to estimate the power demand and energy consumption for a manufacturing system. The simulation model considers various CAS parameters such as air leakages, pressure setpoints, machine-level air demand, sudden air demand, and the size of the CAS is presented and used to provide the effects of these parameters on energy performances, including the peak value of the MA for power demand and the total kWh consumed. The results from the simulation examples based on the proposed model reveal a variety of ways that industrial practitioners might achieve more sustainable and cost-effective manufacturing. Firstly, a reduction in the total compressed air leakages can lead to a reduction in the peak value of the 2-min and 15-min MA for power demand (1% to 4%), total kWh consumed (1% to 3%), and energy costs (1% to 8%). Secondly, a decrease in discharge pressure can also lead to a reduction in the peak value of the 2-min and 15-min MA for power demand (1% to 7%), total energy consumed (1% to 4%), and energy costs (1% to 4%). Thirdly, other factors such as the oversized air receiver and sudden compressed air demand were found to have a limited impact on the peak value of the MA for power demand. Fourthly, unregulated machine-level air consumption (leaks) is also a significant factor that can reduce the peak value of the MA for power demand and total kWh consumed, and as a result, energy costs (1% to 8%). Lastly, the machine utilization and the size (HP rating) of the CAS have been found to be important factors that can affect the productivity of the system and energy costs. For higher machine utilization, the machines should produce more parts, but, without proper sizing of the CAS, the production can be disrupted from time to time due to an inadequate supply of compressed air. Based on the results from our simulation experiments, improper sizing of the CAS can cause production loss by up to 30% in terms of parts produced. This suggests that the manufacturers should wisely choose the CAS size to improve their productivity. Overall, manufacturers and researchers can find more sustainable ways of designing, installing, and maintaining a CAS by minimizing leakages and unregulated usages in the compressed air supply lines,
decreasing the discharge pressure at the minimum level required, introducing a suitable size of a storage tank, and choosing the proper size (HP rating) of the air compressor. Consequently, by taking the best combination of what we have found, manufacturers and researchers will be able to maximize the savings in energy consumption and to minimize the relevant costs in a production system.

We believe that the results from this study can help manufacturers improve energy performance measures by optimizing various CAS operational parameters, thereby taking a step towards sustainable manufacturing. With this study, industrial manufacturers can reduce energy and resource consumption for their production systems, and the investment in power systems from power suppliers can also be decreased, resulting in reduced energy consumption and carbon emissions. Thus, this study can help mitigate the economic and environmental impacts in manufacturing, thereby improving the sustainability in manufacturing. In comparison to previous studies, our proposed work can help test various combinations of the CAS and machining parameters for the combined impacts of the parameters on energy costs such as disrupted production due to low CAS pressure. Thus, this work can complement the previous studies focusing on a single CAS and its impacts on energy performance. Moreover, the proposed simulation tool can be used by manufacturers as well as researchers to generate and study time-series power for the CAS, machine, and factory levels to estimate the electricity costs of a manufacturing system. While this study provides a useful simulation tool for reducing energy costs, it only considers rotary screw air compressors with load/unload control systems. Therefore, for future research, we expect to explore different types of air compressor control systems.

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Abbreviations

| Abbreviations | Abbreviation Description |
|---------------|--------------------------|
| Avg.          | Average                  |
| C             | Case                     |
| CAS           | Compressed Air System    |
| CV            | Coefficient of Variation |
| cfm           | Cubic feet per minute    |
| cu ft         | Cubic feet               |
| DES           | Discrete Event Simulation|
| HI            | Hawaii                   |
| HP            | Horsepower               |
| IAT           | Interarrival time        |
| kW            | Kilowatt                 |
| kWh           | Kilowatt-hour            |
| MA            | Moving Average           |
| MC            | Machine                  |
## Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| min          | Minutes     |
| mm           | Millimeter  |
| MO           | Missouri    |
| MRR          | Material removal rate |
| NE           | Nebraska    |
| psia         | Pound per square inch with respect to atmospheric pressure |
| psig         | Pound per square inch at gauge (gauge pressure) |
| W            | Watt        |
| WA           | Washington  |

