J. Innovative Eng. Nat. Sci., vol. 5, no. 2, pp. 871-883, 2025.
http://doi.org/10.61112/jiens.1705527

Journal of Innovative Engineering and Natural Science
(Yenilikçi Mühendislik ve Doğa Bilimleri Dergisi)
https://dergipark.org.tr/en/pub/jiens

Original Paper

LoRa communication based monitoring of a brake pad factory

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ARTICLE INFO

Article history:
Received 24 May 2025
Received in revised form 20 July 2024
Accepted 28 July 2025

Available online

Keywords:
Data collection
Industrial automation
IoT
LoRa

ABSTRACT

In this study, data collection and analysis were carried out in a brake pad factory environment using Internet of Things (IoT) technology and a long-range (LoRa) communication protocol. Specially designed data collection modules integrated into the press machines recorded the machines' real-time running, downtime and error data, and transmitted this data to a central gateway via the LoRa protocol. The collected data was stored in an SQL-based database, and an interface was designed to allow users to monitor production processes. This interface allows users to monitor, analyze, and intervene in production processes when necessary. With the proposed system, daily production output increased by 9%, while fault detection times were reduced from 45 minutes to 20 minutes. Additionally, a 98% data transmission success rate was achieved without being affected by electromagnetic interference, even in an industrial environment such as a brake pad factory with a large operational area. The results indicated that LoRa-based systems offer a low-cost, flexible, and energy-efficient solution, enhancing operational efficiency by optimizing production processes.

I. INTRODUCTION

The evolution of industrial production to its present form has been shaped by four fundamental industrial revolutions. The First Industrial Revolution, known as Industry 1.0, began with the use of water and steam power in mechanical production systems. Industry 2.0 followed with the use of electrical energy and the widespread adoption of mass production. Industry 3.0 introduced the integration of digital technologies and electronic systems into production processes. Today, Industry 4.0 has brought about a profound transformation in production systems. This new industrial structure centres on the digitalization and automation of production processes, marking a transformative shift in the manufacturing sector. Industry 4.0 aims to improve productivity, quality, speed, and flexibility by promoting the integration of smart systems and automation technologies into production lines. Industrial automation, a key component of digital transformation, enhances the efficiency of repetitive tasks, reduces human error, and increases control over production processes. Within this context, technologies such as the Internet of Things (IoT), cyber-physical systems, and big data analytics offer real-time data exchange and analysis capabilities between machines and systems [1-5].

LoRa technology stands out for IoT applications with its energy efficiency and long-range communication capabilities. By enabling long-distance communication with low power consumption, LoRa facilities real-time monitoring of operational data in factory environments. In industrial automation systems, IoT-based data collection applications enhance both traceability and control, making modern production processes more sustainable and flexible. Real-time, data-driven decision-making processes in production facilities not only improve production efficiency but also ensure more effective use of resources [6-8]. In the literature, various

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studies have investigated the use of LoRa technology in industrial automation applications. In a study conducted by Raza et al., a detailed review of low-power wide-area network (LPWAN) technologies was presented. The researchers highlighted the critical role of LPWAN in the fields of IoT and machine-to-machine (M2M) communication [9]. In another study, São José et al. examined the resilience of LoRa and LoRaWAN technologies against electromagnetic interference (EMI), with a particular focus on railway environments. The researchers analyzed the effects of EMI sources such as transient voltage fluctuations caused by electrical arcs and jamming signals [10]. In a study conducted by Mekki et al., LPWAN technologies such as Sigfox, LoRa, and NB-IoT, which are used in IoT applications, were comparatively examined. The researchers evaluated the technical specifications, performance factors, and application areas of these technologies [11]. In a study conducted by Suhermanto et al., the potential of LoRa technology for motor monitoring and control applications in IoT-based systems was examined in detail [12]. In another study, Ghosh et al. developed LoRaute, a LoRa-based message routing system designed to support network communication in remote areas [13]. In the study by Özdemir and Gökrem, an early warning system was designed using LoRaWAN technology, and its applicability against natural disasters such as fires and floods was investigated [14]. Sundaram et al. presented a comprehensive review of LoRa networks, addressing the research challenges, current solutions, and open issues related to this technology [15]. Zhang et al. developed and evaluated a LoRaWAN-based IoT system for precision irrigation in fresh market tomato production under plastic covers [16]. In another study, Nguyen et al. proposed a new module-based approach for over-the-air device firmware updates in LoRaWAN networks [17].

In this study, the design of LoRa-based data collection modules and their integration into press machines were carried out. Both hardware and software systems were developed to record machine’s running time, downtime, and error data. All collected data were stored and managed using an SQL-based database system. Additionally, a custom user interface was designed for the analysis and visualization of the collected data. The system was tested in terms of reliability and energy efficiency, and its performance in an industrial environment was evaluated. The implemented system enabled real-time monitoring and optimization of production processes, contributing to reduced operational costs and enhanced production quality.

