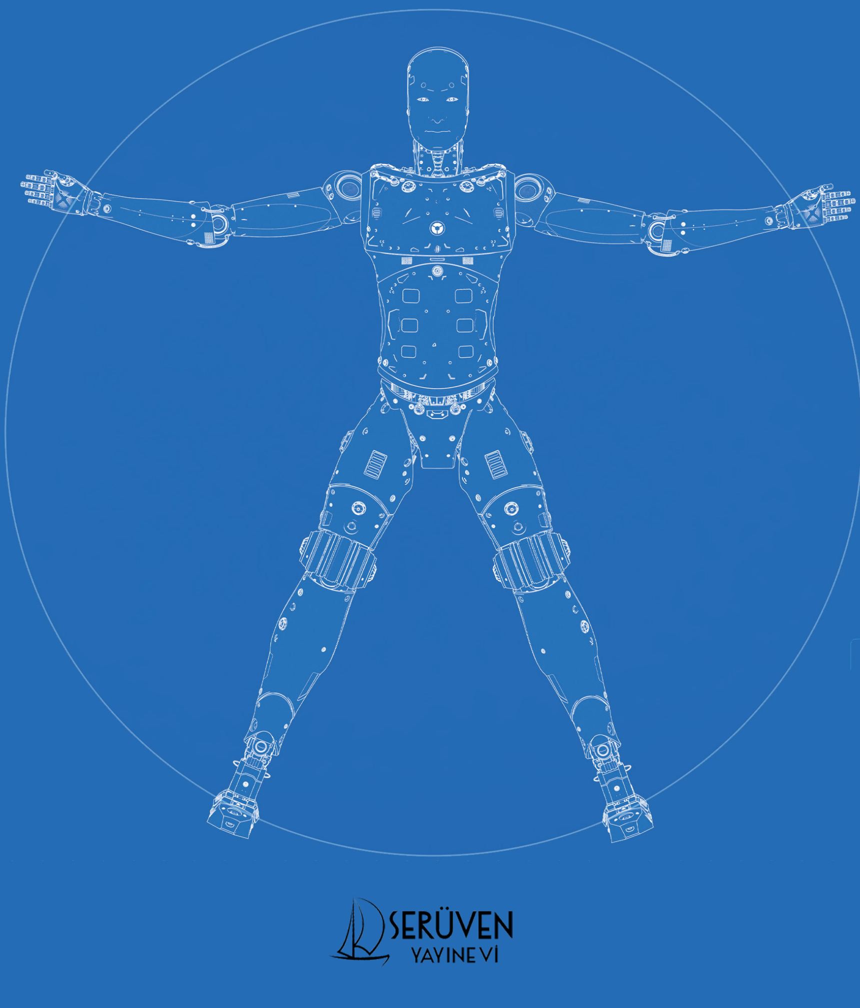
HUMAN-CENTERED INDUSTRIAL ENGINEERING:

WORKLOAD, PERCEPTION, ERGONOMICS, AND WORKPLACE DYNAMICS

EDITOR **PROF. DR. ALPASLAN FIĞLALI**



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EDITOR

PROF. DR. ALPASLAN FIĞLALI[1]

1 figlalia@kocaeli.edu.tr
orcid id: 0000-0002-8364-3313
Kocaeli Üniversitesi, Mühendislik Fakültesi, Endüstri Mühendisliği
Bölümü, Kocaeli, Türkiye

CONTENTS

Chapter 1

THE DYNAMICS OF JOB ROTATION IN THE WORKPLACE: THEORY, PRACTICE, AND FUTURE PERSPECTIVES

Tuğçen HATİPOĞLU[1]

1 Kocaeli Üniversitesi, Mühendislik Fakültesi, Endüstri Mühendisliği Bölümü, Kocaeli, Türkiye, ORCID: 0000-0001-5760-3652

1.INTRODUCTION

With the increased focus away from production efficiency, and global competition among workforce, businesses, organizations, businesses prioritize the workplace, not only the work, but the job itself which promotes health, flexibility and motivation (Zink, 2014). In this setting, job rotation is viewed as an intelligent human resource and production planning instrument that can reduce ergonomic issues, while enhancing organizational performance (Battaià, Delormas & Dolgui, 2013; Rinaldi et al., 2022).

