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Predictive Maintenance Model for Pneumatic Systems Supported by Industry 4.0 and Edge Computing

Ceren Sevin Kelesli[1] **Mehmet Akif Şahman**[2*] **Abdullah Oktay Dündar**[3]

[1] Selçuk University, Institute of Natural Sciences, Department of Electrical and Electronic Engineering, Konya / Turkiye

[2] Selçuk University, Faculty of Technology, Department of Electrical and Electronic Engineering, Konya / Turkiye

[3] Necmettin Erbakan University, Faculty of Applied Sciences, Department of Logistics Management, Konya / Turkiye

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ABSTRACT

Pneumatic systems are actuators that convert compressed air from the atmosphere into pressure energy and use it for mechanical action. The movements referred to here are mechanical movements, such as linear or circular movements. Pneumatic systems have been used in the manufacturing industry since the 1950s. Today, we see that pneumatic installations are also being constructed alongside electrical and water lines in factories that produce goods. This situation clearly demonstrates that pneumatic systems have become an indispensable and fundamental necessity in production processes. When evaluating pneumatic systems from an Industry 4.0 perspective, it becomes apparent that a great deal of data can be collected from the environments in which pneumatic systems are used to increase efficiency. Although there are different approaches to managing and analyzing the data obtained from these sources, cloud computing and edge computing are the two most prominent approaches. Today, it is common to see these two approaches used together. Data obtained from the source via Edge Computing is analyzed at the source and used to obtain quick results, while Cloud Computing is used only for the transfer and analysis of important data. This reduces unnecessary time and performance losses in the system, making it more efficient. In this study, the Industry 4.0 concept's Edge Computing approach was applied to a real-life problem. The problem addressed was predictive maintenance in pneumatic systems. This problem was studied on the fully automated bread processing and stacking line of Brotmas, a company based in Konya that manufactures baking machines. Data was collected from the company on key points in the system, including the detection of leaks in the air piping, compressor oil level control, manometer pressure value control, compressor belt tension control, and inverter-based compressor motor health control. The collected data was compared with new information to prevent potential failures. As a result of this study, it was observed that error notifications caused by compressor shutdown, pressure drop, maintenance deficiencies, and pneumatic piston failures decreased by 67%.

Pnömatik Sistemler için Endüstri 4.0 ve Edge Computing Destekli Kestirimci Bakım Modeli

Makale Bilgisi

Makale Geçmişi

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ÖZET

Pnömatik sistemler, atmosferden alınan havanın, sıkıştırılarak basınç enerjisine dönüştürülmesi ve bunun mekanik aksiyon olarak kullanılmasını sağlayan aktüatörlerdir. Burada bahsedilen hareketler, doğrusal veya dairesel hareket gibi mekanik hareketlerdir. Pnömatik sistemler 1950 yıllarından itibaren üretim endüstrisinde kullanılmaya başlanmıştır. Günümüzde ise üretim yapacak fabrikalarda, elektrik ve su hatları ile birlikte pnömatik tesisatlarının da yapıldığını görmekteyiz. Bu durum, üretim süreçlerinde pnömatik sistemlerin artık göz ardı edilemeyecek kadar önemli ve temel bir ihtiyaç haline geldiğini net bir şekilde ortaya koymaktadır. Endüstri 4.0 bakış açısıyla pnömatik sistemleri değerlendirmemiz gerekirse, pnömatik sistemlerin kullanıldığı ortamlardan verimi arttırabilecek birçok verinin toplanabileceği görülür. Buradan elde edilen verilerin yönetilmesi ve analizi için farklı yaklaşımlar bulunmasına rağmen, Bulut Bilişim ve Uç bilişim en çok göze çarpan iki yaklaşım olarak karşımıza çıkmaktadır. Günümüzde bu iki yaklaşımın birlikte kullanılmasına sıkça rastlanılmaktadır. Uç Bilişim ile kaynaktan elde edilen veriler, kaynağa en yakın yerde analiz edilmekte ve hızlı sonuç almada kullanılırken, Bulut Bilişim sadece önemli verilerin aktarılması ve analizi için kullanılmaktadır. Böylece sistemdeki gereksiz zaman, performans kayıpları azaltılmakta ve daha verimli hale gelmektedir. Bu çalışmada, Endüstri 4.0 konseptinin Uç Bilişim yaklaşımı, gerçek bir hayat probleminde kullanılmıştır. Burada pnömatik sistemlerdeki kestirimci bakım problemi ele alınmıştır. Bu problem Konya'da bulunan, fırın makinaları üreten Brotmas firmasının tam otomatik ekmek işleme ve dizme hattı üzerinde çalışılmıştır. Firmadan, borulardaki hava tesisatındaki kaçakların tespiti, kompresör yağ seviyesi kontrolü, manometre basınç değer kontrolü, kompresör kayış gerginliği kontrolü ve invertörle kompresör motor sağlığı kontrolü dahil olmak üzere sistemdeki kilit noktalardan veriler toplandı. Toplanan veriler ise olası arızaları önlemek için yeni bilgilerle karşılaştırıldı. Bu çalışmanın sonucunda, kompresörün kapalı olması, basınç düşmesi, bakım eksikliği ve pnömatik piston arızaları nedeniyle oluşan hata bildirimleri %67 oranında azaldığı gözlemlendi.