II. EXPERIMENTAL METHOD / TEORETICAL METHOD

LoRa is a wireless communication protocol specifically developed to enable long-range data transmission with low power consumption. The LoRa technology consists of three layers: the physical layer (PHY), the medium access control (MAC) layer, and the application layer. The LoRa layer structure is illustrated in Figure 1.

While the physical layer uses a special modulation technique, the MAC layer uses an open communication protocol known as LoRaWAN. The LoRa PHY is one of the fundamental components of wireless communication technology. The key technique used in this layer is chirp spread spectrum (CSS) modulation. CSS provides encoding data using chirp signals, in which the frequency varies linearly over a defined time interval [14, 18]. The LoRaWAN network consists of three fundamental components that work in an integrated manner to provide long-distance and low-power data transmission: end devices, gateways, and network servers. These components ensure that data transmission is carried out securely and efficiently from the endpoint to the cloud. In LoRaWAN networks, the application layer plays a critical role in processing, managing, and securing the data after data transmission. This layer includes various tools and mechanisms to extend the functionality of the protocol and provide an end-to-end solution [19, 20]. In addition to LoRa, other wireless communication protocols include Sigfox, Narrowband IoT (NB-IoT), ZigBee, Wi-Fi, Bluetooth Low Energy (BLE), and others. Similar to LoRa, Sigfox is a long-range, low-data-rate protocol that offers low power consumption. However, Sigfox operates on a fixed bandwidth and is dependent on network infrastructure. Therefore, the local control and network flexibility provided by LoRa are considered more advantageous compared to Sigfox. NB-IoT is a protocol based on cellular infrastructure and offers advantages over LoRa in terms of data transmission security and quality. However, higher energy consumption and the requirement for cellular infrastructure make NB-IoT a more costly option, particularly in wide-area deployments. NB-IoT is preferred in applications that require large data transmission capacities and high levels of security, whereas LoRa is advantageous for systems that demand wide-area coverage with low energy consumption. ZigBee stands out for its short-range data transmission and low power consumption. However, due to its range limitations, it offers only a limited option for data collection in large industrial facilities. While ZigBee is commonly used in indoor applications or systems that require high data transmission rates over short distances, LoRa is more suitable for outdoor or industrial environments where wide-area coverage is needed. Wi-Fi stands out as a protocol with high data transfer rates and is ideal for short-range applications that demand high bandwidth. Nonetheless, its high energy consumption and restricted coverage area limit its applicability in large-scale industrial environments. Although Wi-Fi is often preferred in data-intensive applications that require real-time analytics, it is not efficient for low-bandwidth scenarios where protocols like LoRa are more appropriate. BLE, known for its low power consumption, short-range communication, and compatibility with mobile devices, also faces limitations in large industrial plants due to its range of constraints. Compared to other communication protocols, the limitations encountered in wireless communication are overcome by the solutions provided by LoRa, making it a favorable option for industrial automation. LoRa's low energy consumption, wide coverage, resistance to interference, and security features distinguish it as a leading technology in this field [15, 21–23].

