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Evaluation of Ergonomic Safety Performance in Apparel Manufacturing Systems: An Integrated Decision Model Based on Fuzzy AHP-TOPSIS

Murat KODALOĞLU[1], Selçuk ASLAN[2*], Feyza AKARSLAN KODALOĞLU[3]

[1]Isparta University of Applied Sciences, Vocational School of Technical Sciences, Isparta, Turkey
[2] Kafkas University, Vocational School of Fine Arts, Kars, Turkey
[3] Süleyman Demirel University, Faculty of Engineering and Natural Sciences, Isparta, Turkey

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Abstract: Despite the high prevalence of musculoskeletal disorders in the apparel industry, no integrated fuzzy decision-support framework has been developed to simultaneously evaluate the interacting effects of postural, workstation, repetitive motion, and environmental factors on ergonomic safety performance. This study aims to identify and evaluate the ergonomic safety performance factors that directly affect worker health in labor-intensive garment manufacturing processes and to analyze the importance levels of these factors. Within the scope of the research, work posture, workstation design, repetitive motion levels, and work environment parameters were examined using the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and Fuzzy TOPSIS methods to manage uncertainties in the decision-making process. The Fuzzy AHP results indicate that, the most decisive criterion affecting ergonomic safety performance was identified as work posture, with a weight of 40%. This primary factor is followed, in order, by workstation design (30%), repetitive movements (20%), and the work environment (10%). On a performance scale ranging from 3.5 to 8.5 points, the highest safety value (8.5) can only be achieved under optimized conditions where ideal posture and minimal repetitive movements are combined. The analyses further revealed that is that when workstation design quality falls below 5 points, overall performance cannot exceed the 7-point threshold no matter how much the work posture is improved. In conclusion, the research indicates that, in the apparel industry, the priority for improvements to establish safe working conditions should be given to improvements in physical ergonomics (posture and design). The developed integrated fuzzy model enables the assessment of risks and working conditions in production systems..

Konfeksiyon Üretim Sistemlerinde Ergonomik Güvenlik Performansının Değerlendirilmesi: Bulanık AHP-TOPSİS Tabanlı Entegre Karar modeli

Anahtar Kelimeler:
Ergonomi,
Konfeksiyon Üretimi,
Bulanık AHP,
Bulanık TOPSIS,
Çok Kriterli Karar Verme (MCDM),
Güvenlik Performansı

Özet: Bu çalışma, yoğun emek gerektiren konfeksiyon üretim süreçlerinde çalışan sağlığını doğrudan etkileyen ergonomik güvenlik performansı faktörlerini belirlemeyi ve bu faktörlerin önem düzeylerini analiz etmeyi amaçlamaktadır. Araştırma kapsamında; çalışma duruşu, iş istasyonu tasarımı, tekrarlı hareket seviyesi ve çalışma ortamı parametreleri, karar verme sürecindeki belirsizlikleri yönetmek amacıyla Bulanık Analitik Hiyerarşi Prosesi (Bulanık AHP) ve Bulanık TOPSIS yöntemleri kullanılarak incelenmiştir. Bulanık AHP sonuçlarına göre, ergonomik güvenlik performansı üzerinde en belirleyici kriter %40 ağırlıkla çalışma duruşu olarak saptanmıştır. Bu temel faktörü sırasıyla iş istasyonu tasarımı (%30), tekrarlı hareketler (%20) ve çalışma ortamı (%10) takip etmektedir. 3.5 ile 8.5 puan arasında değişen performans skalasında, en yüksek güvenlik değerine (8.5) ancak ideal duruş ve minimum tekrarlı hareketin birleştiği optimize edilmiş koşullarda ulaşılabilmektedir. Analizlerin ortaya koyduğu en kritik etkileşim bulgusu ise, iş istasyonu tasarım kalitesi 5 puanın altına düştüğünde, çalışma duruşu ne kadar iyileştirilirse iyileştirilsin genel performansın 7 puan barajını aşamadığıdır. Sonuç olarak araştırma, konfeksiyon sektöründe güvenli çalışma koşullarının tesisi için iyileştirme önceliğinin fiziksel ergonomiye (postür ve tasarım) verilmesi gerektiğini bilimsel verilerle kanıtlamaktadır. Geliştirilen entegre bulanık model, üretim sistemlerinde risklerin değerlendirilmesi ve çalışma ortamlarının iyileştirilmesinde yöneticiler için etkili bir karar destek mekanizması sunmaktadır.

