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Research article

Predictive worker safety assessment through on-site correspondence using multi-layer fuzzy logic in outdoor construction environments

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ABSTRACT

Construction sites remain highly perilous work environments globally, exposing employees to numerous hazards that can result in severe injuries or fatalities. To resolve this several solutions based on quantitative approaches have been developed. However the wide adoption of preexisting solutions is hindered by lack of accuracy. To this aim the development of an efficient fuzzy inference system has become a de-facto necessity. In this paper, we propose an edge inference framework based on multi-layered fuzzy logic for safety of construction workers. The proposed system employs an edge computing-based framework where IoT devices collect, store, and manage data to offer safety services. Multi-layer fuzzy logic is applied to infer the worker safety index based on rules that consist of construction environment factors. The multi-layer fuzzy logic is fed with weather, building and worker data collected from IoT nodes as inputs. The safety risk assessment process involves analyzing various factors. Weather information, such as temperature, humidity, and rainfall data, is considered to assess the risk to safety. The condition of the building is evaluated by analyzing load, strain, and inclination data. Additionally, the safety risk to workers is analyzed by taking into account their heart rate and location information. The initial layer's outputs are utilized as inputs for the subsequent layer, where an integrated safety index is inferred. Ultimately, the safety index is generated as the final outcome. The system's results are conveyed through warnings and an error measurement on a safety scale ranging from 1 to 10. Furthermore, web service is developed to allow the construction management to check the worker safety condition of the construction site in real-time, while also monitoring the operational status of the IoT devices, allowing for the early detection of sensor malfunction and the subsequent guarantee of worker safety. Extensive evaluations conducted to test the performance of the developed framework verify its efficiency to provide improved risk assessment, real-time monitoring, and proactive safety actions, encouraging a safer and more productive work environment.

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1. Introduction

The construction industry is one of the most hazardous industries in the world [1]. In the United States, 5,333 fatal industrial accidents were reported in 2019 [2]. Injuries, occupational risks, and accidents are just a few of the threats that construction site workers face. Consequently, the construction sector is characterized by its capacity to subject workers to a range of severe and potentially catastrophic hazards [3]. Due to the dynamic nature of the construction industry and the many hazardous duties performed on construction sites, health and safety issues for construction workers are complex [4]. Construction safety systems and information and communication technologies are the subjects of considerable study to prevent construction site accidents [5]. These activities include sensor-based location monitoring and hazard detection systems that protect underground workers [6], safety management systems for a group of tower cranes that use a set of custom sensors to detect the operating status of tower cranes used on construction sites [7], and safety management systems that mount various cameras and sensors on worker helmets to monitor the condition of workers and construction sites [8].

The term “Internet of Things” refers to a system composed of physical objects from the real world as well as sensors attached to or integrated into these objects, and which is linked to the internet via wired and wireless network technology. It is the future information and communication technology that will digitalize physical objects [9]. IoT devices can connect to the internet via a variety of different technologies, including GPRS, GSM, LTE, and 3G for wide-area connectivity, ZigBee, Bluetooth, Wi-Fi for local connectivity, and so on. IoT devices communicate their current status as well as the environmental data they have collected with other software programs, individuals, and other things via the aforementioned internet technology. The IoT has made tremendous advances in making the world smarter in a variety of fields, including smart healthcare, smart cities, smart homes, and smart buildings [10]. There are constrained resources for IoT-enabled things. Data collectors, sensors, actuators, autos, cameras, cars, and trains are all examples of devices that use IoT technology [11]. Also, there is a wide range of IoT devices. Connected objects are electrical gadgets that can interpret their environment and respond accordingly to digital data. It takes in external stimuli in analog or digital form and displays them in a format that can be understood by machines as well as humans. Embedding nodes in a vehicle or a house with various wireless networking capabilities like Bluetooth, Wi-Fi, ZigBee, and so on is possible [12].

Data collected through IoT can be used in the decision-making process only when it is processed through specialized knowledge. A fuzzy logic system (FLS) is a rule-based expert system that transforms input data into meaningful outputs by expressing expert knowledge as fuzzy sets and rules [13]. FLS has many practical applications in the construction sector. For example, operations of maintenance [14], construction risk management [15], decision-making support in construction control systems [16], or sustainability [17]. In addition, the uncertainties of occupational threats of the construction site are modelized with a fuzzy system [18]. FLS may contain a priori expertise and may represent systems for which a mathematical model cannot be obtained. The author [19] proposes a multi-grade fuzzy-based safety practice index calculation mechanism. To calculate the safety index, a conceptual model is implemented. The unique advantage of using fuzzy logic is that it allows clear quantitative calculations that are compatible and avoid bias. To quantifies, the ease of landing a spacecraft on a planetary surface, the author [20] introduces a fuzzy logic-based safety index that uses sensor-derived topographical characteristic measurements. These properties include roughness, slope, etc. The proposed terrain safety representation incorporates an intuitive and linguistic approach for expressing robust terrain characteristics concerning inaccuracies and uncertainties in sensor measurements. Integrating data capture technology at some stage of the construction project process, along with the use of IoT paradigms and FLS, introduces an exciting challenge that can provide significant benefits for real-time accident prevention at the construction project stage.

These perspectives have motivated current work with the idea of defining IoT infrastructure as the core of ubiquitous computing and using Fuzzy Markup Language (JFML) to define automatic data transfer from sensors to monitor the risk of falling objects at some stage of the construction process [21]. Further the study’s motivation is driven by the alarming risks faced by construction workers on a daily basis, highlighting the urgent need for a robust safety framework. Existing quantitative solutions may lack the desired accuracy, necessitating the development of a powerful fuzzy inference system. This study aims to present a comprehensive strategy in light of the dangerous working conditions faced by construction workers around the world and the requirement for precise safety solutions. By putting forth a new multi-layered fuzzy logic-based edge inference framework, we hope to fill in the gaps in current research and promote a safer working environment. The research questions below direct our investigation.

- RQ1: How can a multi-layered fuzzy logic-based edge inference framework effectively enhance real-time safety assessment for construction workers?
- RQ2: How can IoT data, encompassing weather, building conditions, and worker information, be effectively integrated into the multi-layer fuzzy logic system to ensure accurate safety risk assessments?

Our proposed system leverages edge computing-based IoT devices to collect, store, and manage data effectively. By employing multi-layer fuzzy logic, we derive a worker risk index for the construction site based on the data collected at the site. This index serves as a valuable indicator of safety levels. Administrators gain real-time access to the web page, allowing them to monitor the safety status of construction site workers. Furthermore, the system enables administrators to oversee the performance of IoT devices, thereby facilitating early detection of sensor malfunctions and ensuring worker safety. The proposed study encompasses several significant contributions, including:

1. Development of an innovative Worker Safety Prediction System: We introduce an innovative on-site worker safety prediction system that leverages multi-layer fuzzy logic within an AIoT framework for outdoor construction settings.

2. Edge Computing Integration for Enhanced Safety: Our approach strategically integrates weather data, building conditions, and worker information through an edge computing network. This integration aligns with the evolving demands of IoT and ensures more efficient and resource-effective safety prediction.
3. Advanced Fuzzy Logic Quantification: Employing sophisticated fuzzy logic techniques, we provide a robust methodology for quantifying the stability of construction sites. This quantitative approach enhances the precision and clarity of site evaluation using numerical expressions.
4. Real-time Monitoring and Hazard Mitigation: Through the deployment of a sensor-based system, we enable real-time monitoring of construction site conditions. This implementation empowers proactive risk management, contributing to the overall safety of workers in dynamic construction environments.

The rest of the paper is structured as follows: Section 2 provides an overview of relevant studies. Section 3 introduces the proposed multi-layer fuzzy logic-based construction worker safety inference system. Section 4 details the materials and methods, and section 5, implementation results. Section 6 provides an evaluation of the performance of the proposed worker safety inference system. Section 8 concludes the paper by discussing future research directions.

2. Related work

Due to the risky working environment of construction sites, the personal safety of construction workers is frequently exposed to potential safety and health risks during the construction process [22]. According to international occupational safety statistics, the construction industry has one of the highest rates of occupational accidents [23]. The National Census of Fatal Occupational Injuries survey conducted by the U.S. Bureau of Labor Statistics in 2015 indicates that due to fatalities and illness, there were 4836 workers died on construction sites, 9% of injuries occurred in a hazardous environment and 3% of accidents were due to explosions and fire [24]. According to the accident investigation, the characteristics of the industry, wrong human behaviour, poor environment, and poor safety management are the main causes of accidents [25].

2.1. Integration of IoT technologies for comprehensive construction site safety monitoring and management

Several studies have been conducted to ensure the safety of personnel at the construction site. The impact of the construction site environment often exposes workers to a variety of health risks. Some studies monitor worker health status to ensure safety. Different systems such as the Physiological Status Monitoring (PSM) system and GPS tracking sensor automatically collect and analyze the physiological data which include body posture, heart rate, breathing rate, body speed, and body acceleration to estimate worker and construction equipment operator health status [26,27]. The authors [28] developed a real-time intelligent video surveillance system that identifies specific dangers and the operational status of equipment (such as excavators). This system can detect people and whether the equipment is moving or stationary within hazardous zones. It offers quick feedback on unsafe behaviour, enabling prompt interventions to prevent such incidents from happening again.

Workers are exposed to health and safety risks not only by weather factors in the construction work environment but also by certain materials that pose a hazard. To inform construction workers with early warning alarms, automated collecting of these inclement weather factors and injurious elements is necessary. In the study [29], a novel weather monitoring system was created utilizing a variety of sensors connected to a Raspberry Pi. This system enables the tracking of weather variables such as temperature, humidity, PM 2.5 and PM 10 levels, as well as the Air Quality Index (AQI). There is a study that improves the safety management of harmful gases at underground construction sites by combining Building Information Modeling (BIM) and Wireless Sensor Networks (WSN) technology. The gas concentrations and environmental data (temperature and humidity) from various site locations were collected and fed into the site BIM model. The model can dynamically display the condition information of the building site collected through the sensor node by changing the corresponding colour to the BIM model to monitor the complete safety condition [30]. The study of [31] created an IoT network model to enhance the monitoring of construction site safety in real time. The aim was to not only decrease accident rates but also to store digital data for future training and system improvements. This model introduces a cost-effective solution for optimizing construction safety, catering to the needs of all stakeholders.

To monitor safety and productivity, tracking and locating techniques are important in industrial applications. There are many technologies, for example, GPS [32], RFID and RF localization [33], UWB [34,35], sonar, magnetic field, and radar are introduced for safety monitoring. The author [36] proposed another safety monitoring system based on infrared and ultrasonic sensors to protect workers on construction sites. When workers approach a specific hazardous region in a construction site, the safety monitoring system alerts workers through a Mobile Sensing Device (MSD). However, this system only relies on an estimate of the proximity between the MSD and workers. In other words, it did not provide safety managers and construction with comprehensive information about the construction environment and worker's behaviour. The tracking system developed by the author [37] integrates BIM, RFID sensors, and cloud communication technologies for the safety management of indoor construction. However, this study involves costly infrastructure- as it applies proximity-based location tracking that requires many signal readers. Resultingly, the system can be intrusive for operators and ended up leveraging BIM to visualize resources and space. The author [38] presents a low-cost indoor tracking system that utilizes motion sensors, Bluetooth Low-energy (BLE), and BIM. The proposed system may be effective for field investigations, but because it uses internal motion sensors in mobile devices, it is not flexible enough for general tracking.

The study [39] develops a cloud-based on-site application for the safety monitoring system. The system consisted of a cloud-based communication platform, hazard identification based on BIM, and a location detection function based on BLE. The hazardous

Table 1
Summary of existing notable works done and research gaps addressed.

Study	Application area	Methodology	Main contributions	Research gap addressed
Zhang et al. [22]	Construction safety	IoT-based health monitoring	Physiological data analysis for worker Health monitoring	health and safety monitoring
Luo et al. [28]	Construction safety	Video-based behaviour recognition	Video surveillance system for preventing accidents on sites	Identify specific hazards in real-time
Joseph et al. [29]	IoT technology	Sensor-based data collection	IoT devices for sensing environmental factors	Iot based weather monitoring system
Cheung et al. [30]	Construction safety	BIM and WSN integration	BIM-integrated safety management at underground sites	Safety management through BIM-WSN
Chung et al. [31]	IoT Application	IoT-based safety monitoring	Safety monitoring system to reduce accident rates	IoT network technology for construction site safety
Singh et al. [47]	Occupational safety	manufacturing industries	SPSS based regression analysis monitoring	Developed an occupational Safety Evaluation Index (OSEI)
Park et al. [38]	Safety tracking	BLE, motion sensors, BIM	Indoor tracking system using BLE and BIM	Flexible indoor tracking
Mahmoudi et al. [41]	Decision-making models	Fuzzy logic	Utilizing fuzzy logic for decision-making models	Devised a method for solving multi-objective linear programming
Topal et al. [43]	Construction tasks	Fuzzy risk assessment model	Risk evaluation for small-scale construction tasks	Safety risk assessment
Danish et al. [45]	Underground coal mines	Fuzzy logic controller	Fuzzy logic-based prediction of mine fires	Safety prediction
Hendiani et al. [46]	Social sustainability	Fuzzy logic evaluation	Fuzzy logic assessment of social sustainability	Social sustainability
Current Research	Construction safety	Multi-layered fuzzy logic	Real-time safety assessment and risk inference	Comprehensive safety

locations are defined manually or automatically in a BIM model. To identify incidents where workers are approaching risk areas, the worker locations are collected in real-time. Then, the output of the safety monitoring system is instantly spread over the cloud for effective safety control. Many studies manage construction site safety using weather information, worker location, and health status respectively by integrating with IoT technology, but no study considers the environment, building, and workers at the same time.

