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Research Article

Optimization Control of Pneumatic Compressor System

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ABSTRACT

This research addresses the optimal control for air compressor system. Compressed air is an essential utility for the main manufacturing processes in most industries. However, only 10% to 15% of the energy consumed to produce compressed air is useful, while the remainder is waste due to heat losses, air leakages, and non-optimized operations. Therefore, improving the energy efficiency of the pneumatic compressor system is desired. In this paper, a scheme for enhancing the energy efficiency of a compressed air network is proposed. The scheme mainly focuses on reducing energy consumption via monitoring the compressed air system, identifying leakages, optimizing the operation, and advising how to appropriately size and number of compressors for the demand. In this scheme, the audit is performed, wherein the pressure, temperature, and flow in the system's critical points are gathered using a sensor network. An IoT software for data acquisition and audit is developed. The data from the audit is stored in the server's database and used to monitor the system via a website. Additionally, an algorithm is developed for determining the operating schedule of each compressor through optimal problem-solving with the gathered data. The optimization proposed in this study is based on the mixed integer linear programming (MILP) algorithm. The proposed algorithm is presented generically, allowing for its application to any compressed air network with parallel compressors. Based on the optimized operating schedule, a centralized control system is implemented to control all compressors with high energy efficiency. Finally, a testbed is used to verify the centralized control system and the IoT software, whereas the performance of the optimal algorithm is validated by considering a simulation case study. This research provide a framework for designing a working schedule and providing recommendations for investment in compressors.

Key words: compressed air network, energy efficiency, data acquisition and audit, centralized control system, optimal control, mixed integer linear programming

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INTRODUCTION

Compressed air is widely used in manufacturing due to its cleanliness, usability, and practicality. In industrial processes, compressed air is used for various purposes, including stirring, sorting, blowing, and molding [1–3]. Typically, electricity is used as the energy source for producing compressed air. However, energy supplied to compressed air systems is often wasted due to heat losses occurring during the compression stage or leakages within the system. It results that the energy efficiency of compressed air systems is frequently relatively low. Some researches pointed out that just 10 to 15 percent of the energy supplied into a compressed air system is actually used as useful work for tools propelled by compressed air [1]. Therefore, energy saving for compressed air systems has been a concern for many years [4–9].

McKane and Hasanbeigi [10] investigated the cost-effective electricity-saving potential for the compressed air system based on data from six countries, including Vietnam. According to this research, the infrastructure for compressed air systems in Vietnam is still low. Therefore, Vietnam has a high percentage of cost-effective potential compared to total motor systems energy, i.e., the technical saving potential is up to 54%. This reflects that the energy efficiency of compressed air systems in Vietnam can still be improved further. In this research, the authors point out some of the most effective ways to enhance the cost-effectiveness of the compressor air system, including fixing leaks, establishing ongoing plans, modifying compressor controls, and initiating predictive maintenance programs. Kaya et al. [11] investigated improving the energy efficiency of the compressed air system based on fixing air leaks, utilizing outdoor air to drop the average inlet air temperature, lowering the air compressor pressure, and replacing high-efficiency motors. Fixing leaks is often considered the most cost-effective measure among the ways to increase cost efficiency. Many studies deal with this issue. Soylu et al. implemented ultrasonic to evaluate the energy costs of air leakages [12]. Ming Yang [13] revealed that the energy loss observed resulted from inadequate operations of the air compressor systems

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and the presence of air leakages. The author additionally presents methodologies employed in the auditing and assessment process, which serve as a framework for analyzing energy efficiency within a compressed air system. The effectiveness of the leak-fixing way is contingent upon the execution of a continuous leak management program. Therefore, conducting an energy audit is a critical measure in enhancing energy efficiency of a compressed air network [14–18]. Major brands e.g., VP Instrument, have developed high quality and expensive products for energy audits [19].

In this paper, the problem of optimization in a compressed air network consisting of a finite number of compressors and an air receiver tank is addressed. This paper proposes a scheme for improving the energy efficiency of a compressed air network. In this scheme, IoT software is developed for data acquisition and audit, i.e., gathering the data from the sensors installed in the compressed air system and storing and analyzing the data. This software allows the user to query the data via a website. The proposed scheme includes a control algorithm that provides an operating schedule for each compressor through optimal problem-solving with collected/predicted data. Finally, a centralized control system is used to control all compressors in the network based on the optimized operating schedule. A testbed is constructed for validating the centralized control system and the IoT software, whereas the effectiveness of the optimal algorithm is verified via a simulation case study.