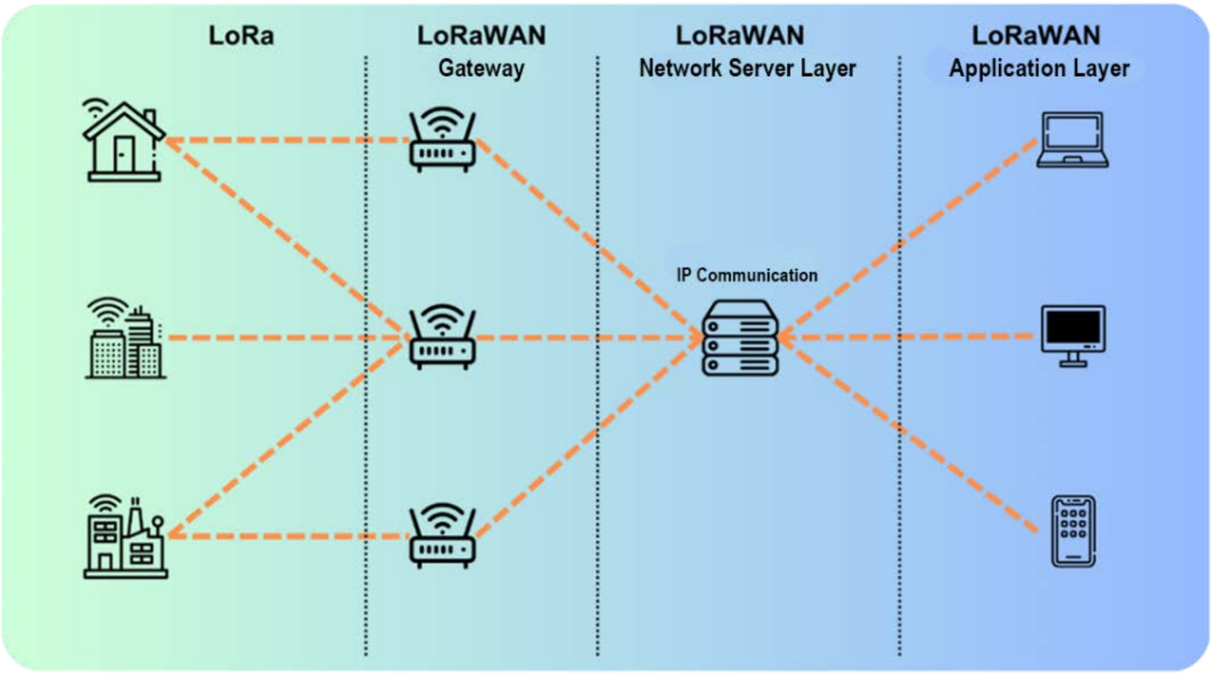


Figure 1. LoRa layers and operating principle

2.1 System Design

The system developed in this study is designed for real-time monitoring and data analysis of industrial press machines, and consists of four main components: data collection hardware, a central gateway, an analysis server, and a user interface. The optocoupler-based hardware integrated into the press machines was designed to monitor the operational status of the machines and record the relevant data. As shown in Figure 2, the hardware consists of an ATMEGA328P-AU microcontroller and an RA-01 LoRa module. Optocouplers detect the machine's operation and stop signals and transmit them to the microcontroller. These data are then sent to the central gateway via the LoRa module. The gateway, which includes an ESP8266 Wi-Fi module and an RA-01 LoRa module, transfers the signals received from the data collection hardware to the computer via the COM port. The gateway plays a critical role in enabling wide-range data transmission. The central gateway is illustrated in Figure 3.

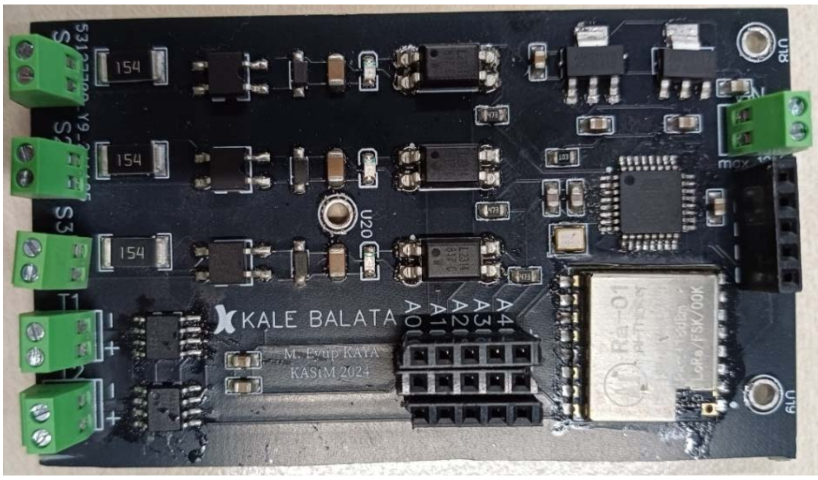


Figure 2. Data collection hardware

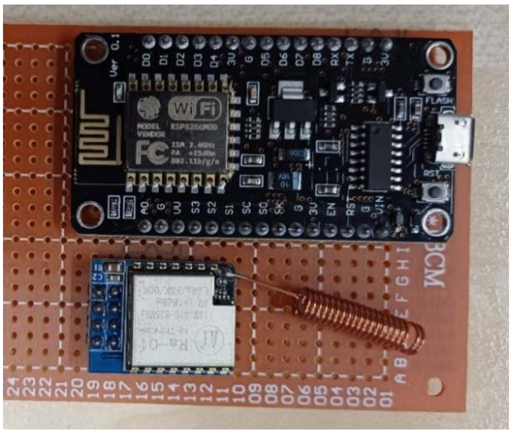


Figure 3. Central gateway

The analysis server is an SQL-based database system used for storing and analyzing the collected data. The server processes incoming data and enables integration with the user interface. A Windows Forms application developed using the C# programming language in Visual Studio allows users to monitor the real-time status and production history of all press machines. This interface enables users to easily monitor the production processes and intervene when necessary.