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***Corresponding Author:** Mehmet Akif Şahman, *asahman@selcuk.edu.tr*

INTRODUCTION

In particular, the use of technologies such as artificial intelligence, cyber-physical systems, big data, cloud computing, the Internet of Things (IoT), and edge computing in production processes has significantly contributed to the emergence of the Industry 4.0 concept. The integration of these technologies into production systems, supporting many innovative activities, has brought about a new industrial revolution (Avcı & Candan, 2023). During this Industrial Revolution, production takes place in smart factories that integrate autonomous robots and other related technologies (Koç & Özcan, 2023). The integration of these developments into production sites has brought about a new industrial revolution. The transformation brought about by Industry 4.0 has begun to offer advantages such as increased production efficiency, monitoring and optimization of maintenance processes, and a reduction in error rates. In addition, artificial intelligence approaches can be used to make predictions and estimates, providing insight into the future (Atalar et al., 2025). In production lines where pneumatic systems are commonly used in industry, the technological capabilities brought by Industry 4.0 have brought predictive maintenance applications to the forefront.

Air, a clean energy source that is readily available and abundant in the atmosphere, is the main reason why pneumatic systems are frequently used in industry. In pneumatic systems, air is compressed and pressurized to generate motion. This motion can be linear, angular, or circular. Pneumatic systems, which have been used in industrial production processes since the 1950s, are now being installed alongside electrical and water lines in new factory construction. This demonstrates that pneumatic systems have become an indispensable element of automation for production facilities (Krompf, 2005). However, these systems have brought with them issues such as energy efficiency, maintenance requirements, and management of potential malfunctions. Approaches brought together under the Industry 4.0 concept are being used to solve these problems.

A wide variety of data can be collected from sensors and systems located on production lines. Analyzing this data and optimizing production lines based on the results is possible with big data and cloud computing. In the study by Velásquez and colleagues, a data-driven and network-centric model was proposed. The data obtained in this model was analyzed using cloud computing and big data technologies. As a result, system efficiency was greatly improved (Velásquez et al., 2018). Goldin and his colleagues stated in their study that real-time optimization and fault detection can be performed with data transferred to cloud computing. The data obtained was processed using machine learning algorithms, enabling the early detection of potential system failures. This aimed to prevent production line stoppages and financial losses (Goldin et al., 2017). In the study of Küçüköz, discusses maintenance using cloud computing methods based on data collected from the field regarding improvements in pneumatic systems with Industry 4.0. The study focuses on the processing of data collected from the field in a cloud structure for shock absorber wear control, leak detection, valve life control, and air consumption optimization (Küçüköz, 2017).

Cloud computing has been used to achieve successful results in many industries. However, this infrastructure has some disadvantages, especially in high-precision applications that require responses in real time. In particular, delays that occur when data is transferred to the cloud system, analyzed there, and then sent back to the system can result in significant losses. At this point, edge computing has emerged as an approach that accelerates decision-making processes by enabling data to be collected and evaluated at the point closest to the source. Edge computing has particularly established itself in small data sets. In their study, Bajic and colleagues demonstrated that real-time predictive models could achieve successful results without errors in small data sets by utilizing edge computing (Bajic et al., 2020). Additionally, Hussain and colleagues discussed the disadvantages of diversity and the presence of many users in environments where cloud computing is used and noted that edge computing could be an alternative in this regard (Hussain et al., 2020). In their study, Stankovski and his colleagues showed that micro/mini-PLCs/PACs, which are frequently used in industry, can be used as edge computing technology to prevent cylinder failure. It was stated that modern micro/mini-PLCs/PACs contribute to improving the performance of cloud computing by demonstrating sufficient performance for edge computing (Stankovski et al., 2020). In addition, Scotece and his colleagues compared cloud computing and edge computing in terms of efficiency and data transfer. This comparison showed that edge computing had four times fewer service interruptions than cloud computing. For these reasons, they recommended the use of edge computing, especially for real-time fault detection (Scotece et al., 2021).