2.2. Application of fuzzy logic for enhanced construction safety and beyond

Fuzzy logic has also been used in many fields such as constructions [40], decision-making models [41], and project management [42], where it is used to model uncertainty and evaluate performance. To provide a safer and healthier work environment for construction workers, the author in [43] proposed a fuzzy risk assessment model to evaluate the risks connected with various construction tasks in the small-scale construction sector. Also, in the study [44], fuzzy logic is utilized as an analytical and scientific method to identify and mitigate risks in construction projects. The study explains how fuzzy logic can be used to construct fuzzy rules that can be applied as a referent database in the task of risk analysis. Moreover, they highlight how fuzzy theory can mathematically formulate many concepts and variables which are considered unclear and ambiguous, thus preparing the ground for presenting arguments and making decisions in uncertain situations. To predict mine fires in underground coal mines, the study in [45] used the fuzzy logic controller that processes all fuzzy inputs using IF-THEN rules and creates fuzzy output sets for decision-making. Multiple IF-THEN rules are created for predicting coal fires with the fuzzy logic system. The authors in [46] utilized fuzzy logic to evaluate the social sustainability status of associated construction projects. The proposed approach involves gathering important social sustainability attributes and utilizing a fuzzy construction social sustainability index to uncover hindrances and difficulties related to the concept of socially sustainable construction. Table 1 presents a summary of the notable works done for ensuring human safety in various domains and the research gaps addressed by these systems.

In summary, the data presented in Table 1 offers a comprehensive examination of significant research undertaken in several fields such as construction safety, IoT technology, occupational safety, decision-making models, and related areas. The data highlights the specific deficiencies that these studies aim to address. Every study contributes notable progress to their respective fields, including activities such as examining physiological data for the purpose of monitoring worker health and developing safety monitoring systems based on IoT. The present study presents a novel approach that utilizes a multi-layered fuzzy logic framework to enable real-time evaluation of safety and inference of risks in the construction industry. Through the utilization of this sophisticated methodology, our proposed system adeptly addresses significant deficiencies within the sector, providing a comprehensive and robust solution for enhancing safety in a comprehensive manner. The results of our research demonstrate an increased efficacy of our proposed approach in mitigating critical safety issues within construction settings, as compared to the previously mentioned studies. This deduction is derived through thorough examination and empirical application of our research findings.

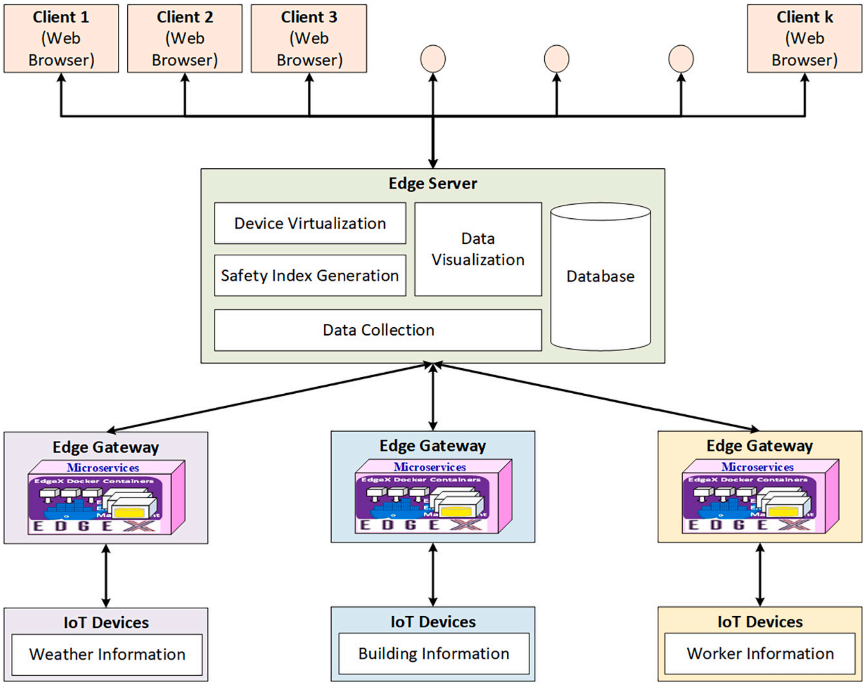

Fig. 1. Proposed conceptual architecture for worker safety inference in outdoor construction AIoT environment.

3. Proposed construction worker safety inference system based on multi-layer fuzzy logic

3.1. Proposed system for worker safety inference in the construction site

We propose an on-site safety index based on the multi-layer fuzzy logic approach, for construction workers, aimed at enhancing their safety at the construction site. Fig. 1 provides an operational overview of the proposed system. The system includes IoT devices, edge gateways, a server, and clients. The IoT devices are responsible for collecting information about the construction site and the workers. The edge gateways manage the information from the IoT devices, temporarily store the collected data, and facilitate the connection between the server and the IoT devices through edge computing services. The server utilizes the collected data to predict the safety conditions of the construction site. Clients can monitor the information provided by the server. To predict the safety of workers on the outdoor construction site, IoT devices accumulate environmental information and worker status information. The environmental information includes data on weather conditions and building specifications, while worker status information comprises heart rate and location data. The required data are periodically collected by the IoT devices, transferred to the edge gateway, and then delivered to the server.

The framework employed in our study strategically utilises the capabilities of the edge server, referred to as EdgeX, which is strategically positioned in close proximity to the construction site. The selection of this particular design option plays a crucial role in addressing the obstacle of data management infrastructure. The system effectively alleviates potential bottlenecks related to data processing and storage by conducting data processing at the edge, using the data obtained from IoT devices. This approach reduces the burden on centralised data management systems. The edge server assumes a critical role in facilitating efficient data management by receiving data from diverse IoT devices deployed across the construction site. The data that has been gathered is subjected to a rigorous processing procedure within the server, encompassing various tasks including data cleansing, filtering, and aggregation. The process of optimising data preparation not only improves the quality of the input data but also facilitates the efficiency of subsequent analysis.

Significantly, the processed data is effectively stored within a specialised database, which is an essential component of the edge server's functioning. The purpose of this database is to function as a centralised storage system for the processed data, guaranteeing its ease of access and availability for subsequent analysis and inference.

One crucial element of our framework's approach to addressing the data management challenge is the implementation of a systematic conversion process subsequent to data processing. The data that has been gathered is subsequently processed and organised according to a clearly defined methodology, resulting in its conversion into a numerical format. The numerical representation provides valuable insights into the risk level associated with the construction site, enabling a quantitative assessment of safety concerns.

The core of this quantification process is centred around the utilisation of a function that generates a safety index. The safety index value is generated by this function using refined and numerical data as input, providing a quantitative measure of the risk level at the construction site. Through the utilisation of this function, our framework provides a distinct and standardised measure for appraising safety conditions, thereby augmenting the accuracy and efficacy of safety evaluations. The edge server, located near the

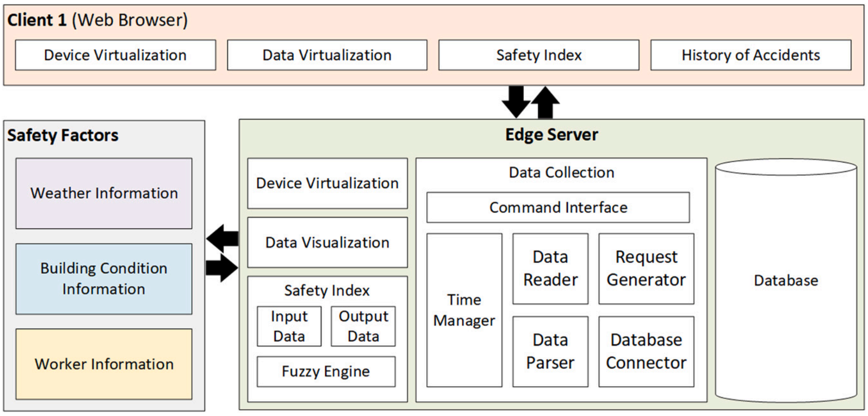

Fig. 2. Block diagram of construction worker safety inference system.

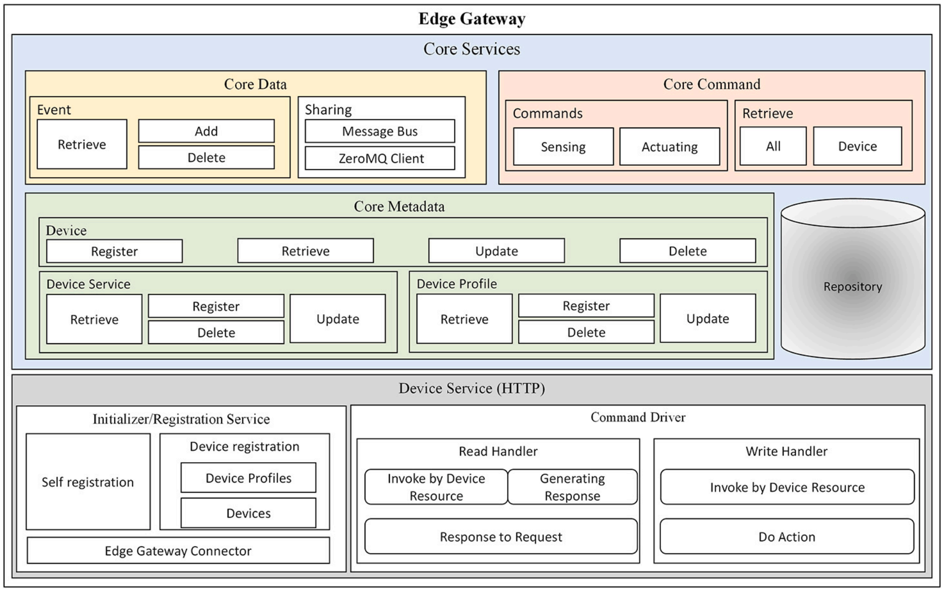

Fig. 3. Edge gateway functional block diagram for data collection.

construction site, processes the data collected from the IoT devices to predict the safety status of the construction site where workers are present. The server collects, processes, and stores the data in a database, converting it into a numerical value that represents the risk level of the construction site through a safety index generation function. Additionally, the client has access to device and data visualization functions, allowing them to monitor the state of the IoT devices and review the history of collected data. The client can be any device with internet connectivity, such as a mobile phone, computer, or tablet, connected to the edge server.

Fig. 2 provides an architectural overview of our construction worker safety platform, which serves to enhance the safety of workers at construction sites. The core of the system is an edge server that performs safety analysis on collected data using a multi-layer fuzzy logic approach. To infer the condition of the construction site, we analyze various types of data. Weather information is crucial for verifying the safety of the working environment. Building condition information is utilized to monitor the status of the structures on the site. Furthermore, worker information is leveraged to assess both the health condition and proximity to danger zones for workers. The edge server plays a pivotal role in monitoring the status of connected data collection resources and provides a comprehensive visualization of the collected data. This functionality empowers workers to proactively identify and understand potential risks by assessing the safety status of their current location on the construction site through the edge server.

Fig. 3 illustrates the functional block of an edge gateway responsible for data collection. An edge gateway acts as a host for edge computing services and encompasses various EdgeX services. These services encompass core metadata, which stores information about IoT devices managed by the edge gateway, and core data, which facilitates the storage and dissemination of data from IoT devices. Additionally, there is a core command that converts IoT device services into command formats for delivery, and a repository that provides storage space. The core metadata enables inquiry, registration, deletion, and updating functionalities for IoT devices, device profiles, and device service information. The device profile contains details about the services offered by the device. Core data allows querying, adding, and deleting of data collected from IoT devices, as well as delivering the data to applications. The core

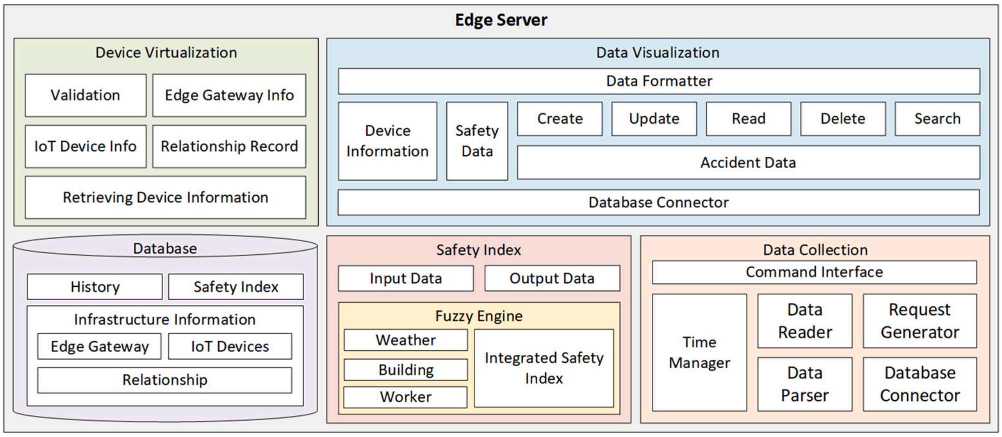

Fig. 4. Edge server architecture for device virtualization, monitoring and data visualization.