2.2 Hardware and Software

The hardware infrastructure of the system consists of data collection hardware and a central gateway. These components are designed to detect the operating status of press machines, process the data, and transmit it. The optocouplers located on the data collection hardware are components that safely transfer 220V signals to the microcontroller. They provide electrical isolation during operation and convert signals into meaningful data, which is then transmitted to the microcontroller. The 817 series optocouplers are used, offering effective protection against electrical noise. The central processing unit of the data collection hardware is the ATMEGA328P-AU microcontroller. The RA-01 module on the hardware is a low-power communication module used to wirelessly transmit data over long distances, ensuring reliable data transfer. The thermocouple inputs on the hardware are used to monitor the mold temperatures of the press machines. Since mold temperature affects production quality, it is of critical importance. MAX6675 integrated circuits capable of measuring temperature from K-type thermocouple sensors are used on the hardware.

The system shown in Figure 4 was modeled within the framework of the industrial automation pyramid. The sensor level consists of components such as EL817 optocouplers, MAX6675 thermocouple sensors, and buttons, which perform the data collection process. The control level includes the ATMEGA328P microcontroller and the RA-01 LoRa module, which process the data received from the sensors and manage wireless communication. The supervisory level, through the ESP8266 module, transmits the data to an SQL database, supporting analysis and reporting processes. The management level includes the production monitoring system and enables decision-making aimed at optimizing processes using data analyzed via the SQL database.

The system's software infrastructure was supported by a software package that performs data collection, transmission, storage, and analysis processes. The software responsible for data collection and analysis was developed using the C# programming language within the Visual Studio development environment. It provides a comprehensive solution that includes COM communication and SQL integration. The software records the data received from the central gateway via the COM port to an SQL server for processing.

The data received from the LoRa modules is recorded in the SQL database. The database design includes start and end times, machine identification information, and other key parameters. Based on the type of incoming data, appropriate triggers are executed to automatically perform updates and modifications. The user interface software allows users to monitor production data in real time. This application presents the current status of machines, historical data, and performance analyses in a single interface. The harmonious operation of the software and hardware ensures that the system meets the operational requirements of the factory environment. The software infrastructure has been optimized to ensure that data collection and analysis processes are carried out reliably and efficiently.

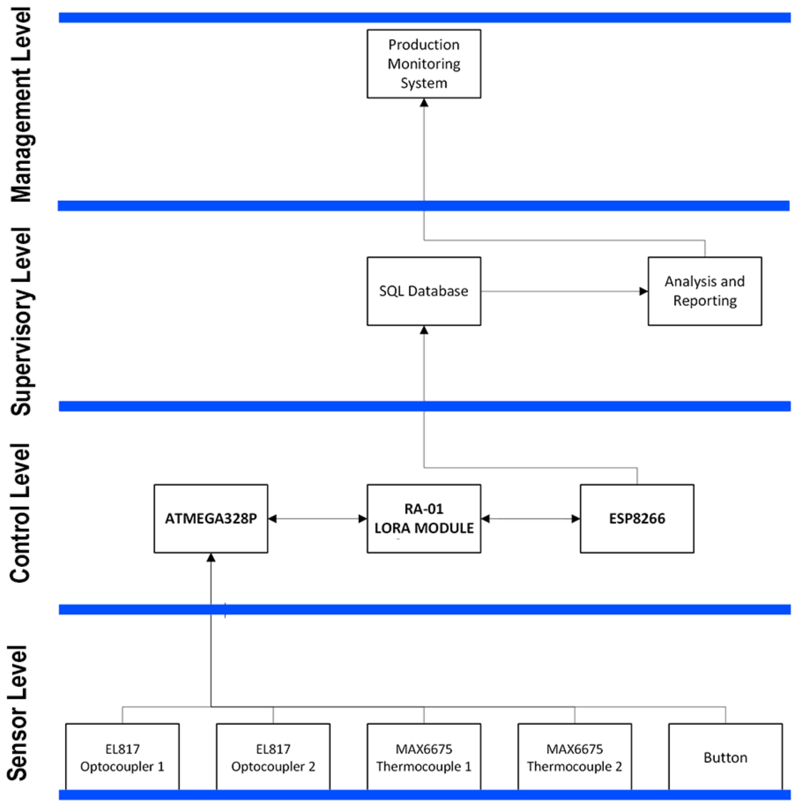


Figure 4. Modeling of the system within the industrial automation pyramid

2.3 Data Collection and Transmission Process

The data collection process from the press machines is carried out through sensors and data acquisition modules specifically positioned for each machine. The data collection process is carried out through a system specifically designed to monitor the running and stop states of the press machines. In this system, the start signal from the main time counter on the press machine is read by the first optocoupler, while the stop signal is read by the second optocoupler. The optocouplers transmit the received signals to the ATMEGA328P-AU microcontroller. Additionally, two MAX6675 integrated circuits perform data reading from K-type thermocouples, and this data is used to monitor mold temperatures. Data transmission is carried out to the microcontroller via the SPI communication protocol. The system also includes five analog input ports, which are designed as backups for additional sensors. In total, four press machines with the same specifications were used in production and one of the machines used is shown in Figure 5.