## Glossary

| Glossary | Description |
|----------|-------------|
| A        | Processing amount, $\text{mm}^3$/minute |
| $B_{CF}$ | Conversion factor to convert HP to kW |
| $b_1$    | Specific energy consumption, $W \times \text{min}/\text{mm}^3$ |
| $b_2$    | Idle power of the machine, $W$ |
| $C$      | Compressed air flow rate from the receiver to equipment, cfm |
| $C_i$    | Summation of all the compressed air demand at an $i$th time interval, cfm |
| $C_j$    | Summation of all the compressed air demand during $j$th load/unload cycle, cfm |
| $C_M$    | Machine-level compressed air demand, cfm |
| $C_S$    | Sudden compressed air demand, cfm |
| $E_m$    | The efficiency of the air compressor motor |
| $F_R$    | Compressed air supply/demand flow rate, cfm |
| $H_F$    | Full-load HP of the air compressor |
| $H_R$    | Rated horsepower of the air compressor |
| $L$      | The total intensity of the compressed air leakages, cfm |
| $M$      | Total number of load/unload cycles for a CAS |
| $N$      | Total number of discrete-time interval |
| $PD_2$   | The peak value of the moving avg. for 2-min power demand, kW |
| $PD_{15}$| The peak value of the moving avg. for 15-min power demand, kW |
| $P_{\text{initial}}$ | Initial receiver pressure, psig |
| $P_{\text{final}}$ | Final receiver pressure, psig |
| $P_a$    | Absolute atmospheric pressure, psia |
| $P_i$    | The pressure inside the air receiver at $i$th time interval, psig |
| $P_{i-1}$| The pressure inside the air receiver at $(i-1)$th time interval, psig |
| $P_U$    | Unloading pressure, psig |
| $(P_{U/R})$ | Manufacturer rated discharge pressure, psig |
| $P_L$    | Loading pressure, psig |
| $\Delta P_L$ | Pressure change during the loading condition, psig |
| $\Delta P_U$ | Pressure change during the unloading condition, psig |
| $Q_T$    | Total Parts Produced |
| $R_{HF}$ | The proportion of full-load HP of the air compressor consumed during the unloading condition |
| $R_L$    | The proportion of the time a CAS is running in the loading condition |
| $R_U$    | The proportion of the time a CAS is running in the unloading condition |
| $S$      | Compressed air flow rate from the air compressor to the air receiver, cfm |
| $S_R$    | Manufacturer rated compressed air flow rate from the air compressor at rated discharge pressure, cfm |
| $T$      | Machine processing time, minutes |
| $t$      | A fixed discrete time interval after which the pressure in the air receiver will be monitored and updated if needed, minutes |
| $t_p$    | Time allowed for a pressure drop to occur, minutes |
| $t_0$    | The time when the simulation starts, minutes |
| $t_i$    | Simulation time at an $i$th time interval, minutes |
| $t_{i-1}$| Simulation time at $(i-1)$th time interval, minutes |
| $t_L$    | CAS loading time, minutes |
| $t_U$    | CAS unloading time, minutes |
Glossary

| Symbol | Description |
|--------|-------------|
| $t_{(L)}$ | CAS loading time for $j$th load/unload cycle, minutes |
| $t_{(U)}$ | CAS unloading time for $j$th load/unload cycle, minutes |
| $V$ | Size of the air receiver, cubic feet |
| $W$ | Machine-level power, $W$ |
| $W_{CAS}$ | Average power required by a CAS, $kW$ |
| $W_L$ | Power required by a CAS during the loading condition, $kW$ |
| $W_U$ | Power required by a CAS during the unloading condition, $kW$ |

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