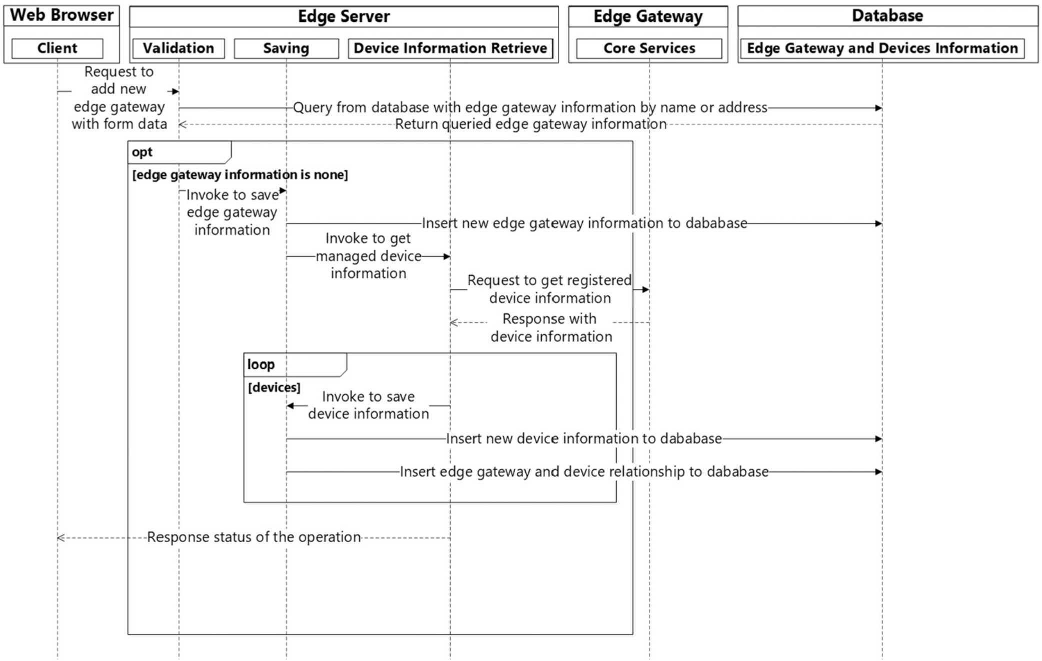

Fig. 5. Sequence diagram for edge gateway registration to the safety inference system.

command provides query and command functions for the services provided by IoT devices. Furthermore, a device service ensures connectivity to IoT devices, aiding in their registration with the edge gateway and serving as a bridge for data transmission and command delivery.

Fig. 4 showcases the functional block of an edge server, which comprises four key components: device virtualization, data visualization, safety index, and database. The device virtualization function enables device registration, allowing managers to monitor the state of construction sites within the system. During the registration of an edge gateway, the device virtualization function verifies the gateway's status, retrieves information on connected devices, and records the connection relationship in the database. The data visualization function simplifies the presentation of data stored in the database for users. It integrates device information with a map, represents construction site safety information through bar charts, and displays existing construction site accident cases in a table format. Additionally, it provides administrators with functions to easily record, update, delete, and inquire about accident case information. The safety index function, in conjunction with the data collection function, converts real-time construction site information into a safety index. By inputting environment, building, and worker status information into fuzzy logic, the safety index function generates safety information as output. The database serves as a comprehensive repository for all system-related information, housing the necessary data for operation.

Fig. 5 depicts the sequence diagram for edge gateway registration. The process begins when the user sends a registration request to the edge server through a client browser. To ensure no duplicate registrations occur, the edge server checks the database for

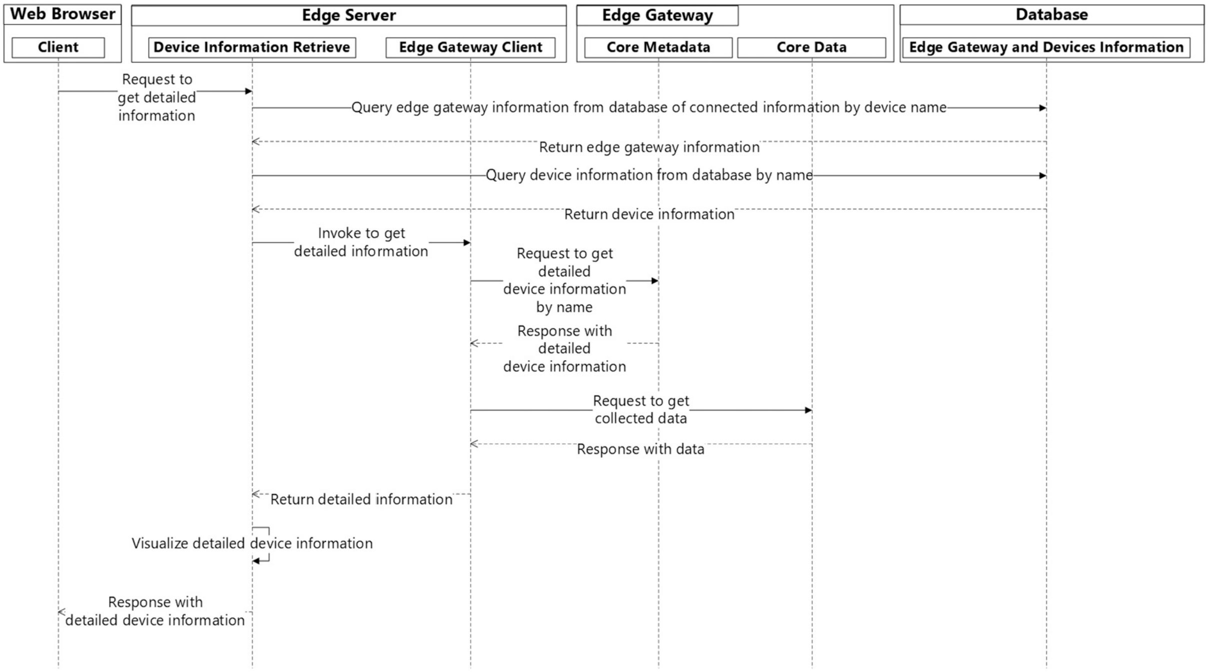

Fig. 6. Sequence diagram for detailed device information visualization.

existing registration information. If no registered information is found, the provided details are stored in the database. Next, the address information of the edge gateway is used to retrieve the managed device's information. The obtained device information, along with the connection relationship to the edge gateway, is saved in the database. Finally, a success message is sent to the client, signalling the completion of the registration process.

Fig. 6 illustrates the sequence diagram for visualizing detailed device information. This information encompasses details about the connected edge gateway, the device's location and basic information, as well as statistical data collected. The process of obtaining and presenting this detailed information is as follows: When a request for detailed information is made, the relevant data associated with the device is retrieved from the database. This includes the edge gateway data linked to the device. Next, the device information is fetched from the database, enabling access to specific details about the device. Subsequently, detailed device information is collected from the core metadata service of the edge gateway. This service provides comprehensive information about the device. Finally, the accumulated information is visualized and displayed on a web page through the edge server, enabling users to view and interact with the detailed device information.

Fig. 7 displays the sequence diagram for the data collection function. There exists a mutual dependency between the edge server and IoT devices, as the edge server processes data collected from these devices. To ensure smooth system operations, the edge server provides users with the capability to manually initiate the data collection function through a command interface. When a user sends a data collection command to the edge server via the command interface, the command interface triggers the data collection process based on the command received. It accomplishes this by invoking the request constructor, which generates a request for data collection from the IoT device. The request generator accesses the database through the database connector to retrieve information about the edge gateway and the resources provided by the edge gateway. With this information, the request generator requests the edge gateway to respond with the collected data. As the response from the edge gateway is in JSON file format, the data value is extracted by parsing the JSON file. This extracted data value is then delivered and saved to the database for further processing and analysis.

Fig. 8 illustrates the sequence diagram for device service initialization. The device service serves as a vital link between the edge gateway and the IoT device. During the initialization stage, the device information is not only managed by the edge gateway but also registered in the core metadata to establish a connection. The device service initiates by checking the operational status of the connected edge gateway. If the edge gateway is not running, the execution is halted. However, if it is running, the process proceeds to the next step. The device service registers its information in the core metadata to establish a connection with the edge gateway. Next, it queries the profile of the connected device and gathers information about the resources it provides. This data is then stored in the edge gateway's core metadata. The information recorded in the core metadata is crucial for the edge gateway to establish a connection with the device, enabling the collection of data and transmission of commands.

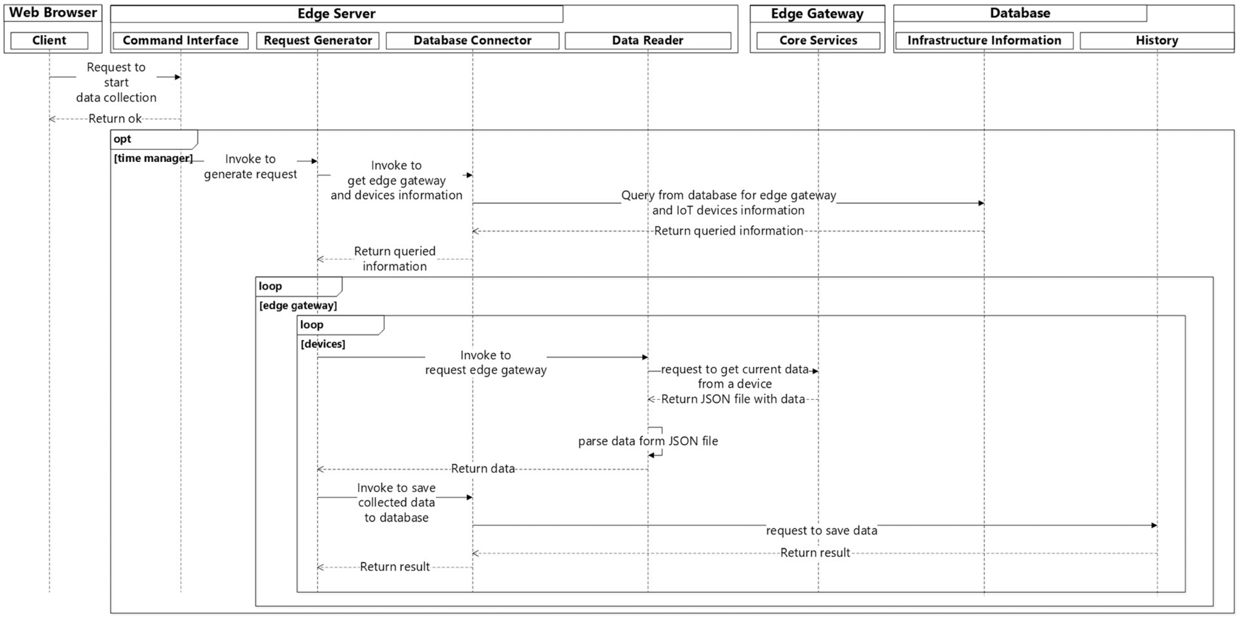

Fig. 7. Sequence diagram for data collection from simulated IoT devices.

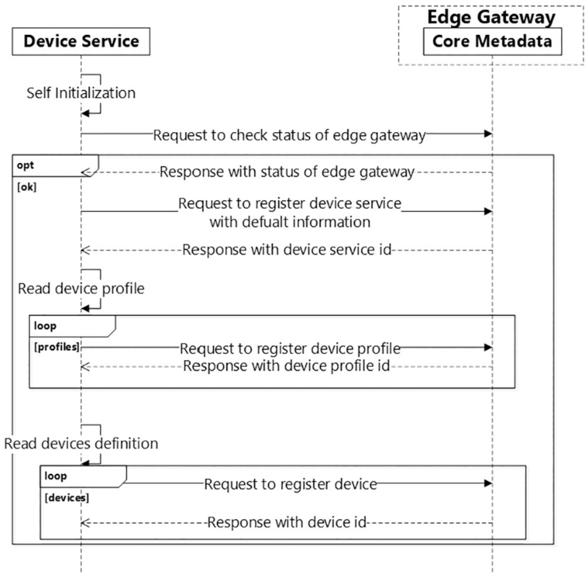

Fig. 8. Sequence diagram for device service initialization.

