Design and Implementation of a Fuzzy Expert System for an Ergonomic Performance Assessment in Modular Construction Operations Using the DMAIC Approach

A. Govindan and X. Li

1 Introduction

The workstation design, which does not take ergonomics into account, often involves awkward body positions for workers, which can contribute to musculoskeletal disorders or injuries. To increase comfort for staff, these stations need to be revamped using ergonomic analysis. In cases where the principles of ergonomics have not been considered in manufacturing plants, there is a need to improve or modify the workstations and the working conditions, which can increase worker comfort and potentially increase productivity for the entire manufacturing plant [18]. At the occupational level, ergonomics study sought critical causes of work-related musculoskeletal disorders (WMSD) such as static work, repetitive operation, exposure to vibration, abnormal posture, over usage of strength, lack of recovery, and monotony of task [26]. Brauner et al. [2] identified work duration as a crucial factor that determines the exposure of employees to physical stress and the availability of their recovery [2]. Researchers have brought about advancements in this domain by introducing ergonomic intervention in lean design, risk assessment tools, questionnaires for assessing physical load [11, 13, 20] etc. to make ergonomic improvements. Ergonomic improvements are usually made in industries considering the principles of occupational ergonomics, where the work environment is designed to match workers capabilities. Ergonomics can bring good results; help improve efficiency and decrease construction time and costs. Construction workers face high ergonomic risks that negatively affect the well-being and productivity of

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the workers. Therefore, it is crucial to accurately assess the workforce's ergonomic risk [4]. Ergonomists contribute to designing and evaluating systems to make them compatible with people's needs, skills, and limitations. Tee et al. [28] discuss the importance of assessing the potential ergonomic risk factors in the workplace using risk assessment tools like Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) [28]. Ergonomic performance assessments are continuous, on-going processes that include the entire workforce present at the organization. Numerous organizations do not have adequate knowledge to execute their self-assessment process for evaluating organizational performance. They also indicate that the development of analysis tools for assessing industrial performance is very scarce [16]. Analyzing a business's performance is not a common practice, and proficiency in this area is obtained from practical experiences rather than formal education. Most managers overlook the advantages of performance analysis. They do not conduct them promptly due to the lack of staff availability and the time consumption that is involved, and thus, valuable information required for improving the organizational performance is lost [1]. Thus, there is a need to utilise a systematic and automated process within industries to minimize time and efforts to conduct ergonomic assessments and make decisions. This can be performed using the FES. Expert systems are a particular type of Decision Support System (DSS) that are a problem-solving software that performs well in a specialized problem field that is considered difficult and requires specialized knowledge and skills. A decision support system based on fuzzy logic can mimic human decisions based on the inputs provided [30]. The design and implementation of a fuzzy logic-based DSS, often called a FES, for ergonomic performance assessment, is expected to cut down the time it takes to identify the required changes in the workplace to make it more ergonomically safely. The FES can then help the ergonomists or managers focus most of their time in executing administrative or engineering controls based on the types of ergonomic hazards identified. This paper explores the effectiveness of utilizing a proposed FES to support the decision-making process to implement changes in the industry. It is done by eliminating or mitigating the ergonomic risk factors and supporting ergonomic performance benchmarking through ergonomic risk identification.

2 Literature Review

This section explores supporting literature that discusses the need to develop an FES for ergonomic assessments and how this form of artificial intelligence is being used in recent research. A brief review of why the DMAIC methodology will help develop the FES has also been included in this section.

2.1 DMAIC Framework

DMAIC refers to a cycle of data-driven enhancement used for business processes and designs to be improved, optimized, and stabilized. The primary method used to push Six Sigma ventures is the DMAIC enhancement loop. DMAIC stage model is not limited to Six Sigma and can be used as the basis for other applications for improvement by acting as a problem structuring device [5]. This problem structuring tool was used for development and application of the FES in this study. DMAIC is preferred for this study as it is a customer-focused, data-driven, and an organized problem-solving system that builds on learning from previous stages. In companies and projects where there is a need for continuously improved processes, this tool proves to be an appropriate and flexible framework to discover and execute best practices.