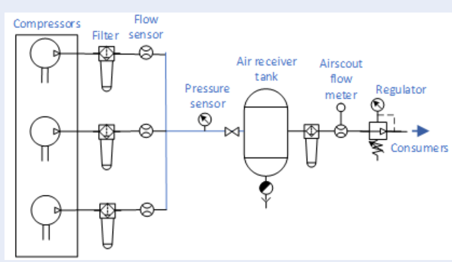

Figure 1: A compressed air network system.

The remaining sections of this paper are organized as follows: Section 2 clarifies the problem and introduces the centralized control system. Section 3 presents the methodologies for the research, including the auditing process, the optimal problem-modeling, the solving framework. In Section 4, some experimental and simulation results are shown. Finally, some conclusions are given in Section 6.

PROBLEM STATEMENT

Networks consisting of parallel compressors are commonly employed to facilitate the distribution of a gas from an upstream process to other downstream processes. A typical compressed air network is demonstrated in Figure 1. As shown in this figure, the compressed air is produced by compressors and stored in the air receiver tank. The compressed air will be transported from the air receiver tank to the end-use point (i.e., downstream) when required. The critical objective of controlling a compressed air network is to ensure that the network provides enough air mass flow demanded by the downstream process, i.e., by maintaining the pressure in the air receiver tank at a desired value. There are several ways for a compressor to control the pressure: speed control, load/unload control, and start/stop control [20–22]. The speed control is only implemented for the variable-speed air compressor (VFD compressor) with high investment costs. In contrast, the remaining ways can be applied to the fix-speed air compressor. For the load/unload control, the compressor operates in three conditions: loaded, unloaded, and stopped. The compressor is still running and consuming energy while in the "unloaded" condition; however, it wastes the compressed air instead of transporting it into the air receiver tank (Figure 2). The start/stop control starts and stops the compressor to control pressure. However, the compressor cannot be flexibly started and stopped to maintain the pressure, especially industrial compressors with high power. The frequent starting and stopping will lead to critical problems such as long starting times, motor overload, and bearing damage. Additionally, an inappropriate start/stop or load/unload control scheme can lead to a significant waste of compressed air (Figure 3). Therefore, a properly operating schedule for a compressed air network that ensures to provide enough amount of compressed air usage to satisfy the conditions on start and stop time, and to minimize the energy consumption is desired.

METHODOLOGY

This paper proposed a scheme for improving the energy efficiency of a compressed air network, as shown in Figure 4. In this scheme, a centralized control system is responsible for controlling the operation of all compressors in the network based on a predefined operating schedule. In addition, the scheme needs an audit system to understand the actual compressed air usage over time and find ways to improve the system's efficiency. The third key of this scheme is an optimal algorithm that develops the optimized operating schedule based on the data collected by the audit system.

A testbed for the centralized control system of the compressed air network is developed, as shown in Figure 1. In the testbed, three compressors compress the air and then store the compressed air in the air receiver tank. An air consumption cluster consisting of five cylinders and five discharge valves is used to simulate compressed air usage. Additionally, the filters and dryers deal with the humidity, dirt, and oil from the air in the network.

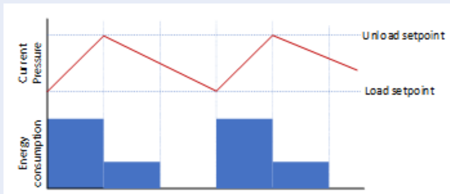

Figure 2: Maintain the pressure using load/unload control

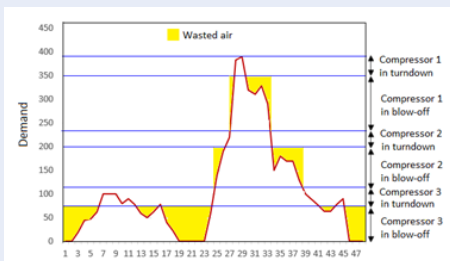

Figure 3: Wasted air when applying start/stop control and load/unload control.