4. Materials and methods

4.1. Multi-later fuzzy logic controller engine for worker safety inference in the construction site

Fig. 9 depicts the multi-layer fuzzy logic architecture for the worker safety inference engine. During the input phase, data related to the construction environment, including building conditions, weather, and the workers' health status, is collected. These input data are represented by numerical values, which are then inputted into the fuzzy logic controllers for building, weather, and worker factors. Each fuzzy logic controller consists of three main components: a fuzzy function that converts the numerical value into a fuzzy set, a predictive interference engine, and a de-fuzzification function that converts the fuzzy set back into a numerical value. These components work together to process and analyze the input data. In the next step, the results from each factor of the construction site are passed on to the second layer of the fuzzy logic controller. This layer predicts the integrated safety level and generates the final result based on the combined inputs from the different factors.

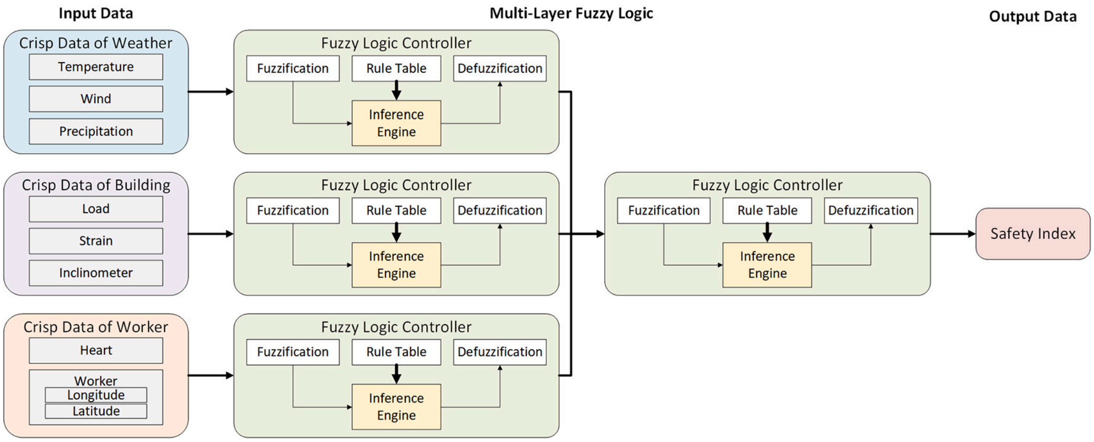

Fig. 9. Multi-layer fuzzy logic architecture for worker safety inference engine.

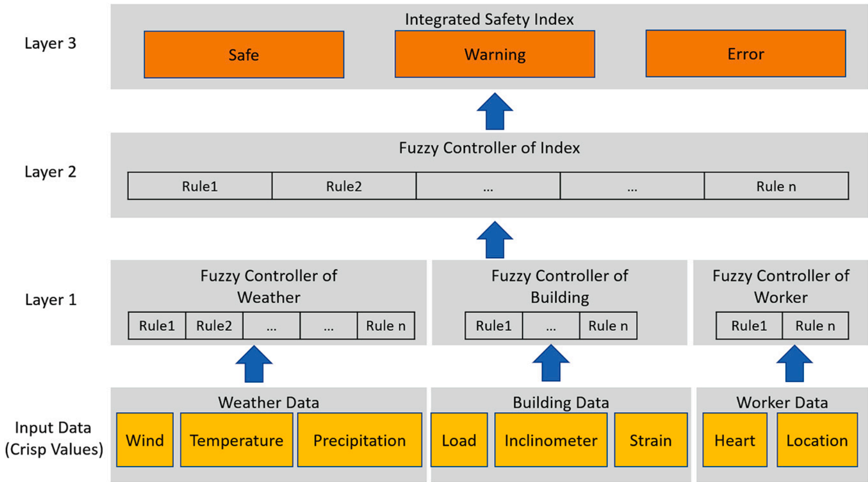

Fig. 10. Layered architecture of multi-layer rule-based modelling for worker safety index.

As depicted in Fig. 10, the multi-layer fuzzy logic system takes into account weather information, building information, and worker information collected from IoT devices as inputs. It assesses the risk associated with weather conditions based on factors such as wind, temperature, and precipitation. Additionally, it evaluates the safety of the building by considering parameters like load, strain, and inclination. The safety risk pertaining to the worker is analyzed by examining the worker's heart rate and location information. The results obtained from the first layer of the fuzzy logic system serve as inputs for the second layer, which combines the individual assessments to infer an integrated safety index. This integrated safety index represents the overall safety level of the construction site. Finally, the safety index is expressed on a scale ranging from 1 to 10, with three distinct grades: safe, warning, and error. This scale provides a visual representation of the safety level, allowing stakeholders to easily understand and interpret the safety conditions at the construction site.

The language that represents the human consciousness process has semantic ambiguity in its expression. Fuzzification preserves the diversity of interpretation by giving the input information a degree of belonging to a linguistic representation (fuzzy set) and the membership degree for each linguistic variable range from 0 to 1. Fig. 11 illustrates membership functions for the load, strain, and inclinometer of the building.

1. The fuzzy sets for linguistic variable load (Fig. 11(a)) are categorized into three categories: loose, medium, and dense.
2. The fuzzy sets for linguistic variable strain (Fig. 11(b)) are categorized into three categories: habitable, caution, and danger.
3. The fuzzy sets for the linguistic variable inclinometer (Fig. 11(c)) are categorized into three categories: maintenance, reinforcement, and emergency repair.

The range of each building's information data varies between 1 and 10. If the range of each input data is lower than 1 then it will be set to the first linguistic variable. If the range of each input data is more than 10 it will be set to the last level linguistic variable.

Fig. 12 depicts membership functions for the weather.

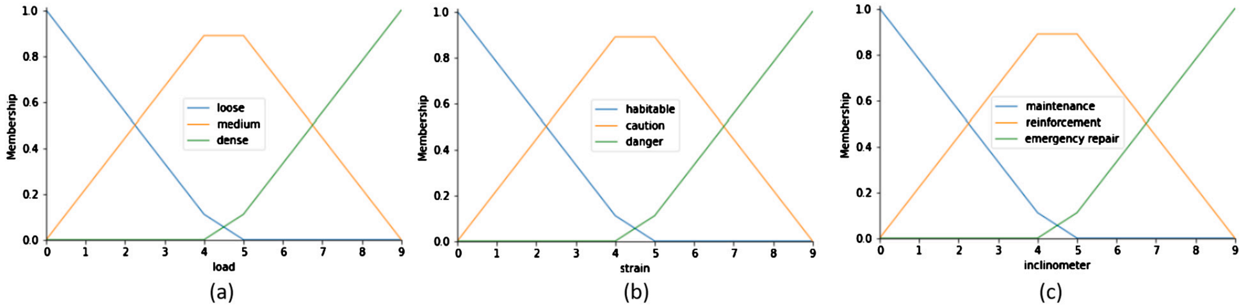

Fig. 11. Fuzzy logic fuzzification for building: (a) Fuzzy sets for load, (b) Fuzzy sets for strain, (c) Fuzzy sets for inclinometer.

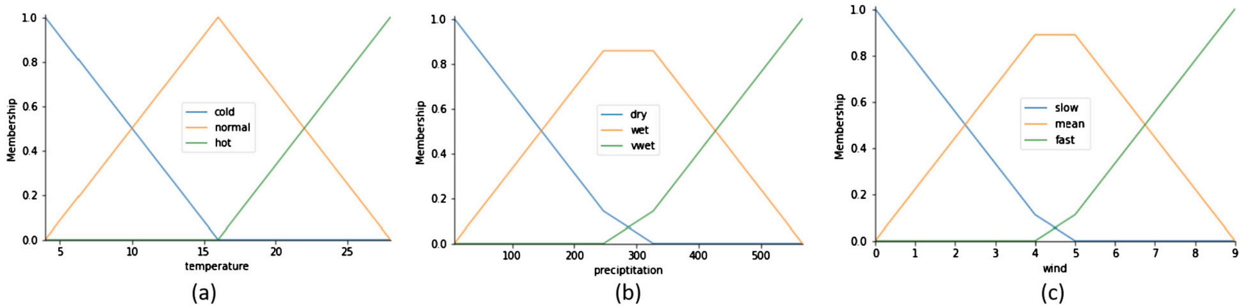

Fig. 12. Fuzzy logic fuzzification for weather: (a) Fuzzy sets for temperature, (b) Fuzzy sets for precipitation, (c) Fuzzy sets for wind.

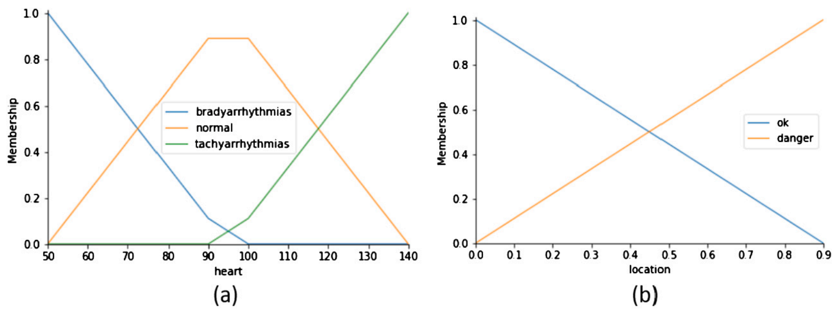

Fig. 13. Fuzzy logic fuzzification: (a) Fuzzy sets for heart, (b) Fuzzy sets for location.

1. The fuzzy sets for linguistic variable temperature (Fig. 12(a)) are categorized into three categories: cold, normal, and hot.
2. The fuzzy sets for linguistic variable precipitation (Fig. 12(b)) are categorized into three categories: dry, wet, and v-wet.
3. The fuzzy sets for the linguistic variable wind (Fig. 12(c)) are categorized into three categories: slow, mean, and fast.

The range of temperature information data varies between 4 and 29. If the input data is lower than 4 then it will be set to cold, if it is more than 29 it will be set to hot. The range of precipitation information data varies between 7 and 614. If the input data is lower than 7 then it will be set to dry, if it is more than 614 it will be set to v-wet which means very wet. The range of wind information data varies between 0 and 10. If the input data is lower than 0 then it will be set to slow, if it is more than 10 it will be set to fast.

Fig. 13 shows membership functions for a worker.

1. The fuzzy sets for the linguistic variable heart (Fig. 13(a)) are categorized into three categories: bradyarrhythmia, normal, and tachyarrhythmias.
2. The fuzzy sets for linguistic variable location (Fig. 13(b)) are categorized into two categories: ok, and danger.

The heart information data exhibits a range spanning from 50 to 150. If the input data is less than 50, it will be classified as bradyarrhythmia; conversely, if it exceeds 150, it will be categorized as tachyarrhythmias. The range of location information data spans from 0 to 1. If the input data is less than zero, it will be assigned the value "ok"; if it is greater than one, it will be assigned the value "danger".

The safety risks of workers on a construction site are varied. Construction sites have different safety risks to workers depending on the stage of construction. The membership function as shown in Fig. 14 is set to give weights using fuzzy logic according to

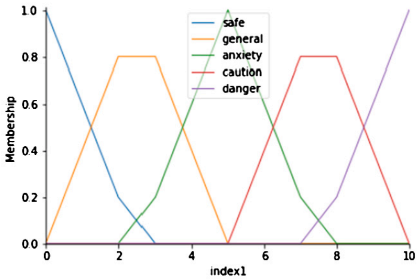

Fig. 14. Fuzzy logic fuzzification for weighting parameters of the construction process.

Table 2
Fuzzy logic rule table for building.

Building			
Load	Strain	Inclinometer	Safety
Loose	Habitable	Maintenance	Safe
Loose	Caution	Reinforcement	Warning
Loose	Danger	Emergency repair	Error
Medium	Habitable	Maintenance	Safe
Medium	Caution	Reinforcement	Warning
Medium	Danger	Emergency repair	Error
Dense	Habitable	Maintenance	Error
Dense	Caution	Reinforcement	Error
Dense	Danger	Emergency repair	Error
...			

Table 3
Fuzzy logic rule table for weather.

Weather			
Temperature	Precipitation	Wind	Safety
Cold	Dry	Slow	Error
Cold	Wet	Mean	Safe
Cold	Vwet	Fast	Error
Normal	Dry	slow	Error
Normal	wet	Mean	Safe
Normal	Vwet	Fast	Error
Hot	Dry	Slow	Error
Hot	Wet	Mean	Waring
Hot	Vwet	Fast	Error
...			

the construction stage. Weights of “safe, general, anxiety, caution, danger” are assigned according to the steps. Depending on the language expression, the weight value is given a value between 1 and 10.