Job rotation is the methodical organization of the transfer and reassignment of employees from one job to another within specific time periods. Especially in a physically repetitive and high-demand job, repeated usage of the same muscle groups may contribute to musculoskeletal disorders (MSDs) which can cost a lot of money at the individual and organizational level (Luger, Bosch & Looze, 2014; Ciriello, Snook & Hughes, 1993). With job rotation one can distribute these loads in such a way as to establish a more sustainable level of work and work environment (Dul et al., 2012).

However, job rotation is not only an individual physical pursuit of wellness but also a managerial method to enhance employees' (Genaidy, Karwowski & Shoaf, 2002) skill acquisition, job satisfaction, and the flexibility of the organization. The employees who become familiar with various tasks can take a more integrated perspective of work activities with their work processes, which in turn enhances quality, safety, and production continuity.

Production systems are reconstituted as not only automation-driven, but also to be human-centered and flexible (Zhang, Hu & Jiang, 2019) under the new-age of Industry 5.0. In this shift, job rotation is being personalized, data-based, and AI-enabled through digital twins, AI planning systems, and wearable ergonomic sensors (Lopez et. al, 2022; Rinaldi, Mora & Gamberini, 2022).

Therefore, this book chapter discusses the theory of job rotation, its formats and modes of application in context of its relations with ergonomics, ways of planning it, an examination of various sectors along with how it may be relevant to the future digital transformation.

2. DEFINITION AND CHARACTERISTICS

Job rotation is the temporary or permanent transfer of an employee from one job, station, or department to another based on a specific plan (Tirloni et al., 2020). This is done both in order to safeguard the health of workers and also to support the development of versatile skills. A good rotation program is a cyclical one of continuity, versatility, planning as well as criteria of managerial decision making.

Job rotation types are categorised based on their implementation form. Horizontal rotation means rotation between jobs at the same level but with different content, whereas vertical rotation is where employees take on roles at different levels of the hierarchy. Another type of rotation discussed in the literature is interdepartmental rotation or reactive rotation (Tuncel et al., 2008; Battaià and Dolgui, 2013). Job rotation can be confused with such concepts as "job enrichment" and "job enlargement." Job enlargement allows an employee to perform similar tasks added to their current job, while job enrichment means giving the employee more responsibility.

Rotation, on the other hand, involves switching between different tasks over time (Dul et al., 2012). The consideration of task suitability, proper training, planned frequency, ergonomic assessment, and employee involvement are the principles that are essential for successful performance of rotation (Possan et al., 2023; Yoon, Ko and Jung, 2016). Especially, ergonomic analyses in rotation planning can alleviate the impacts of the rotation on the musculoskeletal system (Rinaldi et al., 2022).

3. BENEFITS OF JOB ROTATION

Job rotation promotes the health of individual employees and organizational success, through many of its systems in those systems at least. The main advantages are ergonomic relief, psychosocial consolation and managerial flexibility.

3.1. Ergonomic Benefits

Job rotation is a good exercise to reduce stress from building up as a consequence of repetitive work of physical activity and daily effort on the same part of the body (Luger, Bosch & Looze, 2014). In high-force jobs, particularly assembly, welding, transport, packaging, etc., the rotation practice:

- Spreads repetitious movements between multiple workers, therefore minimizing the burden of the musculoskeletal system (Tuncel et al., 2008),

- Stops the repetitive use of the same muscle group, so you can mitigate local muscle fatigue (Possan et al., 2023),

- Eases ergonomic risk scores (e.g., REBA, OCRA) (Tirloni et al., 2020),

- Offers muscle recovery with natural rest periods. Since models were developed in the past few years, minimizing the ergonomic score and balancing load differences between tasks has become one of the goals among the most common models (Rinaldi et al., 2022).

3.2. Psychosocial and Cognitive Benefits

Job rotation also has its upsides to employees' psychological well-being. Repetitive, monotonous tasks produce low motivation and distraction (Dul et al., 2012). Rotation practices:

• Decrease task monotony and thereby increase attention levels,

• Support cognitive development by providing mental stimulation,

• Improve job satisfaction by reinforcing the perceived competence of employees (Zink, 2014),

• Decrease burnout risk and support ongoing staff commitment to the organization (Rinaldi et al., 2022). Task variety and opportunity for development are positive drivers of motivation for young employees, particularly Gen Z (Lopez et. al, 2022).