2.2 FES and Its Applications in Various Fields

Numerous expert systems consist of inference engines based on dual logic, whereas FES's are based on fuzzy logic and approximate reasoning [23]. The basic idea behind a FES is to use fuzzy logic rather than Boolean logic. When conventional statistical reasoning and other techniques to combine degrees of uncertainty are insufficient, we realize a need for a FES [3]. Fuzzy systems can store experts' knowledge in the form of rules or mathematical expressions that can be flexible to envision and adjust the system. The fuzzy system can be perfected to attain good performance by adjusting the membership functions and parameters by involving manual methods of trial and error since the fuzzy system's performance can be susceptible to the specific values of parameters [19]. A fuzzy logic system consists of four main subsystems: fuzzification, inference, rule base, and defuzzification [17]. Implementing intuition, heuristics, and expert knowledge in the domain are some of the main advantages of utilizing a FES. The key benefit of these systems is that the knowledge progressively helps attain expertise and can be used in crucial circumstances as a decision-making method that replaces traditional FAQs [25]. Thus, this system can help benefit ergonomic assessments in modular construction industries to conduct a rapid ergonomic assessment to support the ergonomic intervention plans. It is possible to supplement traditional statistical validation methods based on numerical data with human expertise, which often requires heuristic knowledge and intuition [32]. Fuzzy logic has been successfully used in several areas, such as control systems engineering, image processing, power engineering, industrial automation, robotics, consumer electronics, and optimization. This mathematics division brought a new life into scientific fields that have been stagnant for a long time [27].

Jabłoński and Grychowski [14] have designed a system that assesses indoor environmental conditions using data gathered by numerous sensors based on occupants' comfort. Pokorádi [24] have developed a fuzzy system that can make accurate risk assessments which can help make decisions in the real world to ensure safety. Falahati et al. [6] used the fuzzy logic approach to predict WMSD among automotive assembly workers based on self-reported questionnaires and REBA assessment using the MATLAB software. Golabchi et al. [9, 10] proposed a fuzzy logic approach using Rapid Upper Limb Assessment (RULA) scoring system modelled using fuzzy logic to prevent ergonomic injuries. Fayek and Oduba [7] illustrated how to develop a FES to predict industrial construction labour productivity given the realistic constraints of multiple contributing factors, subjective assessments, and limitations on data sets. Wang et al. [31] proposed a dedicated rule based-fuzzy system paired with an automated 3D ergonomic risk assessment tool to record the incremental transitions of continuous human motion without triggering sudden changes in risk scores. These papers use different tools and techniques to make an ergonomic risk assessment. Although, there has not been a study that demonstrates a method to display the overall ergonomic risk present in an industry that includes physical ergonomics, environmental ergonomics and, cognitive ergonomics at the same time. Generally, in the literature, ergonomic risks are assessed to better workplace conditions for WMSD, focusing on various ergonomic assessment tools, betterment of environmental conditions, and improvement of labor productivity, prevention of ergonomic injuries. In the industry, ergonomics is usually associated with occupational health and safety and related legislation rather than business performance. Ergonomic performance analysis in the perspective of business success is often ignored due to its cumbersome and time-consuming nature. Despite several studies focusing on various aspects of ergonomic risk assessments using DSS, there are no studies that focus on developing a DSS that helps decision-makers quickly make decisions in such a way that the DSS includes all aspects of ergonomics. This paper investigated the preliminary reliability and application of an FES to evaluate overall micro ergonomic performance to minimize ergonomic risks and injuries in the industry.

3 Proposed FES for Ergonomic Assessments

This section discusses the method and benefits of integrating a proposed FES with the DMAIC framework on speeding up the ergonomic assessments without frequent input demands from professional analysts. The contents, detailed development and implementation methodology of the FES will also be further discussed.

3.1 Methodology and Application of the FES using the DMAIC Framework

The novel FES developed in this paper uses DMAIC methodology as a problem structuring device. The proposed FES performs functions such as estimating the

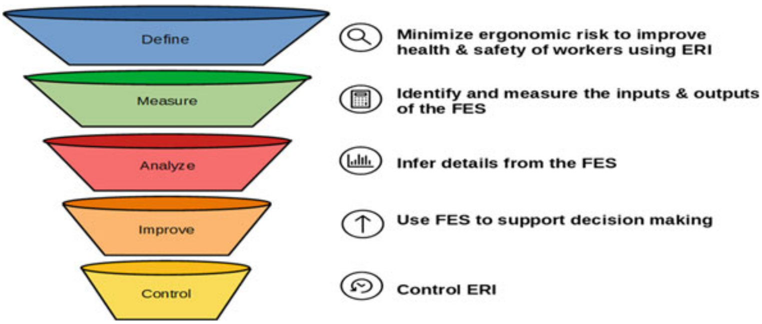

Fig. 1 Development and application of the FES using the DMAIC framework

ergonomic risk present in physical postures of workers, workplace environment, and sensory demands required for the workers to obtain the overall level of ergonomic risk present in the industry. This section discusses the details for the development and application of the FES in terms of DMAIC stages (Fig. 1).