The objective of transforming diverse input data pertaining to buildings into linguistic expressions, known as fuzzification, is to achieve the establishment of building stability. For instance, as the load increases in density, the stability becomes increasingly precarious. In the context of expressing stability based on input information, it can be observed that there exists a proportional relationship between load, strain, and inclination. The evaluation of the fuzzy input information is performed within the rule. Fuzzy inference rules in the form of “IF-Antecedent, THEN-Consequent” are defined in Table 2.

The weather exerts an influence on the safety of workers at a construction site. Working under adverse weather conditions, such as strong winds or heavy rain, poses a potential risk to the safety of workers and is considered to be an irresponsible practice. Similarly, it is advisable to cease working when the temperature exceeds or falls below optimal levels. The guidelines pertaining to the communication of worker safety utilizing weather data within the construction site are presented in Table 3.

There are various factors that influence the safety of workers at construction sites, including the overall health status of workers and the specific circumstances under which they are exposed to hazardous conditions. The assessment of workers’ health is typically conducted by monitoring their heart rate, while the collection of workers’ location data is utilized to ascertain their proximity to hazardous areas. Table 4 is the rules for expressing the safety state using the worker’s personal information.

The safety of workers on a construction site is affected by factors such as weather, building conditions, and worker conditions. The rules for expressing the safety status of the current construction site by considering all the conditions comprehensively were defined in Table 5.

Table 4
Fuzzy logic rule table for worker.

Worker		
Location	Heart	Safety
Danger	Slow bradyarrhythmias	Error
Ok	Slow bradyarrhythmias	Warning
Danger	Normal	Error
Ok	Normal	Safe
Danger	Tachyarrhythmias	Error
Ok	Tachyarrhythmias	Warning

Table 5
Fuzzy logic rule table for safety index.

Safety index			
Weather	Building	Worker	Safety
Safe	Safe	Safe	Safe
Safe	Warning	Warning	Warning
Safe	Error	Error	Error
Warning	Safe	Safe	Safe
Warning	Warning	Warning	Warning
Warning	Error	Error	Error
Error	Safe	Safe	Error
Error	Warning	Warning	Error
Error	Error	Error	Error
...			

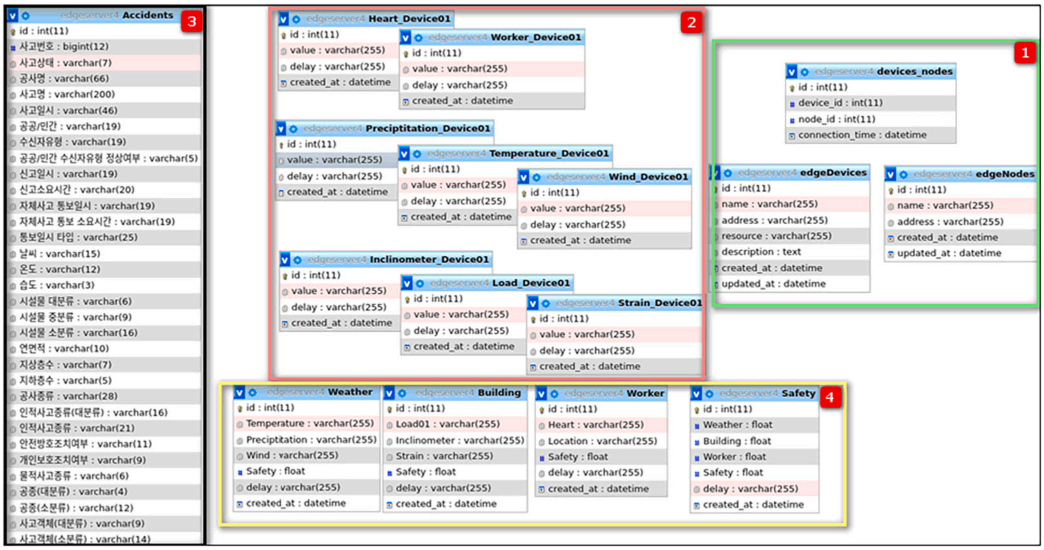

Fig. 15. Entity relationship diagram for the proposed construction worker safety inference system database.

The following Fig. 15 is an ER (Entity Relationship) diagram of the database used in the system. Section 1 comprises the tables pertaining to edge devices and edge nodes, which serve as repositories for data concerning devices and edge gateways. Additionally, the devices_nodes table is responsible for managing the relationships between these entities. Section 2 provides tables that display the names that have been registered on edge devices. The data acquired from the device is stored in its corresponding table. Table 3 functions as a repository for storing records of accidents that have taken place at construction sites. Section 4 of the document encompasses a pair of tables. The initial table is designated for the storage of safety values associated with the environment, structures, and personnel situated at the construction site. The second table is specifically allocated for the purpose of storing the integrated safety index.

Table 6
Developmental environment of the proposed worker safety prediction approach.

Entity	Hardware	Softwares
Edge Server	Ubuntu 20.04 Desktop (VM)	HTML5, CSS3, Bootstrap, JavaScript, Python 3.8, Visual Studio Code, Flask, MariaDB
Edge Gateway	Raspberry Pi 4 Model 4B, Ubuntu 20.04 Server	Golang 3.6, Visual Studio Code, EdgeX, Docker, Docker Compose

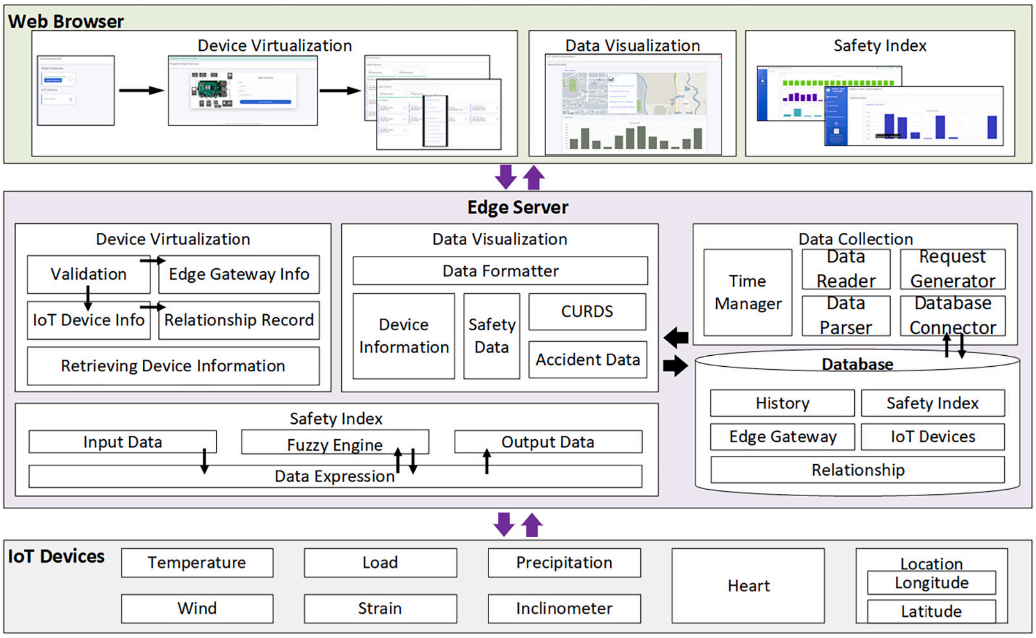

Fig. 16. Implementation configuration for worker safety inference system.

5. Implementation of proposed construction worker safety inference system

5.1. Developed environment configuration for edge server and IoT devices of proposed construction worker safety inference platform

The worker safety system in construction comprises an edge gateway responsible for gathering environmental data and worker personal information. Additionally, there is an edge server that virtualizes, visualizes, and monitors worker safety utilizing the collected data. To facilitate an intuitive representation of worker safety, the edge server was implemented as a web application using the Flask framework, leveraging the Python programming language. The development process involved coding in Python using the Visual Studio Code development tool on Ubuntu 20.04. For data collection, Raspberry Pi devices were chosen. The Ubuntu 20.04 server was installed and services were programmed using Golang and Visual Studio Code. Docker was employed on the Edge Gateway to execute the EdgeX microservices. A detailed development environment for the edge server and edge gateway is presented in Table 6.

Our proposed system has been implemented as depicted in Fig. 16. Every edge gateway is responsible for managing IoT devices that are tasked with collecting data related to construction sites. The edge gateway comprises three distinct devices that are exclusively designed for the purpose of managing weather, building, and worker data. The data collected is regularly stored in the database through the utilization of the data collection function of the edge server. The safety level of the construction site is quantified by converting the stored data into a numerical value using the safety index function. Furthermore, the system integrates a data and device visualization feature, enabling users to observe the data stored within the database. Through the establishment of a connection between the edge server and a client, a multitude of operations can be executed. The aforementioned functionalities encompass device registration, status monitoring, data verification, and safety identification. The integration of connectivity into the system enhances its overall capabilities and offers users a more efficient means of interacting with the system.

Fig. 17 presents the device profile responsible for providing building-related data. This device consists of three components: Inclinometer-Device, Load-Device, and Strain-Device. The Inclinometer-Device offers a resource called Inclinometer-value, which provides data in the Float32 data type. The Load-Device supports both reading and writing commands for the Load-value resource. The details of the sensing device configuration profile for building information are presented below.

```
apiVersion: "v2"
name: "Inclinometer-Device"
manufacturer: "xrx."
model: "Inclinometer-01"
labels:
  - "incli01"
description: "Example of Inclinometer Device"
deviceResources:
  -
    name: "Inclinometer-value"
    isHidden: true
    description: "Inclinometer value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Inclinometer"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource:
          "Inclinometer-value", defaultValue: "0.0" }
```

```
apiVersion: "v2"
name: "Load-Device"
manufacturer: "xrx."
model: "Load-01"
labels:
  - "load01"
description: "Example of Load Device"
deviceResources:
  -
    name: "Load-value"
    isHidden: true
    description: "Load value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Load"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource:
          "Load-value", defaultValue: "0.0" }
```

```
apiVersion: "v2"
name: "Strain-Device"
manufacturer: "xrx."
model: "Strain-01"
labels:
  - "strain01"
description: "Example of Strain Device"
deviceResources:
  -
    name: "Strain-value"
    isHidden: true
    description: "Strain value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Strain"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource:
          "Strain-value", defaultValue: "0.0" }
```


Fig. 17. Sensing device configuration profile for building information.

Fig. 18 showcases the device profile responsible for generating weather data. To differentiate between devices, they have been named as Precipitation-Device, Temperature-Device, and Wind-Device, respectively. The specific data provided by each device is outlined under the deviceResource attribute. For instance, the Precipitation-Device offers a resource called Precipitation-value, which provides data in the Float32 data type. Additionally, the profile specifies the command that needs to be transmitted to the device. Similarly, the Temperature-Device indicates its support for reading and writing commands for the Temperature-value resources it provides. See the picture below for more details.

Fig. 19 showcases the device profiles that support worker-related data. The devices have been named Heart-Device and Worker-Device, respectively, based on the type of data they provide. Examining the deviceResources of the Heart-Device, you will find a resource named Heart-value, which offers data in the Int32 data type. Similarly, the Worker-Device enables reading and writing commands for resources such as longitude-value and latitude-value. Further details are presented below in the worker information sensing device configuration profile.

5.2. Implementation results of worker safety inference system

Fig. 20 (a) presents the testbed displaying the installation results of the execution environment for the edge gateway. In this setup, three Raspberry Pi 4 models are utilized to implement IoT devices. Each device simulates the collection of weather, building, and worker data at the construction site. Furthermore, the edge gateway executes the temporary storage of data generated by the devices and facilitates the connection with the edge server.

The determination of worker safety on a construction site relies on gathering information about the environment, building conditions, and the workers themselves. To collect this vital information, IoT devices are employed. In our proposed system, the initial step involves registering the IoT devices responsible for data collection. Users can conveniently register and monitor the

```
apiVersion: "v2"
name: "Preciptitation-Device"
manufacturer: "xrx."
model: "Preciptitation-01"
labels:
  - "precip01"
description: "Example of Preciptitation Device"
deviceResources:
  -
    name: "Preciptitation-value"
    isHidden: true
    description: "Preciptitation value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Preciptitation"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource:
         "Preciptitation-value", defaultValue: "0.0" }
```

```
apiVersion: "v2"
name: "Temperature-Device"
manufacturer: "xrx."
model: "TEMP-01"
labels:
  - "temp01"
description: "Example of Temperature Device"
deviceResources:
  -
    name: "Temperature-value"
    isHidden: true
    description: "Temperature value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Temperature"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource:
         "Temperature-value", defaultValue: "0.0"
```

```
apiVersion: "v2"
name: "Wind-Device"
manufacturer: "xrx."
model: "Wind-01"
labels:
  - "wind01"
description: "Example of Wind Device"
deviceResources:
  -
    name: "Wind-value"
    isHidden: true
    description: "Wind value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Wind"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource:
         "Wind-value", defaultValue: "0.0" }
```


Fig. 18. Weather information sensing device configuration profile.

required devices through the system's provided web page. Fig. 20 (b) illustrates the main display page of the worker safety inference system which is divided into sections for edge gateways and devices. As it is the system's first run, the page initially appears empty without any information. To proceed with device registration, users can click on the registration button located under the corresponding edge gateway section, which directs them to the registration page.

