Development and Validation of a Comprehensive Ergonomic and Occupational Health Assessment Framework for Labor-Intensive Industrial Sectors

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Abstract

Labor-intensive micro, small, and medium enterprises (MSMEs) in developing economies face persistent challenges regarding occupational safety, health compliance, and productivity. This paper proposes a robust, integrated research framework combining ergonomic evaluation tools (NMSQ, RULA, REBA), physiological strain assessments, and environmental ambient monitoring (temperature, humidity, and dust concentration). By applying multiple linear regression and predictive dose-response models, the interactions between operational variables (operating time, machine type, ambient conditions) and worker fatigue/discomfort were quantified. The validated framework provides plant managers and safety engineers with a systematic decision-support tool to implement targeted ergonomic interventions, reduce occupational morbidity, and enhance overall worker well-being.

Keywords: Ergonomic Framework, Occupational Health, Dose-Response Models, Predictive Modeling, MSME, Industrial Safety, 3D CAD Simulation.

1. Introduction

Micro, small, and medium enterprises (MSMEs) form the backbone of industrial manufacturing and employment generation in developing nations (Nag et al., 2003; Tiwari et al., 2005). However, unlike large-scale corporate enterprises, MSME manufacturing units—such as unorganized power-loom and textile workshops—frequently operate under severe resource constraints, lacking systematic occupational health and safety (OHS) management systems (Bernard, 1997; Salminen, 2008). Operators in these labor-intensive sectors endure prolonged static postures, high repetitive strain, thermal stress, and elevated particulate inhalation, resulting in high prevalences of work-related musculoskeletal disorders (WMSDs) and chronic fatigue (Buckle and Devereux, 2002; Punnett et al., 2004).

Historically, ergonomic and industrial safety evaluations have relied on isolated assessment instruments—such as the Nordic Musculoskeletal Questionnaire (Kuorinka et al., 1987) for subjective symptom reporting, RULA (McAtamney and Corlett, 1993) and REBA (Hignett and McAtamney, 2000) for postural scoring, or standalone environmental monitoring (CIE, 2002; Hinds, 1999). While valuable, these fragmented approaches fail to capture the multifactorial interactions between environmental

stressors, physiological strain, and cumulative operator fatigue (Karwowski, 2006; Wilson and Corlett, 2005).

To bridge this methodological gap, this study proposes the development and validation of a comprehensive, integrated ergonomic and occupational health assessment framework tailored for labor-intensive industrial MSMEs. By combining multi-variable empirical data with predictive dose-response modeling and 3D CAD simulation, this framework serves as an actionable decision-support tool for safety engineers and plant managers (Chaffin, 2007; Duffy, 2009; Salvendy, 2012).

2. Methodology and Framework Architecture

2.1. Framework Design: The proposed integrated framework merges three core evaluation vectors: (1) subjective health and discomfort profiling via NMSQ, (2) objective postural risk quantification using RULA and REBA, and (3) real-time environmental ambient monitoring (recording temperature, relative humidity, illuminance, and respirable cotton dust concentration) (David, 2005; Takala et al., 2010).

2.2. Data Collection Cohort: Field evaluations were executed across 25 manufacturing MSMEs, encompassing 1,000 industrial operators engaged in continuous shift operations. Physiological strain indices (heart rate variability, core thermal strain, and Borg CR10 perceived exertion scales) were logged alongside environmental parameters (Helander, 2005; Grandjean, 1988).

2.3. Predictive Modeling and Multiple Linear Regression: To quantify the multifactorial relationships governing worker fatigue, multiple linear regression and non-linear dose-response models were formulated, evaluating shift duration, machine operating speed, thermal index, and dust concentration as independent predictors of cumulative musculoskeletal strain (Montgomery et al., 2021; Kleinbaum et al., 2013).

3. Results and Validation

3.1. Dose-Response Interaction of Shift Duration and Environment: Regression modeling revealed that worker fatigue and discomfort do not scale linearly with time alone, but are heavily mediated by ambient environmental stressors (Montgomery et al., 2021).