**İlgiliyazar: selcukaslan@kafkas.edu.tr*
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1. INTRODUCTION

The apparel industry is a sector where, due to its production dynamics, high-frequency repetitive movements, static muscle loads, and anthropometric mismatches are frequently observed. In this production setting, operators maintain specific postural positions for extended shifts while performing precise operations such as sewing and assembly. This biomechanical stress creates conditions conducive to the development of musculoskeletal disorders (MSDs) among workers and directly threatens industrial safety performance. In the literature, Kaergaard, A., & Andersen (Kaergaard & Andersen, 2000) and Wang et al. (Wang et al., 2007) emphasize that improper work postures and highly repetitive sewing operations contribute to chronic pain, particularly in the neck, shoulder, and lumbar regions, and that may eventually lead to occupational disorders in the long term.

Punnett, L., & Wegman (Punnett & Wegman, 2004) reported that ergonomic risks affect not only worker health but also operational efficiency and the frequency of workplace accidents. Ergonomic deficiencies often stem from workstations that are incompatible with workers' anthropometric measurements; field studies conducted by Dianat et al. (Dianat et al., 2015) reported that the inability to achieve neutral ergonomic alignment is a key risk factor. Hossain et al. (Hossain et al., 2018), on the other hand, argued that garment workers in developing countries are exposed to higher ergonomic risks due to piecework production pressures.

While traditional ergonomic assessment methods (RULA, REBA, etc.) tend to rely on precise numerical data, human perception and expert judgment inherently involve a degree of uncertainty and ambiguity. The theory of Fuzzy Logic, defined by Lotfi A. Zadeh (Zadeh, 1965) in 1965, translates this type of uncertainty into a mathematical framework through membership functions. Kahraman et al. (Kahraman et al., 2015) have stated that fuzzy multi-criteria decision-making (MCDM) approaches enhance decision consistency in complex industrial systems. Similarly, Bafail and Alamoudi (Karuppiah et al., 2022) and Karuppiah et al. (Bafail & Alamoudi, 2025) have demonstrated the effectiveness of fuzzy methods by emphasizing the central role of the human factor in assessing the occupational safety climate. On the other hand, Dul and Neumann (Dul & Neumann, 2009) reported that environmental factors such as lighting, noise, and thermal comfort support overall safety performance as complementary elements to physical risks. In this study, an interactive model of parameters specific to the apparel industry was developed to address this gap in the literature. Ali et al. (Ali et al., 2026) found that analyzing anthropometric measurements for functional sewing workstation design in the ready-made garment industry reveals the critical importance of matching worker body dimensions with workstation layouts, as mismatches create significant ergonomic risks and discomfort. Hasan et al. (Hasan et al., 2026) showed that using REBA and the Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) among ready-made garment workers identifies a high prevalence of work-related musculoskeletal disorders, confirming that repetitive motions and poor postures are primary risk factors in apparel manufacturing. Joomjee et al. (Joomjee et al., 2026) indicated that integrating ergonomic risk assessment with the hierarchy of controls among informal sewing workers effectively prioritizes physical ergonomic interventions, emphasizing that engineering controls for posture and workstation design should precede administrative measures. Kolge et al. (Kolge et al., 2026) revealed that ergonomic design and analysis of workstations in manufacturing industries simultaneously enhances both worker safety and productivity, supporting the argument that workstation design is a strategic determinant of overall system performance. Luna, Hess, and Gravina (Luna et al., 2026) have demonstrated that artificial-intelligence-enhanced video feedback can effectively improve manufacturing workers' ergonomic postural behavior, suggesting that real-time digital interventions offer innovative solutions for optimizing work posture in production settings. Gündüz et al. (Gündüz & Gündüz, 2019) have demonstrated that supplier selection in the textile industry is a complex multi-criteria decision-making problem requiring evaluation of factors such as quality, delivery time, cost, technology, flexibility, and corporate reputation. Considering the inherent fuzziness in group decision-making processes, they employed fuzzy set theory and fuzzy TOPSIS to address the supplier selection problem of a textile manufacturing firm in Denizli, using linguistic variables to express criteria ratings and weights, and calculating a closeness coefficient to obtain supplier performance rankings.

2. MATERIALS AND METHODS

In this study, a three-stage analysis process was followed to place the complex and often subjective ergonomic risks in garment manufacturing within a scientific and measurable framework. The primary objective of this study was to develop a model that focuses not only on numerical data but also on the uncertainties inherent in human judgments.

2.1. Fuzzy Logic Approach

In systems where human labor is central, such as garment manufacturing, the assessment of ergonomic risks typically involves linguistic expressions and subjective judgments—such as "somewhat tiring," "moderately risky," or "quite unsuitable"—rather than precise numerical data. Since classical mathematical approaches handle such ambiguous situations only with sharp, binary boundaries—such as "true" or "false"—they may fall short in reflecting the flexibility and uncertainty inherent in human perception. To overcome these limitations and model the reality of the production floor more accurately, this study adopts the Fuzzy Logic approach, the foundations of which were laid by Lotfi A. Zadeh in 1965.