3.3. Managerial and Organizational Benefits

Job rotation is one way of assembling a multi-skilled workforce through a strategically thought out job rotation. Such construct is advantageous, due to its benefits in production continuity and crisis adaptation (Yoon et al., 2016). Additionally:

• The perception of fairness in task distribution improves,

• Shift planning can be made more flexible,

• Training and backup systems are strengthened,

• Quality control processes improve. By comparing the tasks performed and promoting a continuous improvement culture, businesses can help reduce error rates (Battaià and Dolgui, 2013).

4. RISKS AND LIMITATIONS OF JOB ROTATION

Job rotation is a boon to some jobs can be overshadowed, if not done effectively for the best and most successful job rotation is ill conceived, and upside down with any well-orchestrated staff, instead organizational dislocation and loss, loss productivity and lower productivity and a negative impact on the work organizational life on organizational order and employee's feelings of dissatisfaction. So, the execution process is also fraught with other kinds of pitfalls.

Training and Learning Costs: Employees must have an understanding and skillset to adapt to the change to new job duties. This process can put substantial time and cost burdens on companies (Tuncel et al., 2008). Insufficient training can lead to mistakes and quality problems.

Adaptation Process and Behavioral Resistance: Employees might undergo temporary performance decrement, stress, and an inability to adjust to a different task when moving from that to one they experience in the usual environment (Yoon et al., 2016). Furthermore, some employees will resist job changes. This can lead to internal conflict and loss of morale (Rinaldi et al., 2022).

Performance and Productivity Concerns: At the beginning of the rotation process, employees may be unable to perform their new duties with the same productivity they used to enjoy. However, this temporary drop-off in productivity may disrupt production continuity. Moreover, unfair evaluations of the assessment of performance are causing dissatisfaction in employees (Possan et al., 2023).

Issues Related to Legal and Policy Compliance: Certain tasks may require certification, experience, or compliance with legal regulations. When these requirements are not fulfilled, rotation processes can result in occupational safety hazards as well as legal implications from an industrial perspective (Liu et al., 2024).

Ergonomic Risks: Rotation (if not properly managed, rotation increases rather than decreases an ergonomic hazard (Cihan et al., 2018). Specifically, when it is done incorrectly you can pile up loads of workload by putting a single muscle group under consecutive task repetitions (Tirloni et al., 2020). That can lead to more muscle fatigue and health issues.

Cultural and Communication Barriers: For businesses which also operate in high cultural diversity or dominant hierarchical structures, rotating can lead to confusion in job descriptions, breakdown of communication patterns, and conflicts of status (Zink, 2014).

5. ERGONOMICS AND JOB ROTATION

Reducing the physical strain workers experience and preventing musculoskeletal disorders form one of the basic principles of job rotation practices. In this context, job rotation has a strong structural relationship to the discipline of ergonomics (Dul et al., 2012; Tuncel et al., 2008).

5.1. Musculoskeletal Disorders (WMSD) and Rotation

Work-related musculoskeletal disorders (WMSDs) are disorders resulting from factors that include prolonged repetitive movements, poor posture, and constant muscle strain (Ciriello et al., 1993).

Job rotation lowers this risk through:

- By preventing prolonged use of the same muscle group,
- By creating rest opportunities,
- By distributing the workload across tasks (Luger et al., 2014; Rinaldi et al., 2022).

Rotation planning, for example, can be carried out using tools such as REBA, RULA and OCRA and preliminary assessments provide concrete data (Tirloni et al., 2020; Possan et al., 2023).

5.2. Ergonomic Assessment Methods

Ergonomic ratings are crucial determinants which influence the optimization of rotational designs. The most common methods of assessing for ergonomics are:

REBA: Evaluates overall body posture (Hignett & McAtamney, 2000).

RULA: Upper extremity strain is investigated here.

OCRA: A method used particularly for repetitive tasks, evaluating parameters such as task duration, movement frequency, and force application (Tirloni et al., 2020).

NIOSH: Sets load limits for manual handling tasks. The basic input for the work rotation plans is the ergonomic scores the occupational psychologist acquired from these approaches.