To gather essential information reflecting the condition of the construction site, it is necessary to register the corresponding devices. Each device responsible for collecting architectural, environmental, and worker-related data has been duly registered. Fig. 21 (see Fig. 21) depicts the registration page for the edge gateway managing building information. Users can effortlessly complete the registration process by simply entering the edge gateway's name and address information, followed by clicking the registration button. It is important to note that names serve as unique identifiers for differentiating edge gateways, thus avoiding any repetitions. It is recommended to use the same name as the hostname set in the operating system. The address should include the Internet Protocol (IP) address, which identifies the end device on the internet, and the port number utilized by the service. Upon successful registration of the edge gateway, a green message will appear at the top of the screen, confirming the successful completion of the registration process. In this particular case, the device name is "edgex05", while the address and port are specified as "192.168.0.24:4327".

Fig. 22 shows the main page of the edge server. This page lists the information of registered edge gateways and IoT devices. Each physical object in the network is virtualized and represented as a card. The physical objects and cards are represented in a one-to-one relationship. The main page allows users to check the execution status of physical objects in real time. The colour of the edge of the card indicates the execution status of the physical object for the edge gateway. Green indicates that the object is functional, while blue indicates that it is non-functional. The name and address of the object can be checked through the text displayed on the card. The edge gateway is represented as a computer-shaped icon, while the IoT device is represented as an icon that looks like a processor. The resources provided by IoT devices are also displayed in text. There are 3 edge gateways and 8 registered IoT devices.

```
apiVersion: "v2"
name: "Worker-Device"
manufacturer: "xrx."
model: "Worker-01"
labels:
  - "worker01"
description: "Example of Worker Device"
deviceResources:
  -
    name: "longitude-value"
    isHidden: true
    description: "longitude value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
  -
    name: "latitude-value"
    isHidden: true
    description: "latitude value"
    properties:
        valueType: "Float32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Location"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource: "longitude-value", defaultValue: "126.56515605551154" }
      - { deviceResource: "latitude-value", defaultValue: "33.45468468580735" }
```

```
apiVersion: "v2"
name: "Heart-Device"
manufacturer: "xrx."
model: "Heart-01"
labels:
  - "heart01"
description: "Example of Heart Device"
deviceResources:
  -
    name: "Heart-value"
    isHidden: true
    description: "Heart value"
    properties:
        valueType: "Int32"
        readWrite: "RW"
deviceCommands:
  -
    name: "Heart"
    isHidden: false
    readWrite: "RW"
    resourceOperations:
      - { deviceResource:
          "Heart-value", defaultValue: "0.0" }
```

Fig. 19. Worker information sensing device configuration profile.

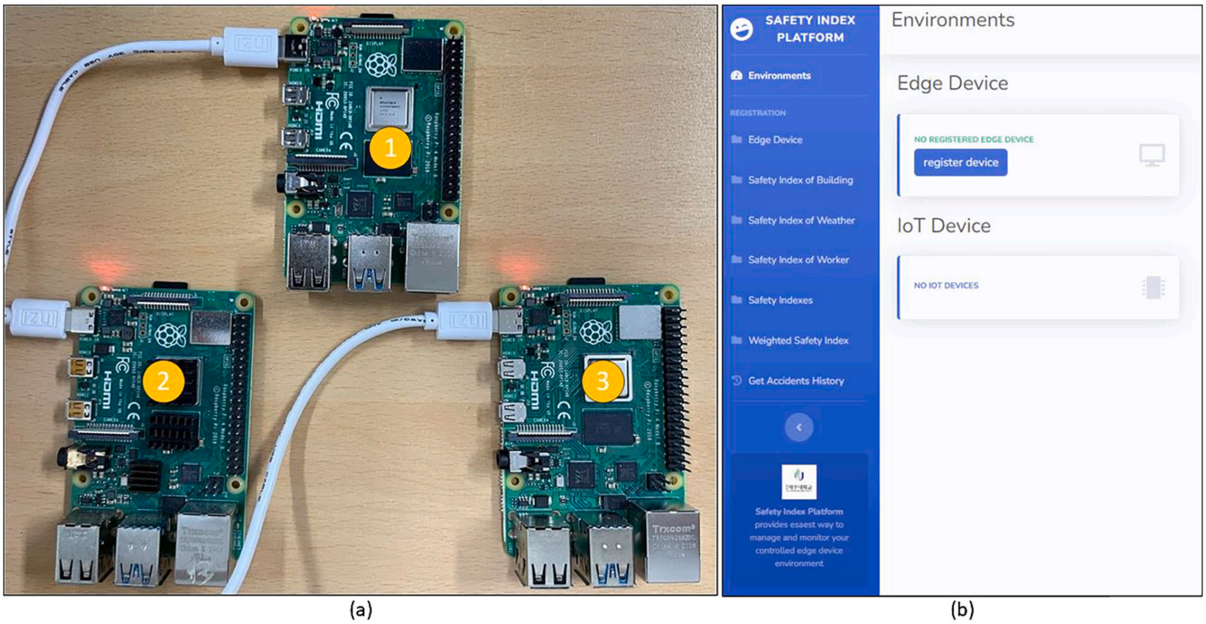

Fig. 20. (a) Edge gateway execution testbed environment. (b) Worker safety inference system main display page.

The device monitoring screen allows users to check the running status of the edge gateway, the basic information of the platform running on the edge gateway, and the information of the connected device. To do this, users can simply hover their mouse over the corresponding item. Fig. 23 shows the result screen for checking detailed information in a popover.

When a user clicks on the name of a mirrored object card, it is converted to a screen that displays detailed information. Fig. 24 shows the detailed information for the edge gateway “edgex05”. The detailed location information is drawn on the map using the IoT device location information. The map not only shows the location of the edge gateway, but also basic information about it. In the upper right corner, there is a small widget that numerically expresses the number of connected IoT devices. If a user clicks on one of the listed IoT devices, it will move to a screen that displays detailed information about the corresponding device.

The edge server provides detailed information about IoT devices and edge gateways. Fig. 25 shows detailed information about an IoT device that collects load-related information. The device is connected to the edge gateway “edgex05” and the collected data can be checked through the bar chart below. Location information can also be found on the map.

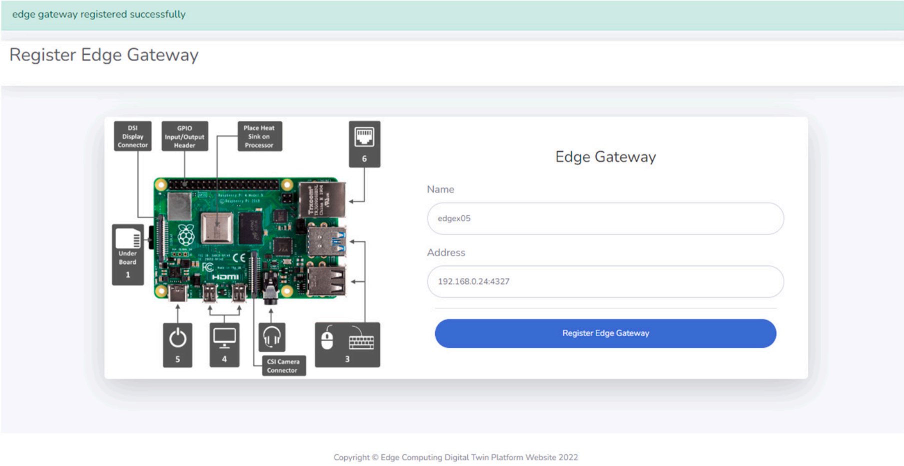

Fig. 21. Building information sensing device registration results.

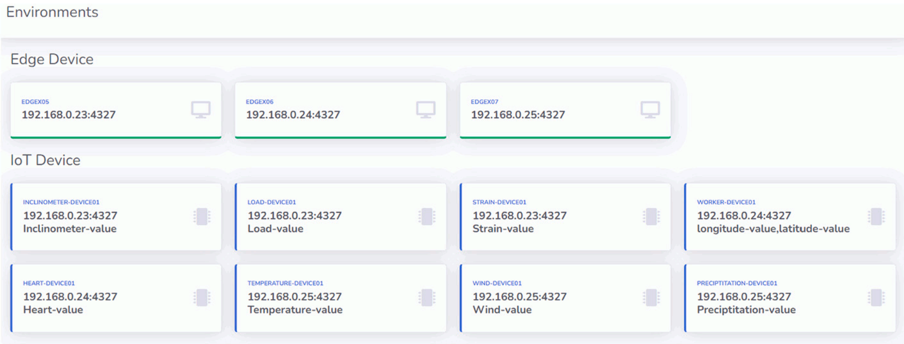

Fig. 22. Registered sensing device monitoring and virtualization results.

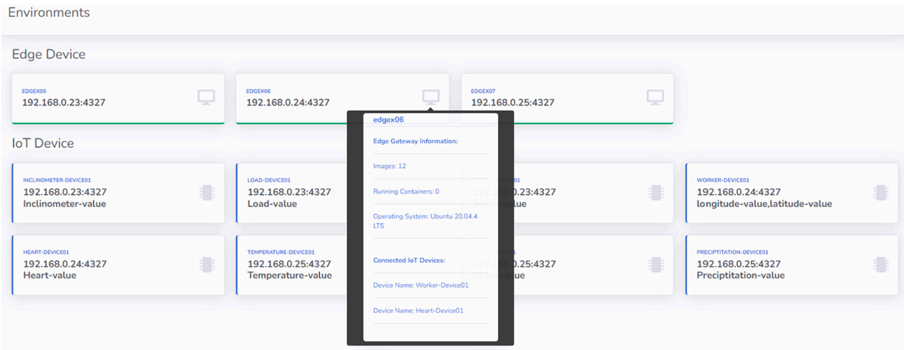

Fig. 23. Registered sensing device status expression results.

Fig. 26 shows the weather-related data at the construction site. The weather-related data consists of temperature, precipitation, and wind. The bar chart on the left shows the 20 most recent data points for each of these variables. The bar chart on the right shows a safety value estimated through fuzzy logic. Different colours are used to distinguish each diagram, and appropriate labels are also used. The client can check the weather information and safety information at the same time on the screen.

Fig. 27 shows the worker-related data at the construction site. The worker-related data consists of heart rate and location. The bar chart on the left shows the most recent heart rate data for each worker. The bar chart on the right shows the most recent location data for each worker. The location data is used to display a marker on the map, and the worker's health status can also be checked through the screen. This feature provides a convenient way to track the location and health status of workers simultaneously.

Fig. 28 shows the building-related data at the construction site. The building-related data consists of load, inclinometer, and strain. The bar chart on the left shows the 20 most recent load data points. The bar chart in the middle shows the 20 most recent inclinometer data points. The bar chart on the right shows the 20 most recent strain data points. The upper part of the screen shows

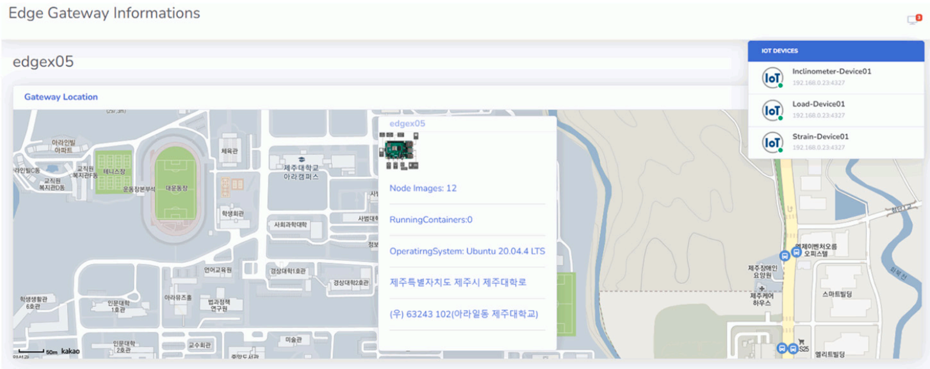

Fig. 24. Detailed information visualization for registered edge gateway of “edgex05”.