Define—Selection of problem and identifying potential benefits: The selected problem and potential benefits are to minimize ergonomic risks to improve workers' health conditions and improve overall industrial productivity by proactively reducing/eliminating the potential ergonomic risks using the Ergonomic Risk Indicator (ERI) of the FES.

Measure—Measurement or quantification of the problem to determine the current performance of the process: Scientific studies show that risk factors such as awkward posture, force, repetition, static loading, contact stress, illumination, noise, extreme temperature, vibration contribute to ergonomic risks and impede workers and their work nature [8, 15]. The design of cognitive work is also an essential aspect of the human operator at work. Operators must not be overloaded with auditory and visual information [4]. Thus, there is a need to cluster types of ergonomic risks under suitable titles. The Physical Metric helps evaluate the whole-body postural WMSD based on the frequency of occurrence, forceful exertion, type of movement or action and, coupling. Environmental Conditions metric helps evaluate the interaction of workers with their physical environment. Sensory Demands Metric helps assess workers' sensory strains, based purely on physiological sensations that occur due to the design and comfort of the surrounding environment. The ERI, as the output of FES, can be used in the industry as a Key Performance Indicator (KPI) to numerically and linguistically indicate the intensity of overall ergonomic risk present in the industry. The ERI shows an increase or decrease in employee safety, comfort, and performance as per the combination of inputs provided. The FES architecture displayed in Fig. 2 indicates the various systems used as a part of FES. The data required for determining the identified metrics will be explored further in detail in Sect. 3.1 and 3.2. Data for the targeted metrics was collected from the industry using observation-based data collection, interview, measurement and supporting industrial documents such as the Physical Demand Analysis (PDA) form and Standard Operating Procedure (SOP).

Analyze—Identification of factors that influence the problem: The nature of the FES is such that it allows us to infer details from the inputs provided and outputs obtained. The FES can be used either in the absence or presence of an expert due to its rule base and help in the process of analysing and effective decision making for making improvements. The FES can be considered as an efficient substitute for the generally used DMAIC tools such as Cause and Effect diagram, Process Map Analysis and Subprocess Mapping for the selected problem statement.

Improve—Design and implementation of a new process to improve performance by eliminating or mitigating the influential factors that caused the problem: This phase of the DMAIC cycle cannot be directly supported by the developed FES but it helps support the decision-making process that can contribute to implementing changes in the industry by eliminating or mitigating the ergonomic risk factors.

Control—Control of the improved process and future process performance: The ERI can be used for internal ergonomic performance benchmarking. This KPI can be used to help practitioners in the process of continuous improvement through monitoring ERI and controlling the ergonomic risks by utilising the FES at regular frequencies.