The LoRa protocol enables wireless data transmission between the data acquisition modules and the central gateway. The data processed by the microcontroller is wirelessly transmitted to the central gateway via the RA-01 LoRa module. The central gateway consists of an ESP8266 Wi-Fi module and an RA-01 LoRa module. This gateway transfers the data received from the LoRa modules to the software on the computer via the COM port, and the data is recorded in an SQL-based database. The predefined table structure on the SQL server includes machine ID, start and end times, temperature data, and status information. The stored data can be viewed and analyzed in real time through the user interface.

Figure 5. Press machine used in production

2.4 Database Design and Management

The SQL-based database used in the system is designed to store and analyze data collected from press machines in a reliable manner. The table design used in the database includes the elements in Table 1.

Table 1. SQL table design

Column	Data Type	Explanation
TAKIPID	int	A primary switch that uniquely identifies each record
DATE	smalldatetime	The date the data was recorded
PRESID	varchar(10)	The ID number of the press machine from which the data was received
START TIME	datetime	Machine operation start time
END TIME	datetime	Machine operation end time
STATUS	int	Machine operating status (e.g., Running, Finished, Scrap)
TEMPERATURE_1	varchar(30)	Temperature data of the press machine
TEMPERATURE_2	varchar(30)	Temperature data of the press machine
ANALOG_1-ANALOG_5	varchar(30)	Data from analog inputs
OPTO_SPARE	varchar(30)	Spare space for additional signal information

The table shows separate records for each machine ID and tracks operating statuses and time information through the primary switch TAKIPID.

Various processes are applied to ensure accurate processing and storage of data. First, incoming data is checked for accuracy before being written to the database. When erroneous or incomplete data is detected, the system issues a warning and requests the necessary corrections. The data received from the LoRa modules is recorded directly into the database through the Windows Form application. When a new press cycle begins, a new record is created in the table, and its status is saved as “Running” (STATUS=1), along with the start time and temperature data. When the press cycle ends, the corresponding record is updated as “Finished” (STATUS=0), and the end time is added. If two consecutive start signals are received before an end signal is detected for an existing record, the status of the first record is updated to “Fault” (STATUS=3), and the standard press cycle process is initiated for the second record.

The tables in the database are optimized for performance through regular backup and indexing processes. Unnecessary data is either archived or deleted, ensuring that all data is stored in a structured manner on the SQL-based server. To prevent data loss, regular backups are performed during these operations. The database is optimized to respond quickly to queries submitted through the user interface. Users can access data from the database to view the operating status of press machines, production history, and performance analyses. The data in the database is transformed into meaningful reports based on user needs, and these reports can be viewed in real time via the user interface. This structure ensures that the data received from the press machines is stored in a consistent and reliable manner. At the same time, it enables the analysis of the collected data to optimize production processes.

2.5 User Interface

The user interface is designed to be user-friendly, allowing production processes to be easily monitored and analyzed, and was developed using the C# programming language in the Visual Studio environment. The main panel functions as a control panel where the status of all press machines is displayed on a single screen, including machine IDs, operating statuses, and date and time information. The detail view presents comprehensive information for a selected press machine, such as production history, running time, downtime, temperature values, and defect rates. Figure 6 shows the user interface screen and detailed information for a specific press machine, while Figure 7 displays the production archive.