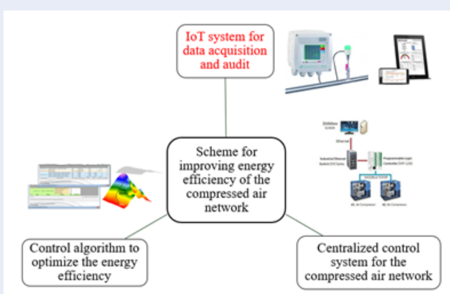

Figure 4: Scheme for improving energy efficiency of the compressed air network.

Figure 5 shows the PLC control system for the testbed. A PLC Siemens S7-1200 controls the solenoid valves

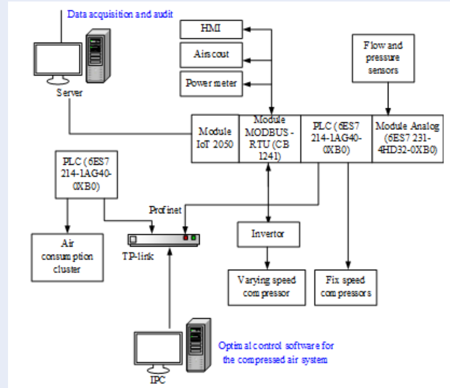

Figure 5: PLC control system for the testbed.

of the air consumption cluster. The three contractors for starting/stopping the compressors are controlled using another PLC, Siemens S7-1200. This PLC further connects to module analog, MOSBUS-RTU, and IoT. The module analog is used to read the signal from the flow sensors and pressure sensors, whereas the module MOSBUS-RTU is responsible for reading the measured value from the power meter and Airscout flow meter, controlling the inverter of the VFD compressor and communicating with Human Machine Interface. The IoT module is used to store the data and transfer them to the server.

Data acquisition and audit

Our main objective is to determine the proper operating schedule, which guarantees that the compressors' network can provide the requested compressed air and minimize the cost of the compressed air network. In order to find out this operating schedule, data acquisition and audit are necessary. This process is performed via various sensors installed in both upstream and downstream areas of the compressed air network (Figure 1). The information, including the pressure, flow, and temperature of essential points in the network and the power consumption of the compressors, are gathered by data loggers for many days. Accordingly, the behavior of the compressed air network and demand fluctuation are observed and recorded. In the testbed, three flow sensors are utilized to measure the airflow of the compressors, an Airscout flow meter from Ingersoll Rand is responsible for gathering the critical performance indicators of compressed air usage, including the pressure, flow, and temperature, and three power meters are employed to collect the information on the compressor's energy consumption. In this paper, we also design an IoT software for data acquisition and audit that allows users to observe the information of the compressed air network via the website. The data flow diagram is demonstrated in Figure 6.

First, the value from the sensor is received by the PLC through the analog module or communication (i.e., depending on the sensor type). The data is read and stored in the registers of the PLC, the IoT module queries the data address and stores it in the local database in the module (using MariaDB), and it also transfers that data to the remote server computer via the virtual private network. When the data is sent to the server, it will be inserted into the database of the server. In the case that the signal transmission to the server is interrupted, the data stored in the local database of the IoT module can be used to make up for the missing data on the server. Users can monitor the data through the website. When the website is loaded, it will query the data from the server's database and display them. The website will query again every 5 minutes.

The developed software is utilized to observe the compressed air network's behavior via the air audit data. Additionally, the information on the demand, i.e., the compressed air usage, from the gathered data is also applied for identifying the current needs, accordingly advising how to appropriately size and number of compressors and finding the optimal operating schedule. Furthermore, in the future, these data can be employed as the database for training an artificial intelligence (AI) model for anomaly warning and leak detection.