Industry 4.0 and edge computing have been used not only in theory but also in real-life applications. Some applications have also explored how pneumatic systems can benefit from these approaches. Ciancio et al. conducted two different industrial applications, confirming that the current and future health status of equipment on the production line can be monitored, unplanned downtime can be reduced, and maintenance processes can be made more efficient (Ciancio et al., 2024). Alves et al. proposed an approach called Maintenance 4.0. In this approach, they combined technologies such as IoT, artificial intelligence, and big data. This ensures transparency in maintenance processes and minimizes human error (Alves et al., 2024).

As a result, Industry 4.0 components offer many advantages over pneumatic systems in terms of increasing production processes, reducing maintenance costs, and minimizing potential failures. With edge computing, fast and effective results can be obtained at the source. Studies in the literature also confirm this result. In this study, the edge computing approach, one of the technologies integrated with Industry 4.0, was applied to a fully automated bread processing and packaging line. For this application, sensors were placed at key points along the line, and the real-time data obtained was evaluated in a PLC-based system, providing users with information about error notifications. This system has achieved a significant reduction in error notifications. As a result, the company has prevented disruptions in its existing line and ensured production continuity.

MATERIALS

Energy conservation means not wasting energy at any stage of its production and use. In other words, energy conservation refers to the efficient use of energy. With concerns about global warming and sustainability, the importance of energy conservation is increasing every day around the world. Energy efficiency is on the agenda of manufacturing companies as a means of reducing production costs and achieving sustainability goals. With the advancement of technology, energy is used in almost all production and consumption activities. The efficient use of energy not only provides financial advantages but also contributes to the goal of a cleaner and greener world, thereby preventing the climate crisis.

For this reason, system efficiency is very important, but each company's definition of efficiency differs. A system that provides the minimum circuit elements and minimum electrical energy required for the company's optimal use of compressed air is called an efficient pneumatic system. In this study, a system for predictive maintenance using the Industry 4.0 approach is proposed. This system aims to reduce downtime losses in automation using pneumatic systems, as well as to detect leaks and increase efficiency. The basic components used in the predictive maintenance system described in this study are detailed below.

System Subcomponents

While it is possible to increase the efficiency of pneumatic systems through proper design, it is also possible to increase system efficiency during operation through maintenance and rapid leak detection methods. Obtaining accurate data in real time is one of the most important factors in detecting errors. In the proposed system, the following sensors are used to obtain data from the field in real time. These subcomponents consist of a digital manometer, reed sensor, background suppression sensor, level sensor, oil tank, inverter, compressor, programmable logic controller (PLC), human-machine interface (HMI), and communication systems.

A digital manometer may show differences between the pressure produced by the compressor and the system pressure. Any differences that may occur indicate that there may be a loss or leak in the system. In the proposed system, the SMC brand ISE30A-01-P-L (0) has been selected as the digital manometer (**Figure 1**). Reed sensors are installed on all pistons and cylinders in the process. Tongue-contact sensors are installed at the upper and lower limits of the piston stroke or the upper and lower limits of mechanical operation. The sensor provides a digital output when the piston stroke is complete. This time is expected to be constant. Any increase or decrease in this time indicates mechanical problems with the piston. In the recommended system, the D-M9PZ tongue-contact sensor has been selected (**Figure 2**).

Figure 1
Digital manometer

Figure 2
Reed sensor

The tightness or looseness of the compressor belt tension can cause irreversible consequences in the system. When the belt is tight, the compressor motor will draw more current, and when it is loose, it will draw less current. We can see this in the current data we obtain from the inverter. However, the looseness of the belt in the compressor has been digitally detected using a background suppression sensor that is not affected by the physical condition of the material. In the proposed system, the LEUZE-HT15 has been selected as the background suppression sensor (**Figure 3**). Monitoring oil levels in compressors and intervening quickly when necessary is a critical issue for both the compressor and the pneumatic system that depends on it. Therefore, the oil level in the compressor is controlled by a sensor that provides a digital output. In the recommended system, IST has been chosen as the level sensor oil tank (**Figure 4**).