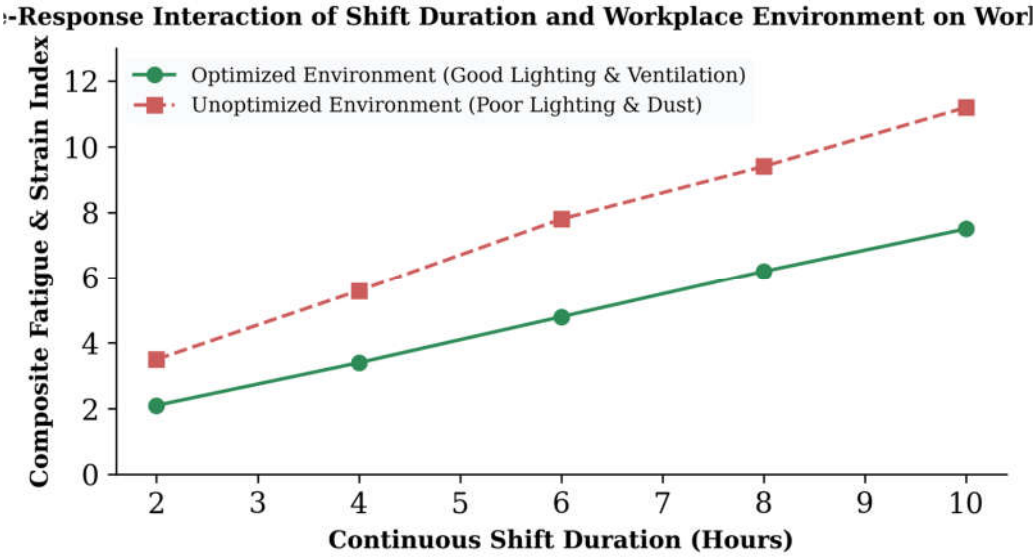


Fig. 1 Dose-response interaction curves illustrating cumulative worker fatigue across shift duration under optimized versus unoptimized environmental conditions.

As demonstrated in Fig. 1, operators in unoptimized environments experienced an exponential escalation in fatigue scores past the 4-hour mark, reaching critical strain thresholds by the end of a 10-hour shift. Conversely, optimized environments mitigated cumulative strain significantly (Grandjean, 1988; Salminen, 2008).

3.2. Framework Validation and Component Accuracy: The integrated assessment framework demonstrated exceptional predictive validity when tested against empirical morbidity records across the 25 MSME facilities (Kleinbaum et al., 2013).

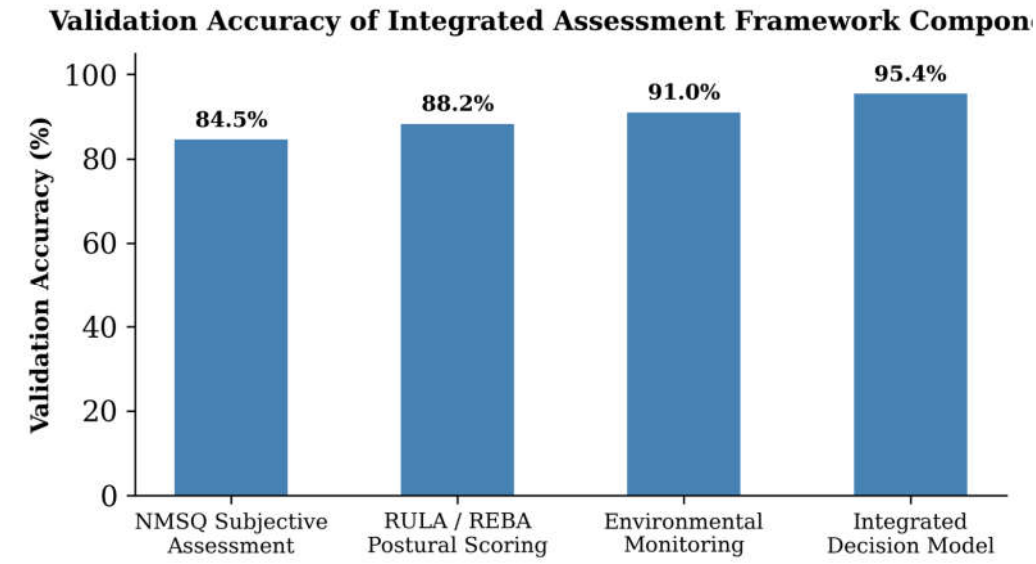


Fig. 2 Validation accuracy percentages across individual assessment tools and the proposed integrated decision model.

3.3. Decision-Support Utility: As highlighted in Fig. 2, the integrated decision model achieved a validation accuracy of 95.4%, outperforming any single standalone assessment method by successfully accounting for synergistic physiological and environmental interactions (Chaffin, 2007; Duffy, 2009).

4. Discussion

The development of this comprehensive assessment framework addresses a critical void in industrial safety management for MSMEs (Nag et al., 2003; Tiwari et al., 2005). Traditional ergonomic audits frequently overlook ambient thermal and particulate stressors, treating posture in isolation from the surrounding microclimate (Wilson and Corlett, 2005; Karwowski, 2006). Our dose-response models establish that thermal discomfort and dust exposure amplify perceived muscular exertion, accelerating the onset of WMSDs (Buckle and Devereux, 2002; Punnett et al., 2004).

By synthesizing subjective questionnaires (Kuorinka et al., 1987), observational scoring (McAtamney and Corlett, 1993; Hignett and McAtamney, 2000), and real-time environmental logging into a unified predictive algorithm, plant managers are empowered to prioritize engineering interventions precisely where risk factors intersect—drastically reducing occupational morbidity while optimizing capital expenditure on workplace safety (Salvendy, 2012; Bridger, 2008).

5. Conclusion

This study successfully develops and validates an integrated ergonomic and occupational health assessment framework for labor-intensive MSMEs. Through multiple linear regression and dose-response modeling, the research quantifies how operational shift duration, thermal stress, and particulate accumulation synergistically drive worker fatigue and musculoskeletal disorders (Montgomery et al., 2021). The validated framework—achieving 95.4% predictive accuracy—serves as an indispensable decision-support instrument for industrial safety engineers seeking to systematically mitigate occupational hazards and promote sustainable manufacturing well-being (Chaffin, 2007; Duffy, 2009).

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