Fuzzy logic converts experts' linguistic expressions into mathematically processable data by offering an evaluation mechanism based on degrees of membership rather than a strict black-and-white distinction. In fields where human factors play a significant role, such as ergonomics and occupational safety, this approach incorporates the uncertainty inherent in subjective evaluations into the process as a natural part of the system, rather than dismissing it as an "error." Indeed, as emphasized in the literature, methods such as Fuzzy AHP and Fuzzy TOPSIS are highly effective and reliable tools for prioritizing risks in complex production systems and for establishing a scientific foundation for the ambiguity inherent in human judgments. As a result, this study has been able to analyze the physical strain experienced by operators not only through numbers but also through the flexibility of real-world work experience.

2.2. Definition of Fuzzy Variables and Mathematical Membership Functions

This phase of the study addresses how qualitative data representing the physical and environmental conditions in the garment manufacturing sector are converted into a numerical model. The four fundamental parameters that form the input basis of our analysis model have been identified as work posture, workstation design, level of repetitive motion, and work environment conditions. In the initial phase, experts evaluated each criterion on a numerical scale ranging from 1 to 10; these scores were then mapped to three basic linguistic levels (Low, Medium, High) that the system could interpret.

To mathematically express the flexibility and ambiguity inherent in human judgments, Triangular Fuzzy Numbers (TFN)—whose reliability has been proven in the literature—were used. A triangular fuzzy number A consists of three components: a lower bound (l), a most likely value (m), and an upper bound (u), and is denoted as A = (l, m, u). The membership function μA(x) of a variable with this structure determines the degree to which each value belongs to the relevant fuzzy set using the following formula:

$$\mu_A(x) = \begin{cases} 0, & x < l \\ \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & x > u \end{cases}$$

Thanks to this mathematical structure, for example, the "average" score assigned to an operator's performance is incorporated into the system not merely as a single number, but as a probability distribution that also accounts for the margin of uncertainty surrounding that score.

The system's output—ergonomic safety performance—is converted into a value within a range of 3.5 to 8.5 points based on the analysis results. The Centroid method was used to reduce the complex results obtained from the fuzzy system to a meaningful and single numerical value for managers. The mathematical expression for this clarification process is as follows:

$$x^* = \frac{\int \mu_A(x) \cdot x \, dx}{\int \mu_A(x) \, dx}$$

Here, x∗ provides us with the final performance score by determining the geometric center of the fuzzy set. This methodological framework not only processes the data but also minimizes the risk of subjective evaluation in human-centered industries such as apparel manufacturing, ensuring that the analysis results show a high correlation with actual production conditions.

2.3. Determination of Criterion Weights Using Fuzzy AHP

Within the scope of this study, the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) method was adopted to determine the relative importance levels (weights—wi) of the key parameters that directly affect ergonomic safety performance in garment manufacturing systems. To manage the inherent subjectivity of ergonomic risks and human factors, pairwise comparison matrices based on expert opinions were created and analyzed within the framework of fuzzy logic principles. This methodological approach converted the uncertainty in experts' verbal expressions and the ambiguity in the decision-making process into rational numerical data, enabling much more consistent and precise weightings compared to traditional methods.

Expert evaluation process: in this stage, a panel of 10 experts specializing in ergonomic risk assessment and garment production processes was formed. The expert panel consisted of 4 occupational safety specialists (with at least 10 years of experience in occupational health and safety), 3 industrial engineers (working in the field of production management and ergonomics), and 3 senior operators with at least 15 years of experience in garment production lines. The criteria for selecting experts included familiarity with actual working conditions in the garment industry, theoretical knowledge of ergonomic risk factors, and experience in decision-making processes. Data collection and scaling; experts were asked to evaluate pairwise comparisons between four main criteria (work posture, workstation design, repetitive motion level, and work environment) using the classical saaty scale (1-9) converted to fuzzy triangular numbers (TFN). Pairwise comparison matrices were created through standard forms completed by each expert via one-on-one interviews. The individual evaluations obtained were combined using the geometric mean method to create the final fuzzy comparison matrix in order to minimize differences in expert opinions and to achieve a common consensus. Criterion weights were determined as a result of calculations made from this matrix.