Optimization of operation of the compressed air network

According to the compressed air usage, the number of compressors, and their properties, the optimization problem of operating the compressed air network is described. In this paper, the optimization problem is modeled and solved by using the mixed integer linear programming (MILP) framework[23–25]. The MILP problem is a mathematical optimization that finds the integer (or binary) decision variables to minimize a linear objective function in which the variables must satisfy the constraint conditions described as linear equations or inequalities. This algorithm has been effectively applied to the compressed air system[26–28]. Consider a compressor air network of N compressors. Assuming that the demand for compressed air in one working cycle is depicted in Figure 7, wherein the demand is discretized into many intervals, each corresponding to a time interval $\Delta\, t$. The demand can be described by a vector The binary decision variables define the operating and stopping status of all compressors, namely,

$$x_t^i = \begin{cases} 1\ if\ the\ i^{th}\ compressor\ operates\ during\ time\ period\ t, \\ 0\ otherwise. \end{cases} \quad (1)$$

$$f_t^i = \begin{cases} 1\ if\ the\ i^{th}\ compressor\ stops\ during\ time\ period\ t, \\ 0\ otherwise. \end{cases} \quad (2)$$

$$s_t^i = \begin{cases} 1\ if\ the\ i^{th}\ compressor\ starts\ up\ during\ time\ period\ t, \\ 0\ otherwise. \end{cases} \quad (3)$$

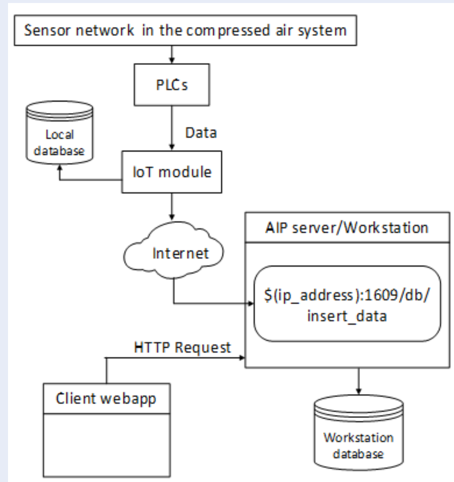

Figure 6: Data flow of the IoT software

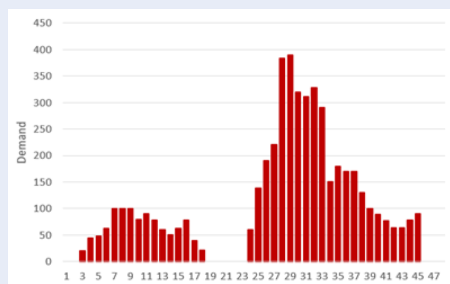

Figure 7: Demand for compressed air in one working cycle

The constraint conditions for these variables are constructed based on the characteristic of the components in the compressed air network. The following constraints show the apparent relationship between the decision variables.

$$s_t^i + f_t^i \leq 1, \quad (4)$$

$$s_t^i - f_t^i = x_t^i + x_{t-1}^i. \quad (5)$$

The compressor cannot be flexibly started and stopped, i.e., after it starts, it must run for some time.

Therefore, the constraints on the minimum operating/stopping time are required. Furthermore, the maximum operating time also should be considered.

$$1 - x_k^i \geq \sum_{k=max\{1,t-\beta_{min}^i\}}^{t} f_k^i, \quad (6)$$

$$x_k^i \geq \sum_{k=max\{1,t-\alpha_{min}^i\}}^{t} s_k^i, \quad (7)$$

$$\sum_{k=max\{1,t-\alpha_{max}^i\}}^{t} x_k^i \leq \alpha_{max}^i \quad (8)$$

where $\alpha_{min}^i > 1$ and α_{max}^i denote the minimum and maximum operating time of the i^{th} compressor; $\beta_{min}^i > 1$ is the minimum stopping time of the i^{th} compressor.

The constraint on the outlet air mass flow rate of the compressor is shown as follows:

$$\mu_{min}^i x_t^i \leq M_t^i \leq \mu_{max}^i x_t^i \quad (9)$$

where M_t^i is the compressed air mass provided by the i^{th} compressor provided during time period t; μ_{min}^i and μ_{max}^i are constants depended on the compressor's properties.