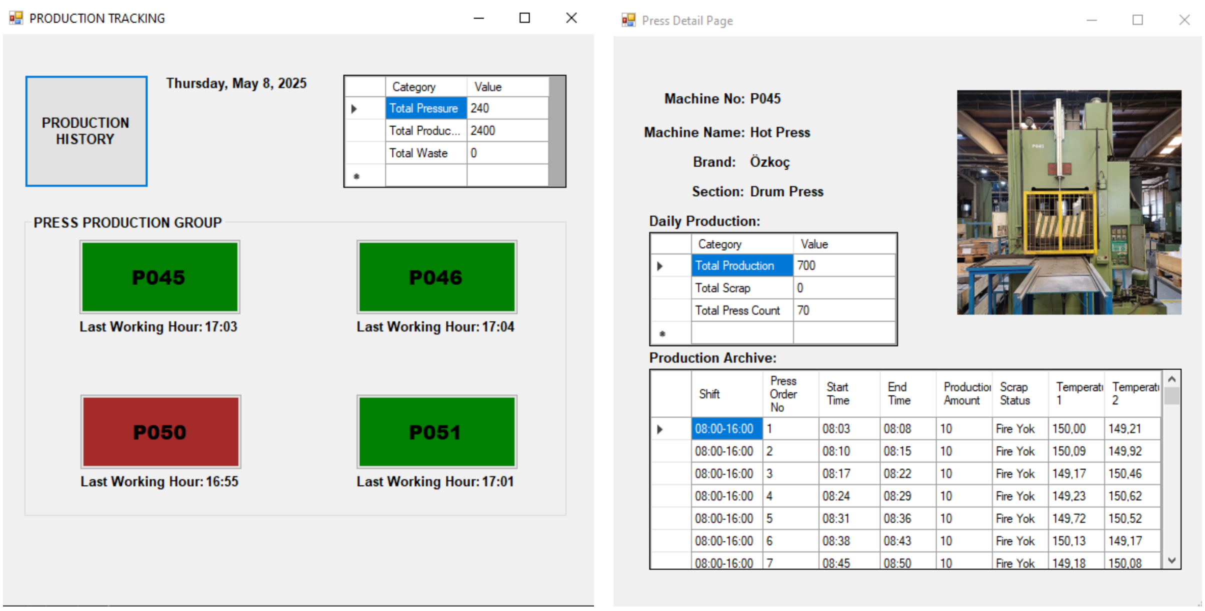
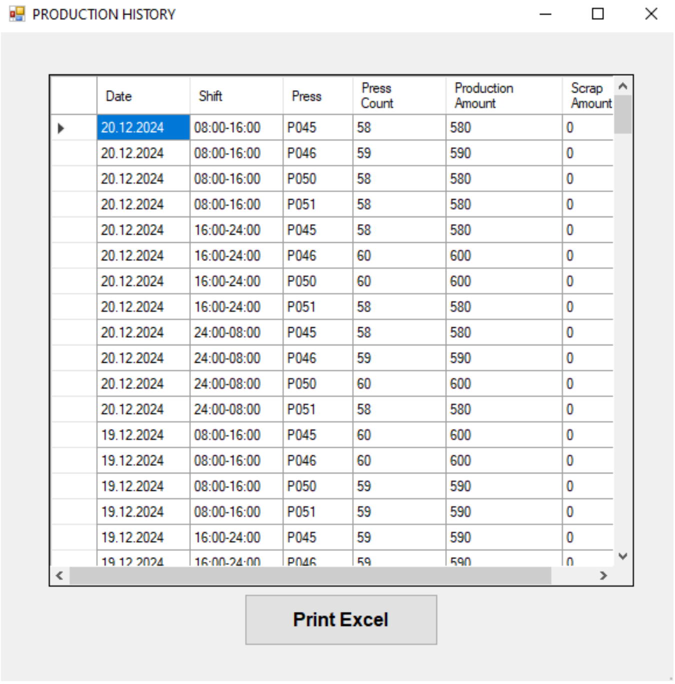


Figure 6. User interface home page and detailed information about the press machine



	Date	Shift	Press	Press Count	Production Amount	Scrap Amount
▸	20.12.2024	08:00-16:00	P045	58	580	0
	20.12.2024	08:00-16:00	P046	59	590	0
	20.12.2024	08:00-16:00	P050	58	580	0
	20.12.2024	08:00-16:00	P051	58	580	0
	20.12.2024	16:00-24:00	P045	58	580	0
	20.12.2024	16:00-24:00	P046	60	600	0
	20.12.2024	16:00-24:00	P050	60	600	0
	20.12.2024	16:00-24:00	P051	58	580	0
	20.12.2024	24:00-08:00	P045	58	580	0
	20.12.2024	24:00-08:00	P046	59	590	0
	20.12.2024	24:00-08:00	P050	60	600	0
	20.12.2024	24:00-08:00	P051	58	580	0
	19.12.2024	08:00-16:00	P045	60	600	0
	19.12.2024	08:00-16:00	P046	60	600	0
	19.12.2024	08:00-16:00	P050	59	590	0
	19.12.2024	08:00-16:00	P051	59	590	0
	19.12.2024	16:00-24:00	P045	59	590	0
	19.12.2024	16:00-24:00	P046	59	590	0

Figure 7. Production archive page

III. RESULTS AND DISCUSSIONS

As part of the study, the system was installed on four press machines (P045-P046-P050 and P051), as shown in Figure 8, and the implementation was carried out in an area of approximately 500 m². However, since the system is planned to be expanded and installed on other press machines as well, signal transmission tests were conducted from various distances within the 12,000 m² indoor area of the factory to the central gateway. It was observed that the entire area could be covered using a single gateway. Continuous communication was maintained even in areas within the factory where metal structures and equipment are densely located.