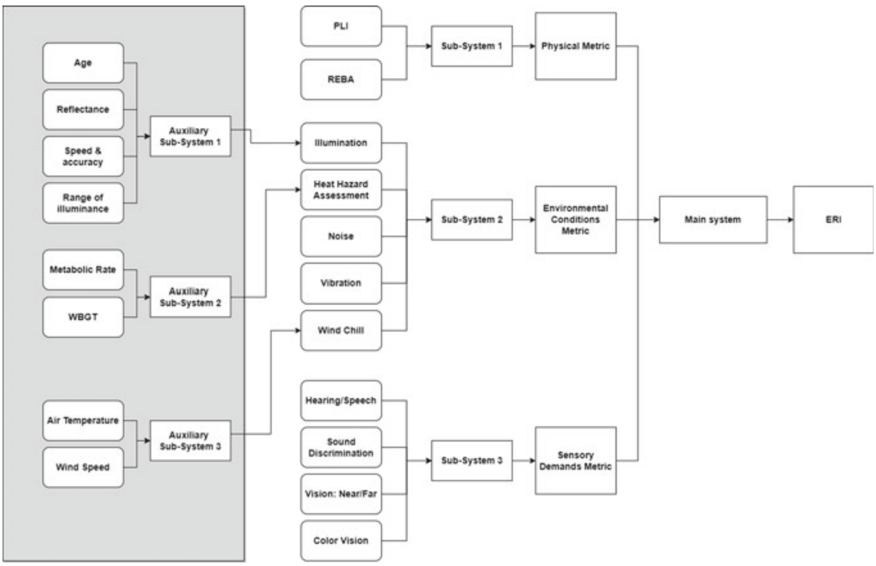

Fig. 2 Architecture of FES

3.2 Development of Sub-Systems and Auxiliary Systems to Support the Main System

The proposed FES was created using the interface provided by the fuzzy logic toolbox that is available in MATLAB. The fuzzy logic toolbox allows the users to customize the linguistic variables and membership functions of the corresponding fuzzy inputs and outputs as per the fuzzy rule base's design. The Mamdani-type inference system is implemented for this purpose in the study. The architecture for the proposed FES is demonstrated in Fig. 2.

The FES was categorized into three separate subsystems 1, 2, 3. In subsystem 1), the input parameters were Physical Load Index (PLI) and Rapid Entire Body Assessment (REBA). The output parameter in this subsystem 1 was physical metric. The reason behind adopting the mentioned input and output parameters was to assess the level of physical, ergonomic risk present in the industry's workstations. The input parameters for this subsystem were adopted from ergonomic assessment tools developed by Hol et al. [13] and McAtamney and Hignett [20]. PLI is a tool for assessing the physical workload based on the frequency of the postures used, which is created by integrating information from a biomechanical model of the lumbar load. REBA assessment can help analyse the musculoskeletal risks in various tasks since it is a sensitive postural analysis system. REBA offers scores for muscle activity caused by static, dynamic, rapidly changing, or unstable postures. The rationale behind using two physical, ergonomic assessment tools was to accurately assess the level of risk present by exploiting the combined advantages of both tools. REBA assessment is primarily based on postural analysis, while PLI assessment is mainly based on the frequency of postures used.

The second subsystem contains the following input parameters: Illumination, heat hazard assessment, noise, hand-arm vibration, and wind chill. This system has the Environmental conditions metric as its output parameter. These parameters were selected as they are the most crucial parameters determining the risk levels present in the workplace environment and most relevant for modular construction industries. The input parameters illumination, noise, and wind chill of this subsystem were based on 'recommended illumination levels for use in interior lighting design', 'permissible noise exposure' and 'equivalent wind chill temperature of cold environments under calm conditions' charts adapted from various sources as suggested by Freivalds et al. [8] The input parameter, heat hazard assessment, was developed based on Heat Stress standards recommended by Occupational Safety and Health Administration [22]. The input parameter, Hand-arm vibration, was based on HSE's recommendation limits [12].

Input parameters such as illumination, heat hazard assessment, and wind chill have their own set of input parameters which are a part of their auxiliary subsystems. The input parameters taken into consideration for building the illumination auxiliary subsystem (auxiliary subsystem 1) were the age of workers, the reflectance of task/surface background, speed and accuracy required, and range of illuminance [8]. The input parameters that were used for building heat hazard assessment auxiliary subsystem (auxiliary subsystem 2) were the metabolic rate of workers and Wet Bulb Globe Temperature (WBGT) [22]. The auxiliary subsystem of wind chill (auxiliary subsystem 3) had input parameters: air temperature and wind speed [8].

In terms of subsystem 3, the input parameters selected were based on the frequency of sensory demands used in workstations such as Hearing/Speech, Sound discrimination, Vision: near/far, and Color vision. The sensory demands were recorded based on the list of frequency categories (1) Never (0%); (2) Rare (1–5%); (3) Occasional (6–33%); (4) Frequent (34–66%); (5) Continuous (67–100%). The input parameters were categorized and recorded subjectively by the observer. The output parameter of this subsystem is called Sensory Demands Metric and was developed based on work of Sensory demands factors proposed by Li et al. [18].

These three subsystems were created using fuzzy logic rules, which were generated using heuristic techniques. This FES can also handle inaccurate or vague data that might be translated for decision-making since fuzzy systems resemble human reasoning, to solve complex problems.