5.3. Sequential Loading and Cumulative Risks

Not only individual tasks but task sequences also are ergonomically important. For instance: Assignment of tasks that strain the same body region consecutively gradually increases the cumulative load; Insufficient periods of rest can lead to microtraumas (Rinaldi et al., 2022); An imbalance between static and dynamic tasks leads to muscle imbalances. For these reasons, rotation strategies that prevent sequential loading can be devised (Possan et al., 2023).

5.4. Integration of Ergonomic Data into Planning

Emerging technologies enable the incorporation of ergonomic information into rotation planning. Example tools: Wearable sensors: Assess parameters such as muscle activity and posture abnormalities (Lopez et. al, 2022); Video analysis software: Assesses postural abnormalities seen during the course of tasks; Digital twin technology: Preemptively tests ergonomic effects by simulating task chains virtually (Liu et al., 2024).

5.5. Ergonomics-Based Strategies

Examples of strategies are listed such as: OWAS or REBA-based task matching (Shahmaleki & Fığlalı, 2021), Daily OCRA score-limited rotation plan, Preventing consecutive tasks that place strain on the same body region, Opposite task sequencing (e.g., assigning a dynamic task after a static task) (Tirloni et al., 2020). These strategies support not only physical health but also psychological well-being.

6. PLANNING AND MODELING APPROACHES

Job rotation is not only based on managerial intuition; it is also a systematic decision problem supported by mathematical modeling, simulation, and algorithms (Rinaldi et al., 2022; Rinaldi et al., 2022).

6.1. Job Rotation Planning Problem

The job rotation problem refers to the time-space-skill matching of tasks with employees within certain constraints. Minimizing ergonomic risks, maintaining production efficiency, ensuring load balance among workers are three aims (Possan et al., 2023). This problem is NP-hard, and heuristic algorithms are commonly used (Yoon et al., 2016).

6.2. Modeling Methods

Common modeling approaches used include the following: Mixed-Integer Linear Programming, MILP): Expresses ergonomic scores and multi-objective goals using linear constraints, Meta-heuristic Methods: Genetic algorithms, particle swarm optimization, etc.; Multi-Objective Optimization: Evaluates ergonomics and production output together; Simulation Models: Enables testing of the planned rotation in a digital environment (Lopez et. al, 2022).

6.3. Integration of Ergonomic Data

Task ergonomic scores (e.g., OCRA score) serve as model inputs. These objectives can be modeled as follows: Limiting each worker's total risk score, Reduce the duration of high-risk tasks, Prevent sequential loading, Ensuring fairness in task matching (Rinaldi et al., 2022; Possan et al., 2023). For example; OCRA integrated assembly line model (Possan et al., 2023), CWJR model: A special algorithm that balances cumulative load (Yoon et al., 2016), Industry 5.0-focused model: Optimizes productivity, ergonomics, and task monotony simultaneously (Rinaldi et al., 2022).

6.5. Software and System Tools

Primary software tools used:

- GAMS, CPLEX, LINGO: For mathematical model solving,
- AnyLogic, FlexSim: For simulation-based analyses,
- Custom Python algorithms: For flexible planning (Lopez et. al, 2022).

With these tools, work rotation plans could be tailored for more reliable, speedier, data-driven planning.

7. APPLICATION AREAS AND SECTORAL EXAMPLES

Job rotation is more than just a theory and it is a strategic device which can be used in most sectors and results in positive effect. Although the overall principles of the organization is different in different approaches according to sectoral dynamics, central objectives of ergonomics, motivation, and flexibility are standard (Battaià and Dolgui, 2013; Rinaldi et al., 2022).

Manufacturing and Assembly-job rotation is the most popular in automotive industry, in electronics and white goods. Especially on assembly lines such as reducing ergonomic dangers, avoiding monotony, focused on workforce continuity (Possan et al., 2023; Tirloni et al., 2020).

The result of these practices has been a substantial drop both in musculoskeletal issues as well as error rates (Luger et al., 2014).

For healthcare sector, rotate job opportunities in nursing, laboratory technical services, and patient care,the navigation of psychosocial stress, to prevent burnout from their jobs, for service quality improvement should be given such as examples (Tuncel et al., 2008; Liu et al., 2024). For instance, structured rotations between emergency departments, outpatient clinics, and surgical units elevate patient satisfaction and employee commitment.