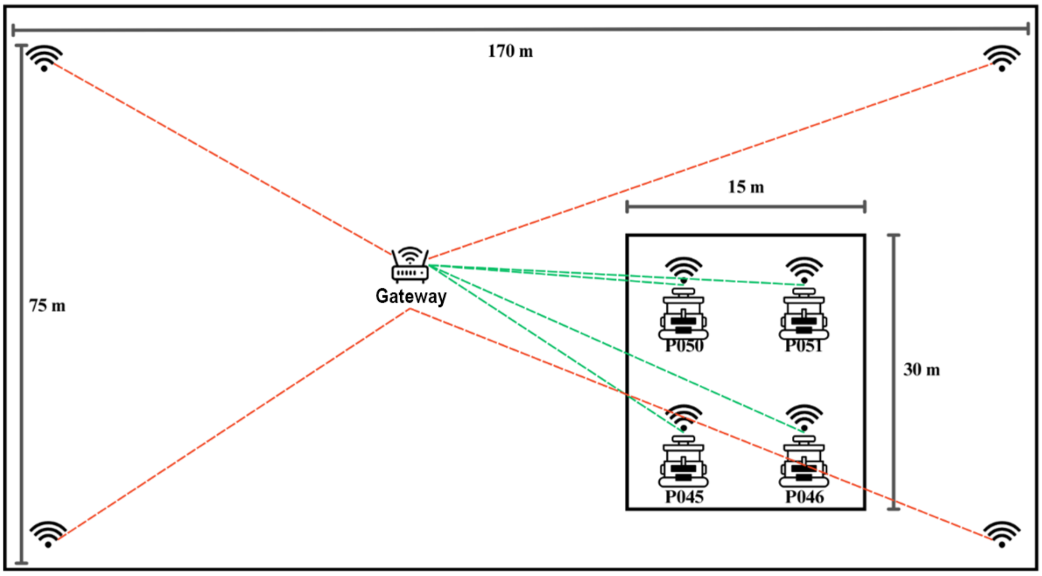


Figure 8. Factory layout diagram of gateway and press machines

The system was comprehensively tested and validated in the factory environment. The testing process focused on two main components: the data acquisition modules and the software. For the data acquisition modules, it was confirmed that the optocouplers accurately detected the signals and transmitted them to the microcontroller, and that the start and stop signals were captured without errors. The RA-01 LoRa module successfully transmitted data packets to the central gateway and delivered them to the server without any data loss. It was also observed that the thermocouple inputs operated reliably, and that temperature data was accurately transmitted to the server. During software testing, the Windows Forms user interface was found to display correct data and perform real-time updates successfully. It was confirmed that the data were accurately recorded in the SQL database, that queries returned correct results, and that the software effectively notified the user in cases of erroneous data entries or system errors.

The system successfully detected and recorded start and stop signals from the optocouplers with an accuracy rate of 98%. This rate corresponds to 12,046 successfully recorded press numbers and 246 instances of data loss. Within the 12,046 successful records, a total of 24,092 successful optocoupler readings were recorded. In contrast, with only 48 failed optocoupler readings, the optocouplers' successful reading rate was measured at 99.8%.

The start and stop times of the press machines were detected with a precision of ±1 ms, demonstrating that the system meets the accuracy requirements for industrial automation. The temperature values measured by the thermocouples and recorded in the SQL database were compared with the temperature readings on the press machine's display. It was observed that the temperature measurements were performed with a precision of ±0.5 °C and that these values were reliably recorded for analysis purposes. The 98% accuracy rate in data transmission achieved by the LoRa modules demonstrates that signal quality was maintained even in the factory environment, where electromagnetic interference is intense. Due to the CSS (Chirp Spread Spectrum) modulation technique, the effect of interference was minimized, enabling successful data transmission even at low signal levels. The average transmission time of 1.2 seconds to the central gateway provided a sufficient speed for industrial automation applications.

The total energy consumption of the entire system was calculated to be approximately 60–90 Wh per day. This minimizes energy costs during long-term operations. With the implementation of the system, the operating cycles of the press machines increased by 9%, resulting in a 9% rise in daily production output. For example, while 55 press numbers were previously completed in a single shift, this number has increased to 60. A comparison of the 15-day results before and after the implementation is presented in Figure 9.

This improvement enabled an increase in production capacity without extending the shift duration. Monitoring the operators through the system and verifying whether the production is carried out under proper pressing conditions have contributed to a reduction in defect rates. The LoRa-based system has also facilitated real-time monitoring of machine downtime and faults. Specifically, when a predetermined downtime threshold (e.g., 15 minutes) was exceeded, supervisors received automatic alerts, which reduced fault detection time from 45 minutes to 20 minutes. This has enabled faster interventions and helped reduce production losses. Additionally, the implementation of performance scoring for operators has encouraged more efficient working habits and accelerated quality control processes.

These results demonstrate that the developed LoRa-based system significantly improves efficiency in industrial production and optimizes operational processes. The system's investment costs were recovered within approximately one month, providing the enterprise with continuous economic benefits. By reducing losses caused by production errors and enabling more efficient use of energy and resources, the system has contributed to overall process improvement. In the future, the integration of artificial intelligence and machine learning techniques is expected to further automate production processes and enhance efficiency. These advancements will increase the system's competitiveness both locally and globally and contribute to advancing industrial automation to higher levels.