Figure 3
Back-illuminated sensor

Figure 4
Oil tank with level sensor

Inverters are digital devices used to convert power in a system. In this study, the motor current value in inverter compressors is measured. In subsequent stages, the optimum operating frequency of the pneumatic system can be determined, and energy efficiency can be increased by operating at lower frequencies. In this study, a Mitsubishi Electric FR-F840-00170-E2-60 model inverter was used (**Figure 5**). Compressors are machines that compress the air they take in from outside and enable us to use compressed air in a controlled manner. Compressors are one of the most important components in pneumatic systems. Faults in compressors prevent the system from achieving sufficient pressure and from operating at the desired level of efficiency. In this study, considering efficiency and cost factors, the screw compressor EKOMAK brand, DMD 250 C series compressor, which is frequently preferred in industry for small and medium-level pressure needs, was used at 8 bar throughout the test (**Figure 6**).

Figure 5
Inverter

Figure 6
Compressor

In this study, a Mitsubishi Electric FX5U-32MT/DSS (**Figure 7**) programmable logic controller (PLC) was used for data collection and processing from the field, and Mitsubishi Electric GX Works 3 software was used for PLC software program fragments. The human-machine interface (HMI) is the structure used by the operator to intervene in the system via the PLC. In industry, the term operator panel is more commonly used. The user's interaction with the system via HMI is limited. HMIs can be Windows or Linux-based, or they can have their own interface. The Mitsubishi Electric GS-2107-WTBD-N HMI used in this study (**Figure 8**) was programmed using the GT Designer interface.

Figure 7
Programmable Logic Controller (PLC)

Figure 8
Human-Machine Interface (HMI)

PLC, HMI, and inverter are connected via a communication structure because they complete their internal cycles. Mitsubishi Electric products communicate directly with each other. Mitsubishi Electric's “Inverter Communication” protocol has been selected between the PLC and the inverter.

METHODS

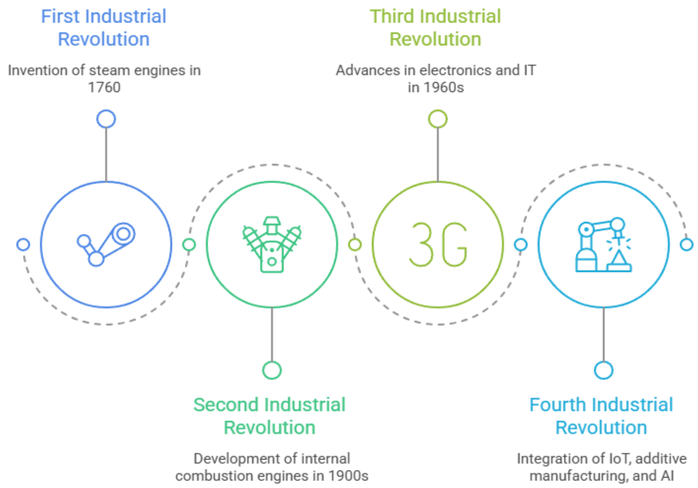
In this section, basic information about the concept is provided first, as the methods used in the study can be considered within the scope of Industry 4.0. Due to the need for fast computing and quick responses, edge computing was used in this study instead of cloud computing. Therefore, information about edge computing is also provided. In addition, information about basic machine maintenance is provided.

The Concept of Industry 4.0

The concept of the Fourth Industrial Revolution was first introduced by Klaus Schwab. This concept aims to reduce errors and increase production efficiency by combining the latest technological approaches (Xu et al., 2018). The First Industrial Revolution began in 1760 with the invention of steam engines. This industrial revolution was followed by the invention of internal combustion engines in the 1900s. Thus, the use of internal combustion engines in various fields gave rise to the Second Industrial Revolution. Advances in electronics and information technology in the 1960s led to the emergence of the third revolution (**Figure 9**). The fourth industrial revolution emerged through the integrated use of cutting-edge technologies such as the Internet of Things, additive manufacturing, and artificial intelligence (Philbeck & Davis, 2018).