Service Sector examples can be sampled such as rotation in call centers, hotels, banks and retail businesses, to increase task diversity, quality of customer service is improved. Job rotation in these fields also translates into enhanced employee loyalty, career development at workplace as well as multi-skill development.

The basic relations among job rotation, the unbalanced development of physical workload, fatigue and fatigue-related developments, and seasonal workload were observed to be in harmony in the logistics and warehousing companies (Rinaldi et al., 2022). In the current scenario, numerous logistics companies provide software-supported rotation planning to optimize their job assignments. In the construction and infrastructure industry, job rotation helps to specialize the profession while controlling the health hazard. Rest-time limitations on hazardous job assignments, seasonal rotations, and job rotations in apprentice and journeyman training departments are some of the important practices that have made this growth possible (Zink, 2014). It involves the education and public organizations promoting career advancement, diversity of workplace employees, and increasing the motivation of the employees through proper public officials care and guidance (Rinaldi et al., 2022). They improve perceptions among employees and act on public standards and distribution.

8. EMPLOYEE PERCEPTION AND BEHAVIORAL DIMENSION

For job rotation practice to succeed, it is not just about technical planning but also how employees perceive the rotation process (Dul et al., 2012). Participation, fairness, and communication, for example, determine employee response. In particular, perceived fairness and adequate preparation are essential factors whereby employees' evaluation of the process impacts their perception of rotation, where they feel that tasks are adequately distributed and sufficient training is provided (Yoon et al., 2016). When employees are randomly allocated to tasks they do not get adequate training for, they are more likely to be stressed, unhappy, or resistant (Rinaldi et al., 2022). Staff involvement in decision-making at rotation promotes a greater attitude of trust in the system. For example, behaviours that may reduce resistance are: seeking employee preferences, using feedback, conducting job-fit analyses. Responses are also influenced by generational differences, with Generation Y (1980 to 1995) and Generation Z (born after 1996) putting greater importance on task variety and career flexibility as motivating factors (Lopez et. al, 2022). They also tended to avoid monotonous tasks better and were more satisfied in roles supported by digital technologies. As a result, personalized rotation plans for younger employees are warranted. Reactions employees have concerning rotation can be either quick adaptation to new tasks, voluntary requests for rotation; passive resistance, such as reluctant participation; or active resistance, the open rejection of rotation. Managerial support, clear communication, psychological safety, and a psychologically safe working environment must be established to manage these behavioral effects (Tuncel et al., 2008; Dul et al., 2012).

9. FUTURE PERSPECTIVES: INDUSTRY 5.0 AND DIGITAL ROTATION

Industry 5.0 is a production model for the future that focuses not only on production automation but also on human well-being, sustainability, and flexibility. In this perspective, worker health, individualized work planning, and technology-supported decision systems are major focus areas (Zhang, Hu & Jiang, 2019; Lopez et. al, 2022). As such, job rotation is no longer just an activity that reduces physical risks, but is becoming more and more a data-driven, individual-focused, and continuously learning system.

9.1. Principles of Industry 5.0 and Rotation Practices

Key aspects of Industry 5.0's high-impact principles of human-centeredness, sustainability, and resilience impact job rotation in these three ways:

- Task planning tailored to employees' individual ergonomic capabilities.
- Rotation based not only on production needs but also on employee fatigue and development levels.
- Balancing task loads during crisis situations (Zink, 2014; Lopez et. al, 2022).

In these respects, rotation is being redefined as a mechanism that places people at the center of production systems.

9.2. Artificial Intelligence and Decision Support Systems

Through AI-guided software, tasks can be matched in real time based on employees' past performance, ergonomic scores, rest levels, and task preferences (Possan et al., 2023). Through big data analysis, task–employee matching suggestions can be automatically generated, and objective, multi-criteria decision mechanisms can be developed to replace intuition-based choices (Rinaldi et al., 2022). Moreover, the daily production plan can be dynamically updated according to variables such as individual health status and work intensity.

9.3. Wearable Technologies and Real-Time Feedback

New-generation sensors can monitor employees'

- Heart rate, muscle activity, postural abnormalities,
- Sweating, trembling, fatigue levels, and other parameters in real-time (Lopez et. al, 2022).