During the analysis process, relationships between criteria were converted into triangular fuzzy numbers based on the Saaty, and calculations were performed using general comparison matrices. As a result of the findings, the weight values of the criteria were determined as follows:

• Work Posture: 0.40 (40%)

• Workstation Design: 0.30 (30%)

• Level of Repetitive Movements: 0.20 (20%)

• Work Environment Conditions: 0.10 (10%)

These results suggest that work posture is the most dominant and critical factor in shaping ergonomic safety performance on garment production lines. It is evident that physical ergonomic factors—along with workstation design, which follows work posture—play a far more decisive role in system safety compared to environmental factors.

2.4. Ranking of Alternatives Using Fuzzy TOPSIS

Based on the criterion weights obtained in the Fuzzy AHP phase, the Fuzzy TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method was adopted to rank the performance of different production scenarios (alternatives). This approach simultaneously calculates each alternative's proximity to the "positive ideal solution" (A+—the highest performance level) and its distance from the "negative ideal solution" (A−—the lowest performance level).

The primary objective of the methodology is to rationally identify the scenario that ensures the highest level of ergonomic safety performance, based on the principle of maximizing proximity to ideal conditions and minimizing proximity to undesirable conditions. In this way, it is possible to rank, on a scientific basis, which working conditions yield the most optimized results in terms of occupational safety within complex production processes.

Positive ideal solution

$$A^{+} = (v_1^{+}, v_2^{+}, \ldots, v_n^{+})$$

Negative ideal solution

$$A^{-} = (v_1^{-}, v_2^{-}, \ldots, v_n^{-})$$

The distance to the ideal solutions for each alternative has been calculated.

$$D_i^{+} = \sqrt{\sum (v_{ij} - v_j^{+})^2}$$
$$D_i^{-} = \sqrt{\sum (v_{ij} - v_j^{-})^2}$$

The proximity coefficient is calculated using the following formula.

$$CC_i = \frac{D_i^{-}}{D_i^{+} + D_i^{-}}$$

The highest cc value represents the production scenario with the highest ergonomic safety performance.

2.5. Creation of the Fuzzy Rule Base

A comprehensive rule base has been established to structure the decision-making mechanism of the fuzzy logic system and to identify the complex interactions among ergonomic risk factors. At this stage, 20 fuzzy rules were defined to reflect the effects of different combinations of input variables (work posture, workstation design, repetitive movements, and work environment) on overall safety performance.

These rules, which form the logical framework of the system, are structured as "If-Then" propositions; some example scenarios are provided below:

• Rule 1: If the work posture is "high" (3) and the workstation design is "high" (3), then safety performance is determined to be "high" (3).

• Rule 2: If the work posture is "low" (1) and the level of repetitive motion is "high" (3), safety performance is assessed as "low" (1).

• Rule 3: If the workstation design is "medium" (2) and the work environment conditions are "high" (3), the safety performance is at the "medium" (2) level.

By modeling the synergistic interactions among parameters rather than their individual effects, this set of rules enables the system to generate a dynamic and realistic safety performance score. This makes it possible to conduct a comprehensive and consistent assessment for each operational scenario.

2.6. Defuzzification and Evaluation Scales

In the final stage of the fuzzy logic system, the Centroid method is employed to convert the fuzzy result sets obtained as a result of the rule-based inference process into concrete and interpretable numerical data. This methodology calculates the geometric center of the area enclosed by the fuzzy set to produce the most reasonable crisp value representing the system's final decision.

To ensure the accuracy and consistency of the analyses, a two-stage scaling mechanism was used in this study:

• Input Parameter Scale: All ergonomic risk factors included in the model (work posture, workstation design, etc.) were evaluated on a broad numerical scale ranging from 1 (very poor/unsuitable) to 10 (excellent/very suitable),

• Output and Performance Scale: The ergonomic safety performance scores obtained as a result of the refinement process were scaled on a range from 3.5 (low safety) to 8.5 (high safety),

This numerical output range clearly illustrates the current state of ergonomic conditions in the production system, while also enabling an objective comparison across different work scenarios and the identification of critical areas for improvement.