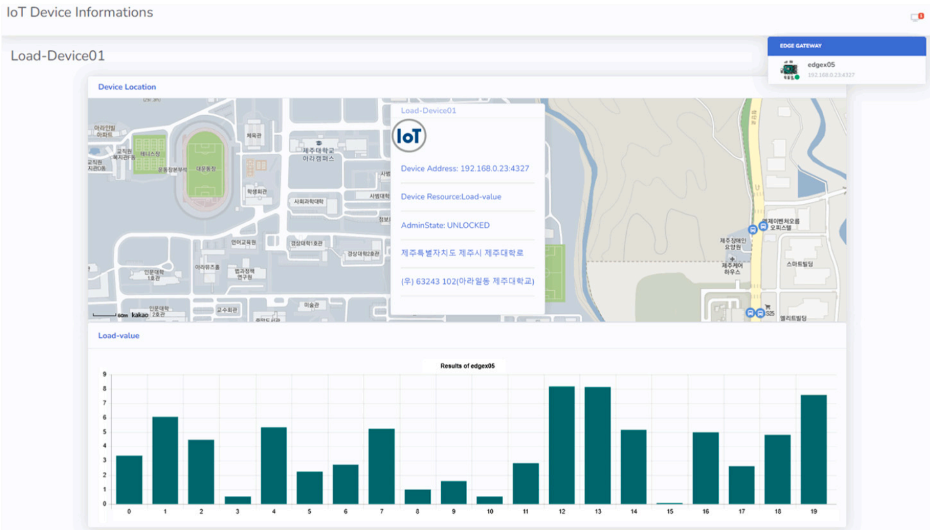

Fig. 25. Detailed information visualization for registered sensing device of load of building.

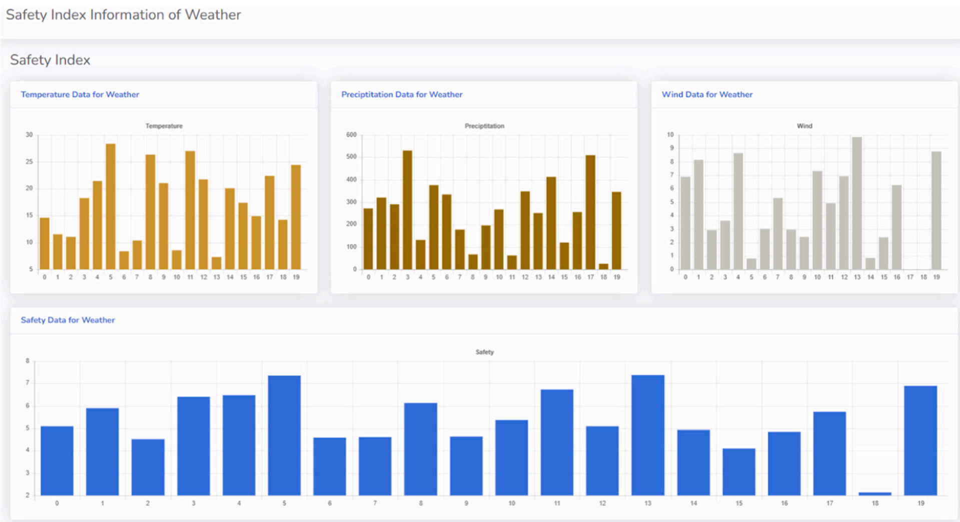

Fig. 26. Fuzzy logic results of weather.

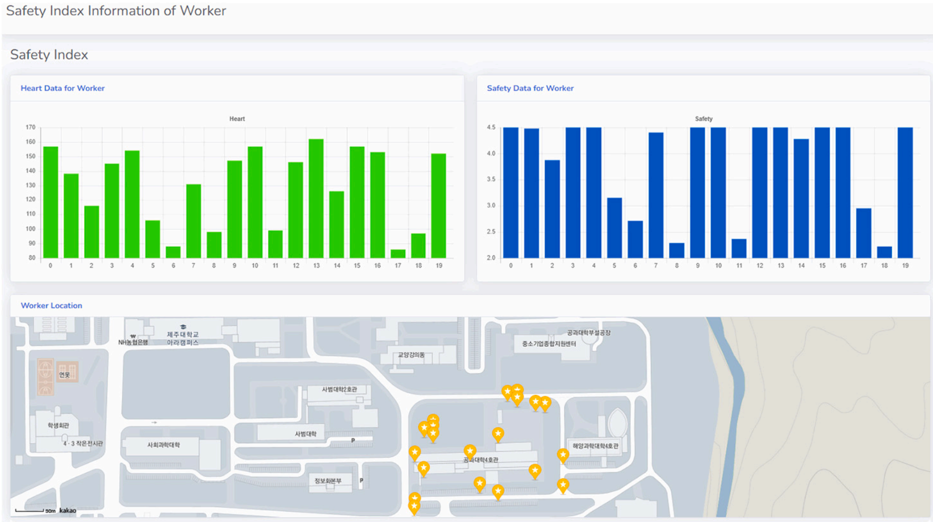

Fig. 27. Fuzzy logic results of weather.

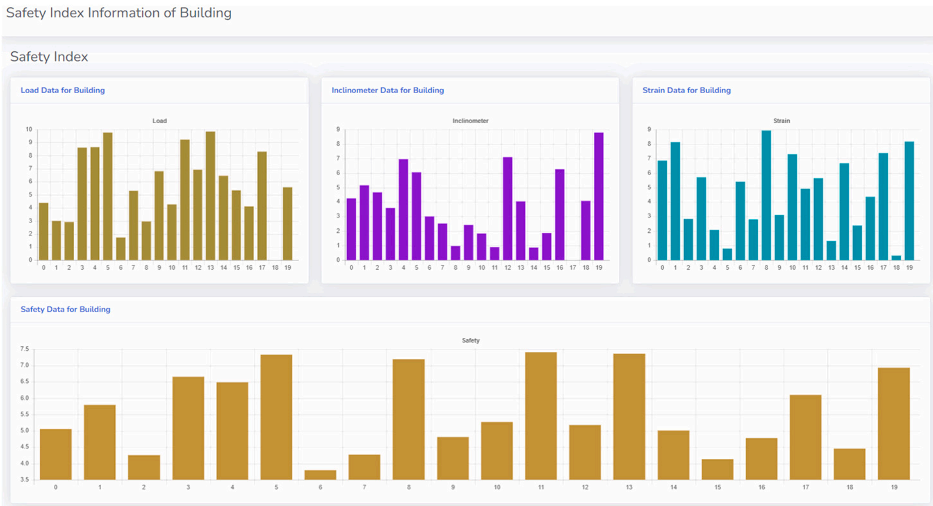

Fig. 28. Fuzzy logic results of worker.

data-related information that constitutes the building, such as the building name, location, and type. The bar chart below is a safety value estimated through fuzzy logic. Different colours are used to distinguish each analysis, and appropriate labels are also used. The client can check the building information and related safety information at the same time on the screen.

Fig. 29 shows the safety numerical results of the construction site predicted using multi-layer fuzzy logic. The safety value of the construction site is predicted using fuzzy logic in consideration of the weather, the building condition, and the health condition of the workers. The safety value of each element and the final result is expressed as shown in the figure.

Workers on a construction site are exposed to different risk factors depending on the stage of construction. To more realistically reflect the safety of the construction site, weights are assigned to different construction stages. The construction phases of a construction site include temporary construction, machinery, concrete construction, exterior and interior construction, and finishing work. For the convenience of the user, each construction stage is represented by a radio button in the upper left corner of the screen. The corresponding result can be seen by selecting the appropriate radio button. The system returns a weight-based safety index result generated by inputting a safety index and a weighted value for the selected construction stage. A bar chart is used to represent the numerical value, the colour is generated randomly, and the latest 20 safety index results are shown. Fig. 30 shows the weight-based construction site safety index for the temporary construction phase.

To prevent construction accidents, past accident data is used to establish safety measures. Due to the large scale and one-time nature of construction projects, the data is prepared as text documents. It is expected that the creation, correction, deletion, and inquiry of construction safety documents will be useful for construction projects. As shown in Fig. 31, construction site accident data is displayed in a table. Since the data cannot all be displayed on the screen at once, users can scroll left, right, up, and down to view

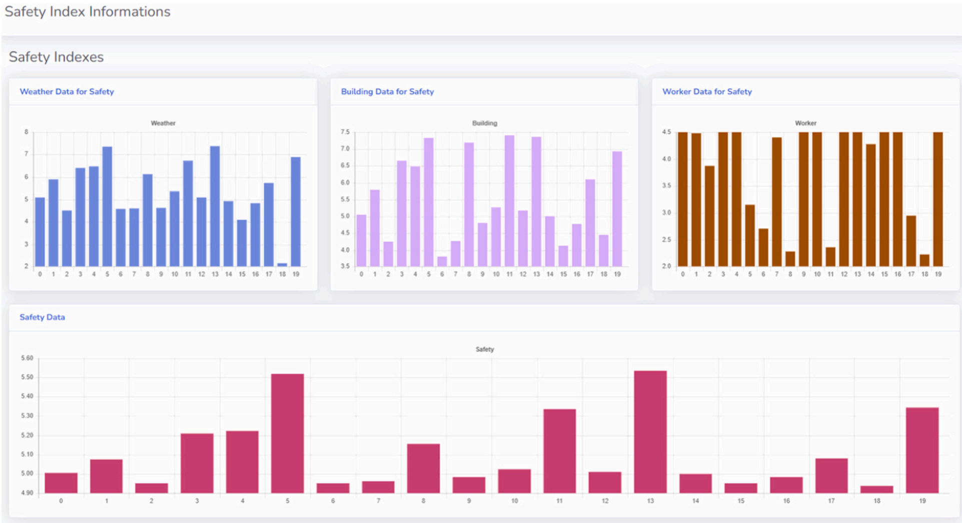

Fig. 29. Fuzzy logic results for integrated safety index.

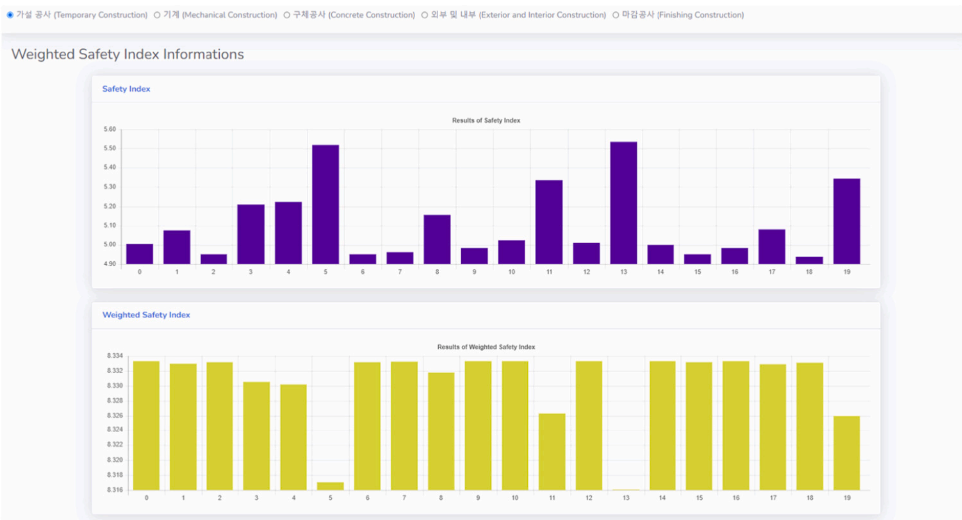

Fig. 30. Safety index results in the temporary construction phase of the worker safety inference system.

it. The figure is divided into two parts: (a) and (b). In Figure (a), there are create, change, and delete buttons on the upper left of the table. These buttons provide corresponding functions. At the top left of the table is a number that indicates the number of data points displayed at once. There is also a search function that allows users to search for desired information from the data stored in the database. Figure (b) is the last part of Figure (a) and shows the total number of data points stored in the database, as well as the number and pages of data currently being displayed.

Fig. 32 shows the screen that appears after clicking the Update button. When a user selects the row of data they want to change and clicks the Update button, the following screen pops up. The selected information is listed in the pop-up window, and the user can modify any necessary parts. Since there is a lot of data, the figure is divided into two parts: (a) and (b). When the user is finished editing, they can click the Update button in Figure (b) to save their changes, or they can click the Cancel button to discard their changes.

Fig. 33 depicts the screen that appears after clicking the Create button. When a user clicks the Create button, the following screen pops up. All of the columns necessary to create new accident data are listed with default values, so the user can enter data by referring to the default values. Since there is a lot of data, the figure is divided into two parts: (a) and (b). When the user is finished creating the new data, they can click the Create button in Figure (b) to save the data to the database, or they can click the Cancel button to discard their changes.