3.3 Development of the Main System

The main system was constructed using physical metric, environmental conditions metric, and sensory demands metric as input parameters. The output parameter obtained in the main system is called an ERI. Nonetheless, it is essential to note that the main system's input parameters were attained from the outputs of subsystems 1, 2 and 3. The FES is responsible for determining the output values based on targeted variables or input parameters, which are based on a set of if–then rules. The mapping of input values to output values acts as a foundation that aids in decision-making. The auxiliary systems, subsystems and main system were created by the selection of fuzzy inputs and outputs, selection of linguistic variables and their corresponding membership functions for the fuzzy inputs and outputs and finally mapping the fuzzy inputs with the fuzzy outputs. The FES was created based on the collective knowledge obtained from physical assessment tools, charts, guidelines and standards. Effective use of ERI includes a detailed understanding of the insights provided in the subsystems as they will assist the industries in identifying the areas in which changes are needed. The membership function of the physical metric was defined using linguistic variables such as Low Risk (LR), Medium Risk (MR), High Risk (HR), and Extremely High Risk (EHR) whereas, the environmental metric and sensory demands metric used linguistic variables such as LR, MR and HR. The membership function of the ERI was defined using linguistic variables such as LR and HR to indicate the overall ergonomic risk present in the industry. The main system was developed by using 36 heuristic rules. For example, if Physical Metric is HR, the Environmental conditions metric is MR, and Sensory Demands Metric is HR, then ERI is HR. Similarly, for different combinations of the input parameters, the plausible ERI was projected in the rule base.

4 System Application and Preliminary Reliability Study

The developed FES system was tested for a modular construction industry to minimize ergonomic risk for the **Define** phase of the DMAIC process. The main system's input parameters (1) Physical metric; (2) Environmental conditions metric, and (3) Sensory demands metric was obtained from the industry data that was collected for all the input parameters to complete the **Measure** phase. The FES generated a value of 0.0326, 0.426, and 0.5 for the physical metric, environmental conditions metric and sensory demands metric. A value of 0.085 was generated for the output parameter ERI. To extract further insights from the FES, the membership functions of the input and output parameters will have to be **Analysed**, and this can be done by exploring the input and output parameters of the subsystems. To properly understand the insights from this study, there is a need to understand the relationship between the main system's input factors. The three input factors of the main system are inter-related to a certain extent and may either positively and negatively affect one another's behaviour and the ERI. For example, an improvement in the environmental conditions can bring forth a positive change on both the physical metric and the sensory demands metric. The proposed FES explores the effect of the different combinations of the three input parameters can have, on the ERI. In this case study, the modular construction industry selected predominantly shows a medium risk in all three input parameters. However, in cases where the input parameters have different degrees of risk, the input parameter that displays the highest degree of risk should be treated and **Improved** first as it will contribute to the majority of the ergonomic risks. The true strength of DMAIC lies in the **Control** phase, where ERI can be used for benchmarking, which helps identify internal opportunities for improvement in the future.

4.1 Relationship Between Ergonomics and Safety Hazards

Due to humans, equipment, materials, environment, and operation, health and safety hazards may occur. Besides, injuries and accident incidences are always not the results of a single occurrence. Multiple variables lead to certain unfortunate incidents. In the sense of occupational safety, when the concepts of ergonomics are applied, the idea of ergonomic safety emerges. Being cautious of the ergonomic and safety hazards in an industry guarantees that the equipment, materials used by a worker, the working environment, and operations performed by the worker are suitable to meet the worker's job requirements and personal capabilities. Thus, there is a need to check the developed FES's feasibility and be compared with an existing benchmarking standard for safety hazards.

4.2 Comparison of OSHA Incident Rate and ERI

An OSHA Incident Rate is a measure of how frequently a reportable accident or illness occurs over a given period, typically one year, in any industry. Incident rates are a very effective indicator tool that serves as a benchmark for assessing the safety program in any industry and can be used to compare relative level of injuries and illnesses between different sectors, companies, or activities within a single company with fairness, no matter the size of the workforce in the industry [21]. To check the feasibility of the developed model, OSHA Incident Rate and ERI results will be displayed in Table 1. The results will also be compared and analysed. The formula to calculate the OSHA incident rate is provided below.

$$\text{OSHA Incident Rate} = \text{N}/\text{EH} \times 200{,}000 \quad (1)$$

where,

N is the No. of Recordable Injuries and/or Illnesses in one year;

EH is the Total no. of hours worked by all employees in one year;

EH = 252 workdays/year × 8-h shift × 130 employers.