The following constraints correspond to the mass balance in the air receiver tank, the total mass flow compressed to the tank, and the tank's capacity:

$$B_t = B_{t-1} + B_t^{in} - B_t^{out}, \quad (10)$$

$$B_t^{in} = \sum_{i=1}^{t} M_t^i, \quad (11)$$

$$B_{min} \leq B_t \leq B_{max}, \quad (12)$$

where B_t, B_t^{in}, and B_t^{out} are the air mass flow inside the tank, the input and output mass flows of the tank during the time period t, respectively. B_{min} and B_{max} denote the limitation of the tank. The output mass flow of the tank must be sufficient to meet the demand during the time period t, i.e.,

$$B_t^{out} \geq \theta_t \quad (13)$$

The objective is to minimize the costs of the compressed air network. Accordingly, the following objective function is constructed: the first term is start/stop costs, and the second term denotes energy consumption costs.

$$minG = \sum_{i=1}^{n}\sum_{t=1}^{T}\left(\varphi_s^i s_t^i + \varphi_F^i f_t^i\right) + \sum_{i=1}^{n}\sum_{t=1}^{T}\varphi_X^i\left(\delta_0^i x_t^i + \delta_1^i M_t^i\right) \quad (14)$$

where φ_s^i, $\varphi_s^i$and φ_X^i are the cost of startup, shutdown, and operation of the i^{th} compressor, and δ_0^i and δ_1^i are objective function coefficient factors for the i^{th} compressor. The formulation of the optimization problem includes the objective function (14) and constraints (5)-(13). By solving this problem, the optimal operating schedule can be obtained.

RESULTS AND DISCUSSION

Testbed and air audits

The designed testbed is shown in Figure 8. Three compressors can operate to compress air to 8 bars independently or simultaneously. Two air filter regulators are installed downstream of the network. It allows to change the outlet pressure; accordingly, the demand can be adjusted as desired for testing.

Figure 8: The developed compressed air network

Figure 9: Website for monitoring and analyzing the data

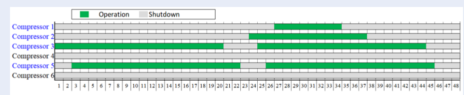

Figure 10: Optimal operating schedule for the considered case

The data gathered by the sensors are stored in the server's database, as mentioned in Section 3. The user can monitor the compressed air network via the website in Figure 9. On the website, the flow, temperature, pressure of the downstream, and energy consumption of the compressors can be observed. Furthermore, the website allows to import or export the data for many purposes.

Optimization of the operating schedule

The optimization model developed in Section 4 is verified via a case study. Consider a compressed air network with six compressors. The demand is depicted in Figure 7, wherein the time interval Δt = 0.5 hours. The dimensionless system parameters and cost are shown in Table 1. The optimization problem is solved by using the MILP algorithm in MATLAB. Accordingly, the objective function reaches the minimum value G_{min} = 6482.70. In order to achieve this value, the compressors must operate according to the schedule shown in Figure 10. This operating schedule is constructed based on the solution of the optimization problem, i.e.,...

Table 1: **Parameters of the optimization model**

Parameters of the air receiver tank						
B_0	100					
B_{max}	700					
B_{min}	100					
Parameters and costs of the compressors						
	1	**2**	**3**	**4**	**5**	**6**
μ^i_{max}	80	85	50	100	30	20
μ^i_{min}	80	85	50	20	30	20
α^i_{max}	24	24	20	20	20	20
α^i_{min}	6	6	4	4	2	2
β^i_{min}	4	4	3	3	2	2
φ^i_X	20	20	15	25	10	10
φ^i_S	0.3	0.3	0.1	0.2	0.1	0.1
φ^i_F	0.1	0.1	0.1	0.1	0.1	0.1
$^*\delta_0 = 1;\ \delta_1 = 0.05$						

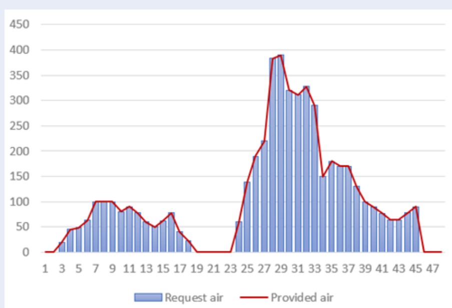

Figure 11: The operating schedule with 4 compressors can satisfy the demand.

Observing the operating schedule in Figure 10, only the 1^{st}, 2^{nd}, 3^{rd}, and 5^{th} compressors need to operate to meet the demand (Figure 11). For the demand in this example, we do not need to invest in the 4^{th} and 6^{th} compressors.