Figure 9

Evolution of Industrial Revolutions

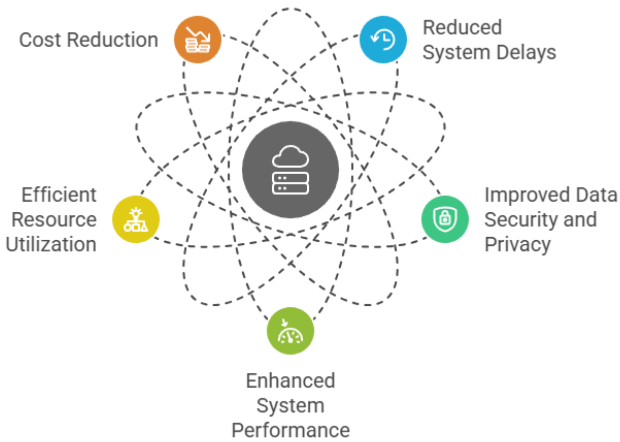


Edge Computing

Edge computing, a distributed information technology, addresses some of the issues inherent in cloud computing architecture. In edge computing, time-sensitive tasks are processed on a local smart device, and most data is stored at the user's source. This distributes the load of cloud computing and improves performance (Varghese et al., 2016). The main benefits of edge computing are as follows (**Figure 10**):

Figure 10

Benefits of Edge Computing

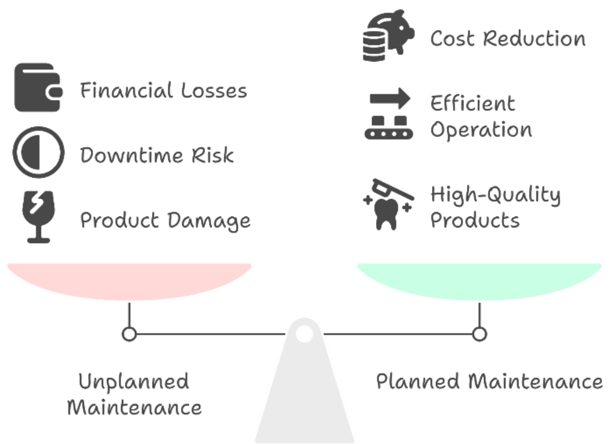


Machine Maintenance

Machine maintenance methods are divided into planned and unplanned maintenance, as shown in **Figure 11**. Maintenance that is performed when a malfunction occurs is considered unplanned maintenance, but it can cause serious financial losses for businesses. There are also cases where a malfunctioning product damages other products.

The importance of planned maintenance is undeniable in terms of producing high-quality products, reducing downtime and costs, ensuring efficient machine operation, and minimizing energy consumption.

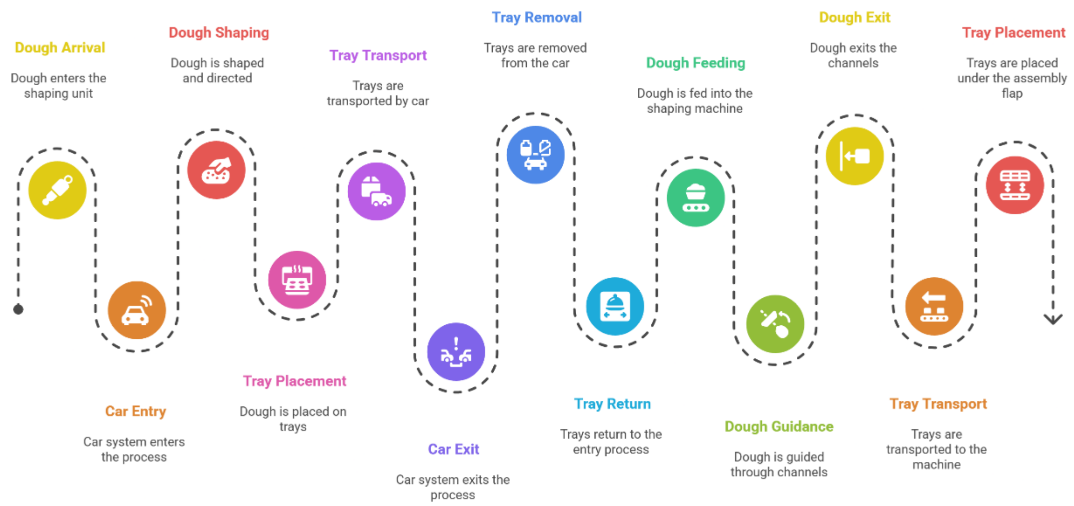
Figure 11
Advantages and Disadvantages of Machine Maintenance Approaches



PREDICTIVE MAINTENANCE APPLICATION with PNEUMATIC SYSTEMS

Dough processing and forming lines are frequently used in the food industry, bakeries, and large pastry shops. Pneumatic systems are used in these lines due to the need for hygienic production environments and the economic benefits of using compressed air as a driving force.