Both OSHA incident rate and ERI were lagging indicators and were expected to have a strong correlation between them before the results were obtained for each indicator. This assumption was made due to the overlapping factors such as humans, equipment, materials, environment, and operation that cause safety hazards and ergonomic hazards. OSHA incident rate of the industry is considered to be safe if it lies below the national average. In 2019, the prefabricated wood building manufacturing industry (NAICS-321992) had an average of 13.80 [29]. The industry partner's OSHA incident rate who belongs to the same sector taken for this case study, obtained an incident rate of 6.87, which is much lower than the national average and is thus considered safe. The ERI developed in the FES is measured on a scale of 0–1. The ERI score based on collected data for the input factors was 0.085 and lay predominantly in the Low Risk (LR) region. We can infer that the ergonomic and safety risks are considerably low for the results obtained from both these indicators, as expected.

Table 1 Comparing the results of OSHA incident rate and ERI of the case study

Year	No. of recordable injuries and/or illnesses in one year	Total no. of hours worked by all employees in one year (h)	OSHA incident rate	Prefabricated wood building manufacturing industry average NAICS-321992	ERI
2019	9	262080	6.87	13.80	0.085

4.3 Limitations and Further Steps for Validation

The developed FES needs to be validated further by comparing its effectiveness in various circumstances and this can be accomplished by comparing and analysing ERI performance based on OSHA incident rate results between various organizations within the NAICS-321992 category; or by comparing the results of the same organization for different years or quarters. The FES's effectiveness also needs to be tested for various seasons since modular construction industries in Canada generally tend to have more workload in summer and lesser workload in winter. If in-depth assessments are to be conducted with the same FES model for each workstation, then the FES's efficiency needs to be tested and validated for individual workstations present in the same organization or various organizations within the NAICS-321992 category as well.

5 Discussion and Conclusion

The development of the FES for ergonomic performance assessment of modular construction operations has been described in this study. This study has presented a novel system for evaluating the overall ergonomic risk present in the industry based on a physical, environmental and cognitive basis. This system is meant to aid ergonomic analysts and managers in understanding the overall ergonomic risk present in the industry with the ERI. Moreover, industries can also use this system to obtain their insights from the ergonomic risk factors within the subsystems which further eases the decision-making. It also helps ergonomists and managers focus the majority of the time in executing administrative or engineering controls based on the types of ergonomic hazards that have been identified as this is the only value-added ergonomic time that can directly contribute to increases in productivity through the betterment of the health and safety of workers. Industries can utilise the power of continuous improvement by using the FES and it can also help establish a growth mindset amongst employees. The proposed FES can support significant efficiency gains and improve working conditions simultaneously. Improving workplace ergonomics may contribute to increased productivity if the industry was not already performing at optimal productivity levels. Additionally, claims and injuries can be reduced, and the worker compensation costs can also be reduced by keeping ergonomic risks under control. In a practical sense, this FES can be used to as a tool for conducting quick ergonomic performance audits for the organization. An additional advantage is that, it is much faster than other methods of ergonomic analysis, and it can be used by ergonomists, managers, other experts, and even staff themselves. Deployment of this FES can shorten decision making cycle, reduce cost of decision making, help make unbiased decisions even without technical knowledge in the field of ergonomics.

6 Future Directions

The presented FES can be altered to suit the evaluation of ergonomic assessment for any industry by tweaking the system's contents. The implementation of the proposed FES is required to be validated in detail for the modular construction industry. The proposed system relies on observatory data collection and this can be time-consuming and error-prone, and thus there is a need to improve the method of data collection. The current system does not support real-time data capture of employees' working conditions in the industry for the FES. Nevertheless, it is possible to collect real-time motion capture data and real-time environmental data using sensors. If data can be collected and integrated in real-time, further improvements can be made to the proposed FES. Real-time data analysis can play a significant role in decision making, especially for eliminating non-value-added time. Furthermore, the DMAIC cycle's improvement phase can utilise Virtual Reality and Augmented Reality technologies to quickly estimate if the suggested ergonomic interventions improve the worker's environment, comfort, and safety without having to deal with implementation costs.

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