By integrating this data into production software, it becomes possible to dynamically assign lower-risk tasks to employees experiencing high fatigue. This enables the creation of **real-time adaptive rotation** systems.

9.4. Digital Twin Technology

Digital twins are real-time virtual copies of a production line or task chain that enable rotation scenarios to be tested before implementation. Through these virtual models, the ergonomic impact of transitions between tasks can be simulated, and optimal rotation plans that balance production requirements with employee health can be identified (Liu et al., 2024; Rinaldi et al., 2022). This approach transforms job rotation into a process that is not only preventive but also predictive.

9.5. Individualized and Flexible Rotation

In the future, job rotation will be tailored based on individual characteristics, including an employee's age, gender, physical condition, and health status, as well as past ergonomic risk data. Psychological resilience and learning speed (Rinaldi et al., 2022), along with individual preferences and career goals, will also shape rotation decisions. Following this model, the duration and difficulty level of tasks, as well as break schedules, will be defined in a personalized manner, enabling job rotation to provide maximum benefit in terms of fairness, efficiency, and sustainability.

10. CONCLUSION AND RECOMMENDATIONS

The multidimensional review of job rotation in the book chapter shows practical and theoretical implications. In this context, job rotation becomes a strategically powerful practice under the lens of ergonomics, human resource management, production planning and digitalization. This study provided a significant amount of results suggesting that job rotation is an effective solution to overcome musculoskeletal disorders and ergonomic risks (Luger et al., 2014; Possan et al., 2023). It improves psychosocial motivation and helps in reducing monotony of tasks and increases job satisfaction (Rinaldi et al., 2022; Çolak and Esen, 2023). Once structured into system with training, involving employees and data-informed decisions, this is likely to yield great productivity development, at the personal and organizational level. In addition, developments in AI, digital twins, and sensor technologies are further shaping personalized and dynamic job rotation (Lopez et. al, 2022; Liu et al., 2024). At the organizational level, rotation planning is the responsibility of the HR, production and occupational health units, while the task analysis based on ergonomic analysis by design to determine rotation structures should also be based on risk. It is crucial to design rotation with an active participation of the workforce as well as to make iterative design with feedback for feedback to have acceptance and long-lasting effect from the employees. Advances in technology also contribute; AI and digital twin systems can be utilized to personalize job assignments and wearable tech makes it possible to monitor employee health in real time. For academic investigations, long-term impact analyses on specific domains and development of sector specific guidelines and software tools are required. There need, also, to be a clear legal and ethical environment for setting sector standards towards job rotation and for including rotation factors in collective agreements.

In summary, rotation of work is a very important and essential part of modern human-centered, digital-enabled and sustainable workers' organizations. Job rotation will transform into a transformative resource not only to increase organizational effectiveness and also increase the human value of work and benefits of the practice, by strategic planning, participatory management and science-based decision making.

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Chapter

2

APPLICATIONS OF MULTI-CRITERIA DECISION-MAKING METHODS IN OCCUPATIONAL HEALTH AND SAFETY PRACTICES

Ali İhsan BOYACI[1]

1 Kocaeli University, Engineering Faculty, Industrial Engineering Department, Kocaeli, Türkiye, ali.ihsan@kocaeli.edu.tr, 0000-0003-3656-6164

1. Introduction

The importance of occupational health and safety (OHS) has been regarded as a fundamental responsibility of organisations since the advent of industrialisation, but the current environment of business has caused occupational safety to become too complex to be addressed with established procedures or policies. Today's production systems are multi-faceted, as automated production and human-computer interaction, intensive workflows, and external stakeholder pressure have become the new normal. Such forces require decision makers to consider several variables at once, both in the course of regular routines and the midst of unanticipated events (Hale & Borys, 2013). Furthermore, some of these variables could be qualitative elements which cannot be measured directly or differ from one person to another. So, the limitations of single-dimensional assessment tools are getting more and more apparent in the OSH sector.