Figure 11
Dough Processing and Forming Line Sequence



The dough arrives at the shaping unit as shown in **Figure 11**, and the dough is directed. At this point, the system we call the car, the pan carrier system, enters. While the dough is being shaped and directed, the car entry process, the locking of the car, and the pan being placed on the car with the help of the auxiliary pusher are carried out. The directed dough is arranged on the tray. The tray is transported by car, and finally, the car exits. The tray is removed from the car and returned to the car entry process.

Software has also been developed to monitor this system. This software allows data to be collected from many points in the automation system and enables potential system malfunctions to be detected.

Figure 12
Operator panel main screen

When designing the human-machine interface, care was taken to ensure that it was not complicated and that only parameters requiring constant access were displayed on the HMI in a basic format. The button on the HMI lights up green to indicate that the system is working properly, black to indicate that the system is not working, and red to indicate that there is a problem with the system.

ANALYSIS and RESULTS

In this study, edge computing was utilized to reduce error rates in pneumatic systems. In the proposed system, real-time status information is continuously obtained from different sensors. The information obtained is processed in the PLC, and real-time information about the system is provided to the user. Since the proposed system was considered a real-life problem, it was desired to obtain real data by applying it in the field.

For the implementation of the system, a fully automatic bread processing and packaging line belonging to Brotmas, a company based in Konya that manufactures baking machines, was selected. In the system, data was collected from important points such as detecting leaks in the air system, checking the compressor oil level, monitoring manometer pressure values, checking compressor belt tension, and monitoring compressor motor health via the inverter.

The applicability and efficiency of the system for the fully automatic bread processing and stacking line currently on sale were tested over one month. During the trials, error reports were first collected without applying the predictive maintenance system proposed in this study. Subsequently, the proposed system was applied to the existing automation, and error reports were collected. The results obtained, with the company's approval, are as follows (Table 1).

With the study, it was observed that there was a decrease of approximately 67% in fault reports in the fully automated bread processing and stacking line of the company where the application was implemented. The decrease in fault report rates reduced the workload of the personnel working in after-sales services and increased customer satisfaction.

Table 1
Comparison of Faults in Fully Automatic Bread Processing and Stacking Lines

Fault Logs	Current System	Recommended System
Fault reports due to the compressor being shut down	8	1
Fault reports due to a pressure drop in the compressor	13	4
Faults caused by the lack of maintenance of the compressor	9	2
Fault reports due to water entering the pneumatic pistons	14	6
Faults caused by a slowdown due to seal wear in the pneumatic pistons	3	1
Faults caused by pneumatic piston sensors	2	2
TOTAL	**49**	**16**

Additionally, since the sources of malfunctions could be identified promptly and accurately, it became possible to intervene at points where errors could occur, and the company also gained the opportunity to implement preventive improvements in those areas for future products.

CONCLUSIONS

The advantages of pneumatic systems include the fact that the air used in them is free and unlimited in the atmosphere, has few adverse effects on the environment, can be adjusted in terms of speed and force, can be transported over long distances, and has inexpensive and safe control elements. Therefore, pneumatic systems are indispensable for many companies operating in our country. Pneumatic systems, which are frequently used in production processes, play a crucial role in ensuring uninterrupted production. Therefore, it is essential to take precautions against errors that could disrupt the operation of pneumatic systems.

In this study, an error tracking system supported by sensors and designed with an edge computing approach in line with the Industry 4.0 concept is proposed. A device with a pneumatic infrastructure was selected for the proposed system. Thus, the proposed system could be addressed as a real-life problem. The proposed predictive maintenance system was applied to the fully automated bread processing and stacking line belonging to Brotmas, a company operating in Konya that manufactures baking machines. Error reports were collected before and after the proposed system was applied to the existing automation. After the proposed system was applied, a 67% reduction in error reports was observed.

In future studies, it is recommended that error reports be collected from devices used for edge computing, processed using machine learning algorithms on cloud computing devices, and the remaining lifespans of key tools in the system be estimated.

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