CONCLUSIONS

This paper proposed a scheme for enhancing the energy efficiency of a compressed air network. The scheme includes three components: An IoT software for data acquisition and audit that is responsible for gathering, storing, and monitoring the system's data; an optimal algorithm for finding out the optimized operating schedule for each compressor; and a centralized control system for controlling the compressors. A testbed was developed for verifying the centralized control system and the IoT software. It is apparent that the control system and the software work well. The real-time data, including the pressure, temperature, and flow in the important points in the network and the power consumption of the compressors is collected and can be queried via a website. The optimal algorithm is also validated via a simulation case study. The solution to the optimal problem is the framework for designing a working schedule as well as providing recommendations for investment in air compressors.

In the future, the optimal algorithm will be validated via more practical study cases. Additionally, based on the audit data, an AI model will be built to predict network leakages.

ABBREVIATIONS

MILP: Mixed integer linear programming

VFD: Variable frequency drive

PLC: Programmable logic controller

CONFLICT OF INTEREST

The authors wish to confirm that there are no know conflicts of interest associated with this publication.

AUTHORS' CONTRIBUTIONS

P.-T. Pham contributed to conceptualization and methodology; Q. P. Tran handled data collection; T. H. Phung was responsible for data analysis; Q.C. Nguyen contributed to supervision, and review; D. A. Nguyen participated in manuscript editing. All authors reviewed and approved the final version of the manuscript.

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Tạp chí Phát triển Khoa học và Công nghệ – Engineering and Technology 2025, 8(4):1-1

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Bài nghiên cứu

Điều khiển tối ưu cho hệ thống máy nén khí

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TÓM TẮT

Bài nghiên cứu này đề cập đến điều khiển tối ưu cho hệ thống máy nén khí. Khí nén là nguồn năng lượng phổ biến được sử dụng trong các quy trình sản xuất trong công nghiệp. Tuy nhiên, chỉ có 10% đến 15% năng lượng điện chuyển hoá thành năng lượng dạng khí nén, phần năng lượng còn lại bị lãng phí do các nguyên nhân như thất thoát do quá trình nhiệt nén, rò rỉ khí và vận hành không tối ưu. Do đó, việc nâng cao hiệu quả sử dụng năng lượng của hệ thống máy nén khí là điều cần thiết. Trong bài báo này, một giải pháp nâng cao hiệu quả năng lượng của mạng lưới khí nén được đề xuất. Giải pháp được đề xuất tập trung vào việc giảm tiêu thụ năng lượng thông qua giám sát hệ thống khí nén, xác định rò rỉ, tối ưu hóa vận hành và tư vấn kích thước, số lượng máy nén phù hợp với nhu cầu sử dụng. Trong giải pháp này, quá trình thu thập dữ liệu và kiểm toán năng lượng được thực hiện, trong đó áp suất, nhiệt độ và lưu lượng tại các điểm quan trọng của hệ thống được thu thập bằng một hệ thống các cảm biến. Một phần mềm IoT để thu thập dữ liệu và kiểm toán được phát triển. Dữ liệu từ quá trình kiểm toán được lưu trữ trong cơ sở dữ liệu của máy chủ và được sử dụng để giám sát hệ thống thông qua một trang web. Ngoài ra, một thuật toán được phát triển để xây dựng lịch trình vận hành của từng máy nén thông qua giải quyết vấn đề tối ưu với dữ liệu thu thập được. Tối ưu hóa được đề xuất trong nghiên cứu này dựa trên thuật toán mixed integer linear programming (MILP). Thuật toán đề xuất có thể áp dụng cho bất kỳ mạng mkhí nén nào với các máy nén bố trí song song. Dựa trên lịch trình vận hành được tối ưu hóa, một hệ thống điều khiển tập trung được triển khai để điều khiển tất cả các máy nén với hiệu suất năng lượng cao. Cuối cùng, một hệ thống thử nghiệm được sử dụng để kiểm tra hệ thống điều khiển tập trung và phần mềm IoT, trong khi hiệu suất của thuật toán tối ưu được kiểm tra thông qua một nghiên cứu tình huống mô phỏng. Nghiên cứu này cung cấp một bộ khung để thiết kế lịch làm việc và đưa ra khuyến nghị về đầu tư vào máy nén.

Từ khoá: hệ thống máy nén khí, hiệu năng năng lượng, thu thập dữ liệu và kiểm toán, hệ thống điều khiển tập trung, điều khiển tối ưu, lập trình tuyến tính số nguyên hỗn hợp

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