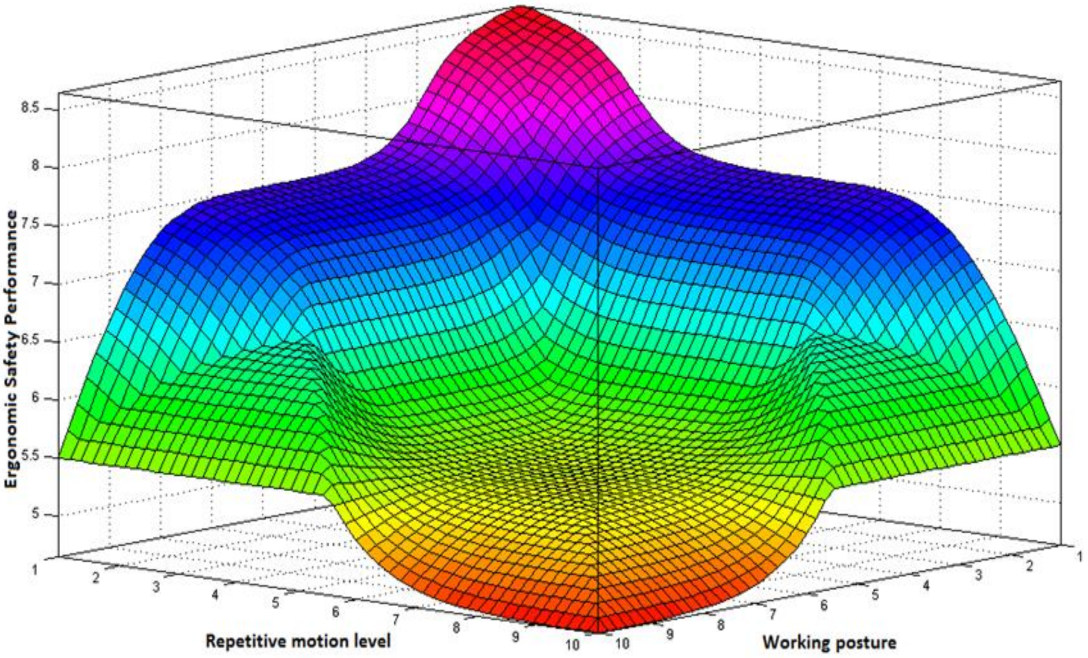

Figure 1. Surface plot showing the interaction between work posture and the level of repetitive movement.

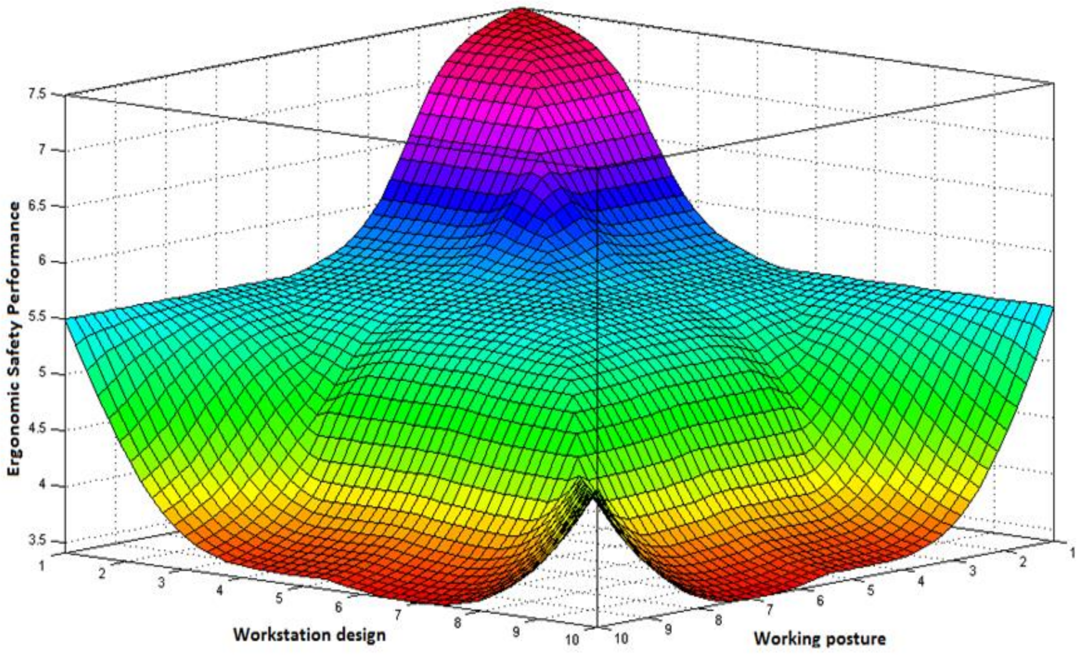

Figure 2. The Effect of Workstation Design and Work Posture on Ergonomic Safety Performance.