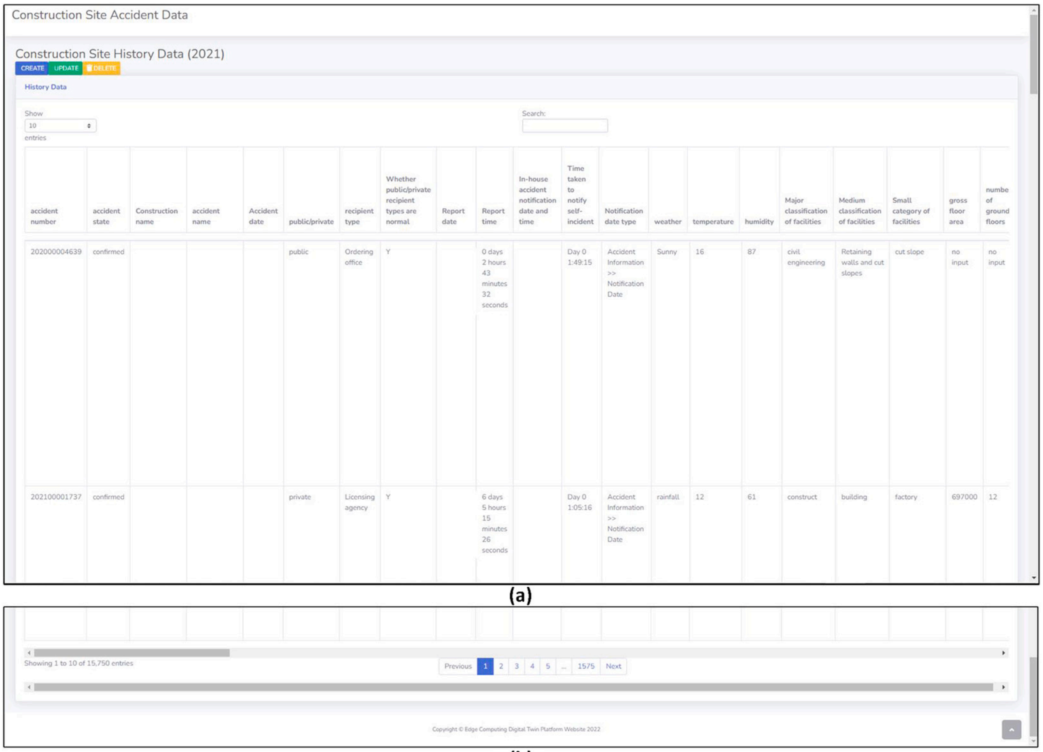

Fig. 31. Construction accidents history data results.

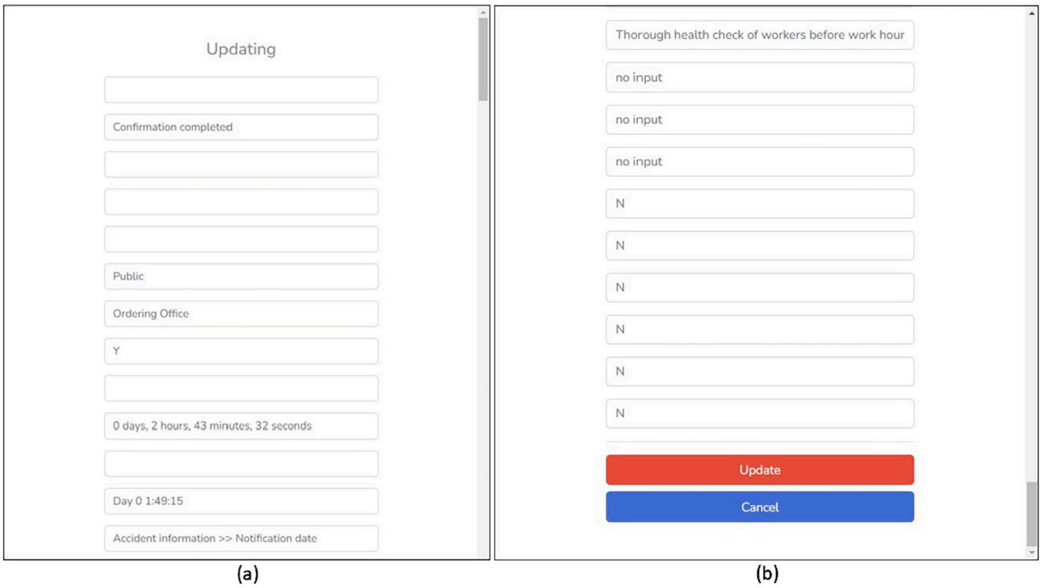

Fig. 32. Construction accidents history update function page.

6. Performance analysis for proposed worker safety inference in construction site

Fig. 34 shows the delay times for retrieving data from an IoT device. There were a total of 20 test results. The delay times for all experiments except for the first and seventh were less than 30 milliseconds.

The safety index is derived from data collected from the edge gateway. The data is fed into a multi-layered fuzzy logic system, which computes the worker's overall safety index. The time taken by the system to compute the output of the safety index is shown in Fig. 35. The highest recorded time is 1 second, and the average is 0.4 seconds.

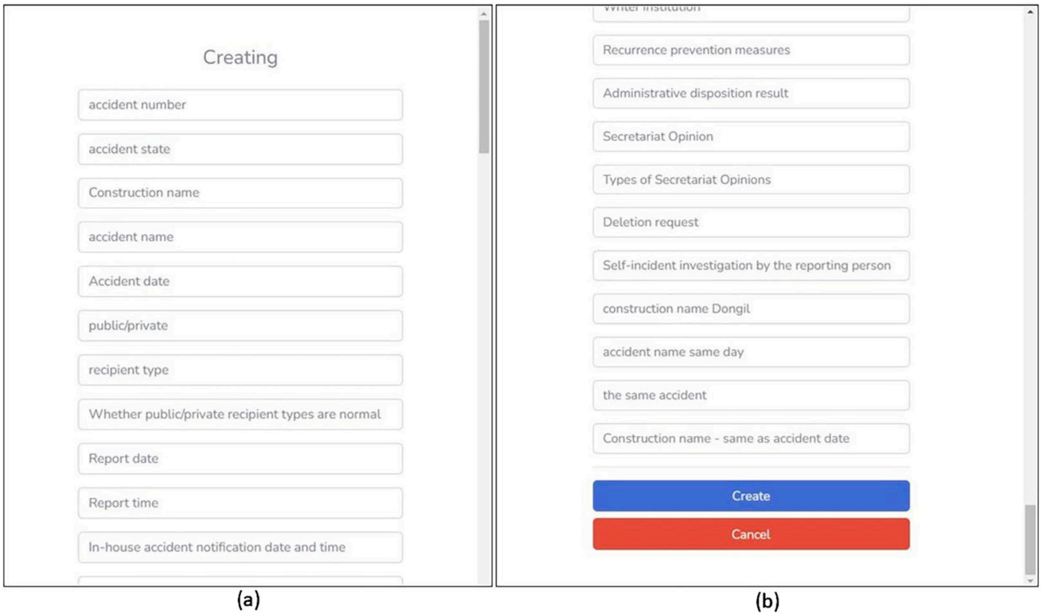

Fig. 33. Construction accidents history create function screen.

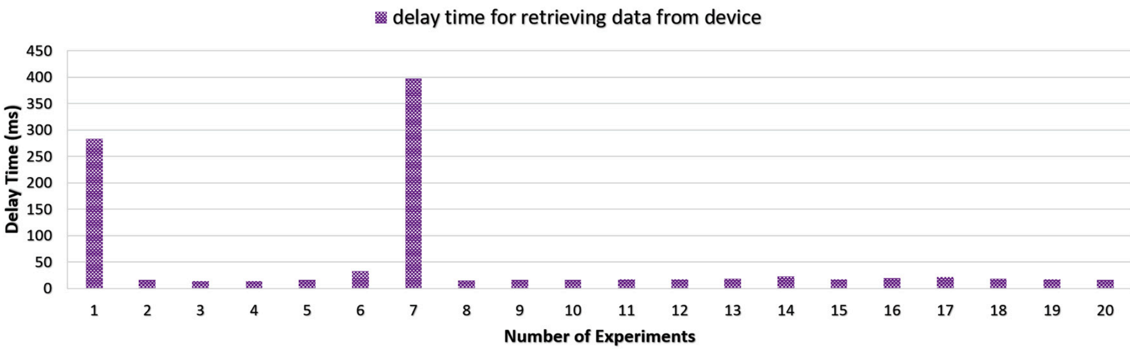

Fig. 34. Delay time statistics for retrieving data from IoT device.

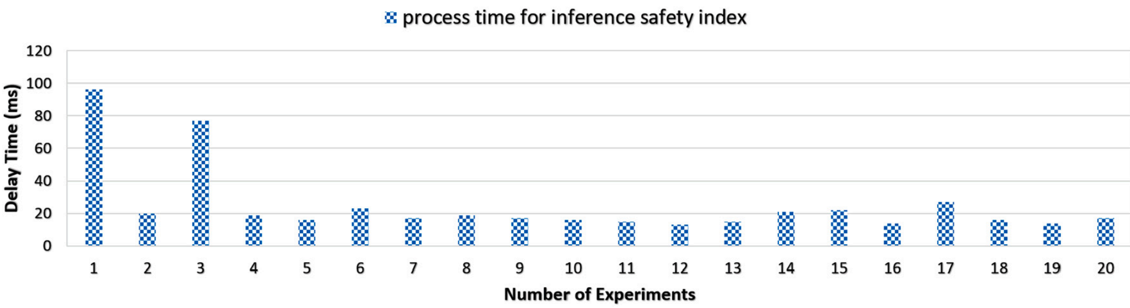

Fig. 35. Process time statistics for inference worker safety index in construction site.

Fig. 36 shows the results of predicting the safety of a construction site. The safety value is an integrated numerical value that is output using the primary predicted value, which is measured based on the weather, buildings, and worker data at the construction site. Different types of numerical values are used to classify each value, and a total of 20 prediction results are shown in the chart. Although the input values for weather, buildings, and workers fluctuate, the experimental results suggest that the safety result value is always close to 5.

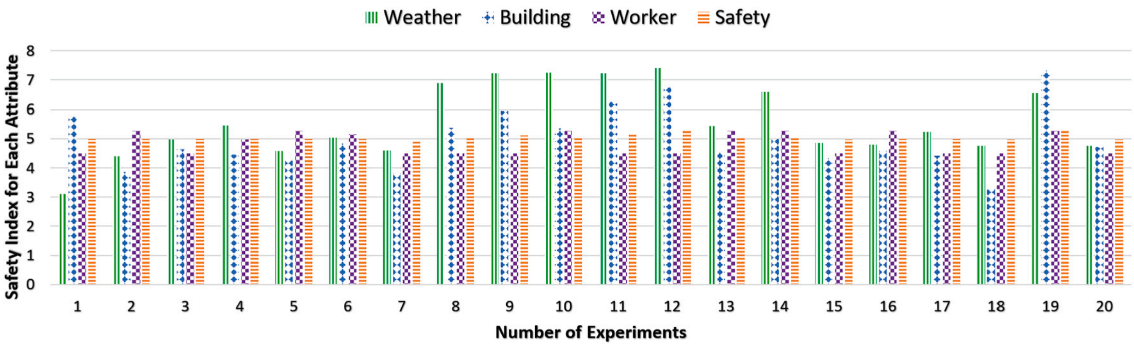

Fig. 36. Comparison of each attributes safety index in construction site.

7. Discussion

The framework developed in this study takes a proactive approach to tackle the data management challenge. By leveraging edge computing principles, our system shifts data processing closer to the data source, alleviating the load on centralized data management systems. This design choice not only enhances system scalability but also addresses potential data processing bottlenecks. Moreover, our framework's architecture is intentionally designed for compatibility with emerging data management technologies and standards. Recognizing the importance of adaptability to future developments, we plan to explore collaborations with experts in data management to refine our methods and seamlessly integrate our system into evolving data management practices. Despite the positive outcomes and significant contributions of our multi-layered fuzzy logic framework in enhancing construction site safety, it's important to acknowledge inherent limitations. While our system comprehensively considers factors such as weather conditions, structural stability, and worker well-being to assess site safety, it's important to recognize that other external variables may also influence safety. Notably, our model doesn't explicitly encompass factors like equipment malfunctions, external security threats, and unforeseen emergencies, which could impact overall safety. Additionally, the accuracy and reliability of the safety index depend on the quality of data from IoT devices. These limitations highlight the need for continuous advancements in data technology and comprehensive modelling to enhance the dependability and breadth of our framework.

8. Conclusions

The construction industry is renowned for its complex and challenging nature, necessitating robust safety management systems. To address this imperative, we advocate the implementation of an innovative on-site correspondence safety index, underpinned by multi-layer fuzzy logic, to enhance the safety of construction workers. Our comprehensive approach involves the integration of edge computing and IoT devices to monitor the construction site's environmental conditions. By embracing edge computing, we ensure optimal fulfilment of IoT device requirements. Leveraging temporary storage, we efficiently manage collected data, while the transparency protocol facilitates seamless communication among diverse IoT devices. The culmination of our efforts materializes in the form of a multi-layer fuzzy logic controller, pivotal in determining the safety index of the construction site. As we look ahead, our strategic trajectory encompasses the practical deployment of the system within a genuine construction site context, affording us a comprehensive evaluation of its performance and efficacy. Through these advancements, we strive to contribute to the ongoing enhancement of construction safety management practices.

CRediT authorship contribution statement

Rongxu Xu: Conceived and designed the experiments; Performed the experiments. **Sa Jim Soe Moe; Anam Nawaz Khan:** Analyzed and interpreted the data; Wrote the paper. **Bong Wan Kim; Kwangsoo Kim; Do Hyeun Kim:** Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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