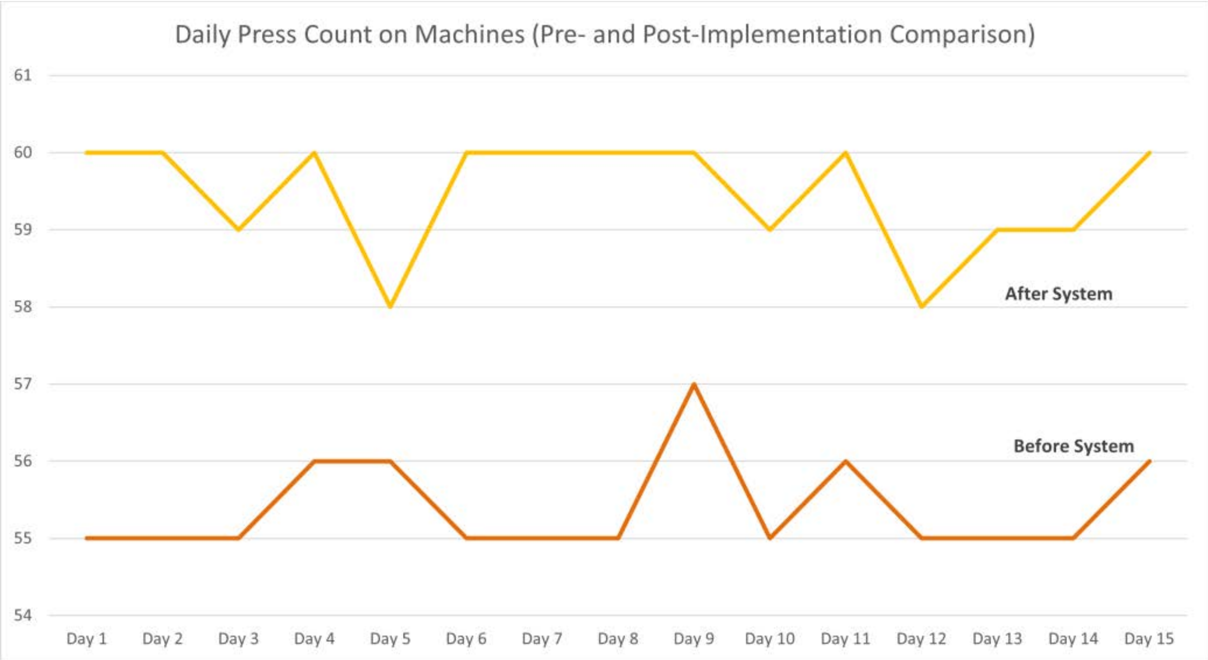


Figure 9. The 15-day results obtained before and after the implementation

IV. CONCLUSIONS

In this study, a real-time data collection and analysis system was successfully developed and implemented on the press machines of a brake pad factory operating in industrial production using the LoRa communication protocol. The system was designed to optimize production processes, increase efficiency, and make production activities more traceable. The hardware infrastructure consisted of specially designed data acquisition modules integrated into the press machines and an ESP8266-based central gateway device. The software infrastructure included an application developed in Visual Studio C# and an SQL-based database system. This software managed the processes of data collection, monitoring, and reporting, offering both real-time and historical analysis capabilities through automated data analysis and reporting mechanisms. The developed system demonstrated reliable performance in industrial environments, achieving a 98% data transmission success rate. Thanks to the wide coverage offered by LoRa technology, the entire 12,000 m² factory area was covered using a single gateway. Despite electromagnetic interference, stable communication was maintained, and data loss was minimized. These technical achievements indicate that the system has a robust infrastructure suitable for industrial automation applications. The reduction in fault detection time from 45 minutes to 20 minutes played a crucial role in minimizing production losses and improving response times. The system's real-time data collection and analysis capabilities contributed significantly to monitoring operator performance and optimizing production processes.

In future studies, it is recommended to integrate artificial intelligence and machine learning algorithms to enhance the current system, making it more efficient, flexible, and comprehensive by equipping it with predictive maintenance features. This will enable proactive approaches in fault detection and optimize maintenance processes. To increase data transmission speed, optimizing LoRa parameters more effectively and expanding the coverage area through the use of multiple gateways will enhance system reliability. Additionally, by incorporating data processing capabilities, data can be processed locally, reducing the load on cloud systems. The inclusion of mobile application support can make the system more user-friendly. Expanding visual analysis tools and developing an automatic reporting system will accelerate decision-making processes. Adapting the system to various industrial processes will broaden the potential of LoRa-based automation solutions.

ACKNOWLEDGMENT

This study was prepared from the first author's MSc thesis. We would like to thank Kale Balata Otomotiv Sanayi ve Ticaret A.Ş. for enabling the field tests of this thesis to be carried out.

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