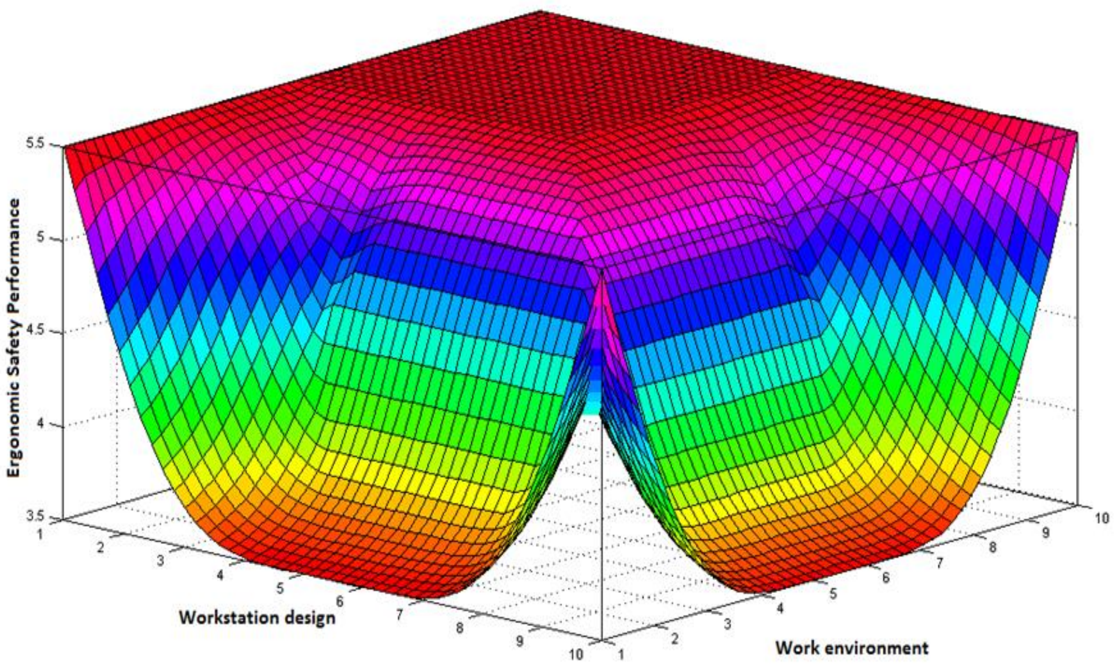

Figure 3. The Effect of the Work Environment and Workstation Design on Ergonomic Safety Performance.

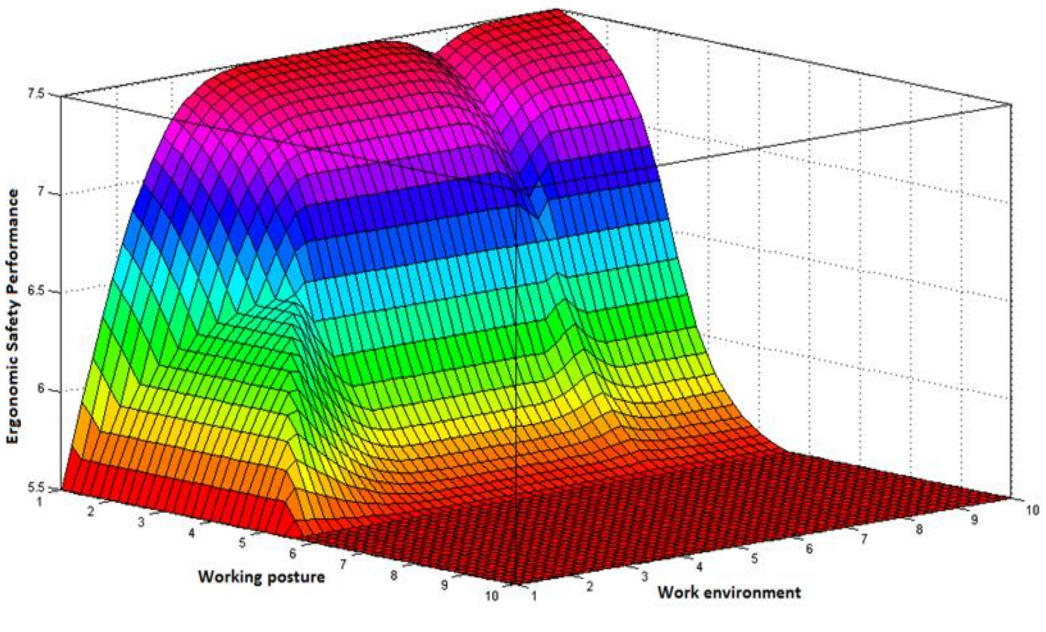

Figure 4. The Effect of the Interaction Between the Work Environment and Work Posture on Ergonomic Safety Performance.

3. RESULTS AND DISCUSSION

Four three-dimensional (3D) surface plots were created to visualize the data obtained in this study and to quantitatively illustrate the complex interactions among various ergonomic criteria. These plots reflect the effects of changes in the input variables on overall ergonomic safety performance from a holistic perspective. The color scale used in the visualizations presents a spectrum ranging from low performance values to high performance values; in this context, shades of blue symbolize low safety performance (3.5), while shades of red symbolize the system's highest achievable safety

(a) (b)

performance (8.5). These surface models enable the analysis, on both an intuitive and scientific basis, of which parameter combinations pose critical risks and which conditions provide an ideal working environment.

3.1. The Interaction Between Work Posture and the Level of Repetitive Motion

In the first analysis scenario of the study, the implications of the synergistic interaction between work posture and the level of repetitive motion on ergonomic safety performance were examined. The three-dimensional surface plot presented in Figure 1 reveals that the system's overall performance output exhibits a dynamic distribution ranging from 4.5 to 8.5 points.

• Evaluation of Numerical Findings: According to the analysis results, the system's maximum safety performance (8.5) was achieved under optimized work posture, where repetitive motion intensity was at its lowest level (10 points) and the work posture was in its most ideal form (10 points). This indicates that the positive development of both parameters has maximized system safety.

• Fuzzy AHP-Based Analysis: Upon examining the geometric slope of the surface graph, it is observed that the rate of performance increase along the work posture axis is significantly steeper compared to that along the "Repetitive Motion Level" axis. This observation is directly consistent with the Fuzzy AHP analysis, which indicates that work posture has a high weight value of approximately 0.40 (wi). This finding suggests that work posture plays a much more dominant and decisive role in overall safety performance compared to movement frequency.

• Fuzzy TOPSIS Approach and Critical Thresholds: From the perspective of fuzzy TOPSIS analysis, it was found that scenarios in which work posture remained below critical levels (1–3 points) clustered in the "Negative Ideal Solution" (A−) region, regardless of improvements in the level of repetitive movements. This result indicates that poor posture creates a "bottleneck" for ergonomic performance and that improvements made to other factors without correcting posture will be insufficient to move the system out of the low safety class.

3.2. The Synergistic Effect Between Workstation Design and Work Posture

Workstation design is a fundamental building block that enables employees to maintain natural body mechanics and posture throughout operational processes. The three-dimensional surface plot presented in Figure 2 illustrates the strong correlation between these two critical parameters and their combined effect on overall ergonomic safety performance.

• Evaluation of Quantitative Findings: It was determined that the safety performance data obtained as a result of the analysis fell within a range of 5.0 to 8.5 points. One of the most striking findings of the study was observed in scenarios where the quality of workstation design fell below the critical threshold of 5 points; in such cases, it was determined that even if the work posture was optimized to the ideal level, the overall safety performance could not exceed the 7.0-point threshold. This data demonstrates that physical hardware inadequacy creates a "ceiling effect" on system performance.

• Interpretation from the Fuzzy AHP and TOPSIS Perspectives: The high level of interdependence between these two criteria laid the groundwork for the Fuzzy AHP weights to be calculated as very close to each other (approximately 0.50/0.50) specifically for this interaction. However, the Fuzzy TOPSIS ranking, which offers a more in-depth methodological analysis, defines an ergonomic workstation design as an "indispensable prerequisite" for a sustainable and healthy working posture.

• Constraining Factor Analysis: A poorly designed workstation or one that does not conform to the worker's anthropometry makes it physically impossible to maintain a technically correct posture. Therefore, workstation design is not merely a comfort factor but a strategic determinant that directly limits or enhances system performance in minimizing risks arising from work posture.

3.3. Interaction Between the Work Environment and Workstation Design

In the third analysis scenario of the study, the interaction between environmental factors—such as lighting, noise, and temperature—and workstation design, as well as the implications of this interaction on overall ergonomic safety performance, were examined. The surface plot presented in Figure 3 illustrates the hierarchical relationship between the physical infrastructure and environmental conditions using numerical data.

• Analysis of Numerical Findings: Among all simulations conducted, the lowest performance value of 3.5 achieved by the system was observed at the coordinates where the workstation design was most inadequate. This data demonstrates that deficiencies in workstation design constitute the most fundamental risk factor for system safety, independent of environmental conditions.

• Critical Evaluation from a Fuzzy TOPSIS Perspective: One of the most striking findings obtained as a result of the fuzzy TOPSIS analysis is the dominance relationship among the parameters. The graphical data concretely demonstrates that even if the work environment conditions are at the "excellent" (10 points) level, the overall safety performance cannot exceed the 5.0-point threshold if the workstation design remains "very inadequate" (1 point).

• Criterion Dominance and System Performance: These results indicate that the workstation design criterion is a far more decisive and dominant performance parameter compared to the work environment. The analyses reveal that an ideal work environment provides a meaningful performance increase only when supported by an ergonomic workstation design; otherwise, environmental improvements have limited effectiveness in enhancing the system's overall safety.

3.4. Interaction Between the Work Environment and Work Posture

The study's final analysis scenario examines the direct effects of environmental factors—such as lighting, noise, and temperature—on the worker's posture, as well as the implications of this interaction for overall safety performance. The data presented in Figure 4 illustrate the hierarchical relationship between physical ergonomics and environmental conditions from a numerical perspective.

• Analysis of Numerical Findings: As a result of the evaluations conducted, it was determined that the safety performance resulting from the interaction of these two parameters ranged between 5.0 and 8.0 points.

• Interpretation from the Fuzzy AHP and TOPSIS Perspectives: It was determined that environmental improvements, such as enhancing lighting quality and minimizing noise levels, can elevate ergonomic safety performance to a certain level (8.0 points). However, the fact that this maximum performance value is lower than the peak value of 8.5 points obtained from the interaction between work posture and repetitive movements (Figure 1) is quite significant in terms of the literature and model results.

• Criterion Characterization and Strategic Importance: This finding demonstrates that the "Work Environment" criterion has a "complementary" and "supportive" nature that aids the process, rather than being a primary factor that directly determines system performance. The analyses suggest that the most significant improvements in safety performance are achieved through the optimization of physical ergonomic factors, such as work posture, while environmental factors act as a lever to enhance this process.

3.5. Comparative Performance Evaluation and Criterion Weight Analysis

Analyses conducted by integrating the Fuzzy AHP and Fuzzy TOPSIS methods have clarified the hierarchical structure and relative importance levels of the key components shaping ergonomic safety performance in apparel production systems. The weight values (wi) obtained demonstrate, on a scientific basis, which parameters are more decisive in the system's overall performance outcomes.

The importance ranking of the criteria and their qualitative contributions to the system are evaluated as follows:

• Work Posture (40%): The analysis results confirm that work posture is the most dominant and decisive criterion affecting overall ergonomic safety performance. With a weight of 40%, this parameter—which holds the highest priority—constitutes the primary risk focus in terms of musculoskeletal disorders and also holds the greatest potential for improvement across the entire system.

• Workstation Design (30%): Identified as the second most critical factor, workstation design is an infrastructure component that directly limits the employee's physical capabilities and operational freedom of movement. This criterion is characterized as a fundamental "indispensable prerequisite" for sustaining a healthy and ergonomic work posture.

• Repetitive Motion Level (20%): This variable, which is directly correlated with workload intensity and fatigue management processes, plays a strategic role in the proactive prevention of chronic musculoskeletal disorders. Optimizing operational cycle times and motion frequency is viewed as a key balancing factor that raises the system's safety threshold.

• Work Environment (10%): As the criterion with the relatively lowest weight, this factor serves as a "complementary" element that supports system performance rather than being the primary determinant of ergonomic safety. It is assessed that environmental improvements—such as lighting, temperature, and noise—indirectly but positively contribute to the safety climate through worker comfort and overall job satisfaction.

Consequently, this weighting model provides a rational roadmap for prioritizing improvement activities in the production area; it indicates that physical ergonomics factors (posture and design) have a far more strategic impact on system safety than environmental conditions.

4. CONCLUSION

In this study, the factors affecting ergonomic safety performance in apparel production systems were analyzed using a model that integrates the Fuzzy AHP and Fuzzy TOPSIS methods, which have a high capacity for managing uncertainties. The research revealed the effects of work posture, workstation design, repetitive motion intensity, and work environment conditions on system performance, both independently and in terms of their interactions with one another. The findings demonstrate that ergonomic safety performance varies within a range of 3.5 to 8.5 points. According to the analysis results:

• Critical Determinants: Fuzzy AHP results indicate that work posture (40%) and workstation design (30%) are the most dominant criteria affecting overall performance. This confirms that physical ergonomics components play a much more strategic role in ensuring system safety compared to environmental factors.

• Performance Thresholds and Interactions: Three-dimensional surface analyses revealed that poor posture and inadequate workstation design create a "bottleneck" in the system. In particular, it was found that in scenarios where workstation design quality fell below 5 points, safety could not exceed the critical threshold of 7.0 points even if all other parameters were improved,

• The Role of Environmental Factors: It has been determined that workplace environment parameters such as lighting and noise (10% weight) play a complementary and supportive role in improving performance; however, they alone are insufficient to ensure a high level of safety unless physical risks are optimized.

The research findings indicate that, to minimize ergonomic risks in the apparel industry, the focus should primarily be on interventions that improve worker posture and anthropometric workstation designs. The developed integrated model based on Fuzzy AHP–TOPSIS provides a scientific decision-support mechanism for businesses. Future studies should adapt the model to different production disciplines and expand it to include new parameters such as cognitive ergonomics.

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