Even in small and medium-sized enterprises, traditional risk assessment models are still widely used. In most cases are practical, due to the fact that risk matrices, Fine - Kinney method, and probability-severity-based ratings tend to give rapid results. One limitation of these types of approaches is their lack of support for uncertainties in large scales, interplay among the multiple expert opinions, disagreements based on differences in expert opinions and various factors (Cox, 2008). For instance, two distinct experts can determine the severity of a single hazard quite differently, and the classical approach could not model this distinction. In time-bound industries like this, the discrepancy can have a real effect on quality decisions. Thus, the research interest in using a more systematic and transparent approach to make decisions in both engineering and management literature has been intensified in recent years.

In such environment, Multi-criteria Decision Making (MCDM) techniques are increasingly attractive methods in OSH applications. Methods such as AHP, TOPSIS, VIKOR, SWARA and WASPAS exist that have been used in diverse industries and yield favorable results in hazard classification, control measures, ergonomic risk assessment, ergonomic hazard analysis, green growth and equipment comparison (Triantaphyllou, 2000; Opricovic & Tzeng, 2004; Çelik et al., 2016). The decision to use such methods is mainly for the purpose of making possible decision making on the multiple contradicting factors in the model. In addition, most of the approaches are able to handle quantitative as well as qualitative inputs, and expert opinion could be more naturally related to decision making. Such flexibility is a huge advantage in an application domain like OSH, that is highly influenced by people.

However, in several OHS uses, the uncertainty level is so great that the most well-known classical MCDM techniques might be difficult to sufficiently model expert decisions in some cases. As a result, in literature, the extended methods (i.e., fuzzy logic-based AHP, fuzzy TOPSIS, and fuzzy SWARA) are increasingly used (Yager, 2014). Pythagorean fuzzy sets help translate experts' linguistic expressions — "not sure," "partially suitable" and "moderate risk" for instance — into more adaptable mathematical sentences. For instance, in ergonomic assessments this is typically not possible to obtain consistent data, so directly incorporating a linguistic assessment into our model can enhance the decision quality. In a similar manner, fuzzy models are good for aggregating expert opinions of different uncertainties of the same structure in hazardous chemicals facilities.

A separate reason for MCDM approaches becoming increasingly well-documented within that OSH literature is that they give decision-making more transparency and debate. The mathematical character of the methods permits reasons for a hazard to be considered high priority or one control method to be seen to be more appropriate. This encourages a set language among managers, engineers, and workers to make decision-making much more acceptable – for instance (Zavadskas et al., 2015). In addition, in today's complex organizations where there is increasing number of decision-making stakeholders, it becomes even more important that there are consensus-based methods such as VIKOR. These approaches are helpful in creating consensus solutions in cases of group decision making, an especially important requirement for high-risk industries.

However, literature review indicates that MCDM techniques have, despite their popularity in OSH, not always met quality for their execution. Many studies suggest that methods are selected without adequate discussion on their suitability for the problem and that methods are chosen because they are popular (Zwetsloot et al., 2017). The validity of the model can be questioned especially when the data diversity demanded by multi-criteria structures are not given or expert judgments are weak. Thus, it is essential that methods be chosen carefully, that they be evaluated in relation to data quality and in conjunction with decision makers in developing the model.

This study seeks to study the MCDM approaches in the OSH field from all angles; its theoretical background and examples. Traditional methods are discussed, multi-criteria structures advantages are discussed, high-profile areas in the literature are analyzed and current methodological approaches are reviewed. Besides that, the study presents examples from different sectors and discusses the situation as to where methods are most effective, their weakness, what is still to be studied and where future studies are needed. This seeks to offer a practical framework for practitioners as well as provide an even deeper foundation for academic research.

2. Decision-Making Problems and Evaluation Criteria in OHS

This simple view of decision making in OHS is often undermined by a series of overlapping considerations that occur in the same decision-making process. In the areas of minimizing risk on a physical workstation, choosing the right personal protective equipment, prioritizing hazards, and how to invest in equipment, managers need to take into account technical and human aspects. This makes it necessary for OSH decisions to be approached in a broader way than simply assessing OSH decisions through a single criterion perspective (Hallowell & Gambatese, 2009). Multi-criteria structures that encompass both qualitative and quantitative data are more effective because precise measurement is often impossible, particularly for risks with human factors.

One of the most common decision problems encountered in OSH is the ranking of hazards identified in the workplace according to their risk level. In conventional risk frameworks, risk consists mainly of the product of probability and severity, but risk cannot be captured in only two aspects when working in real-life conditions. Other factors such as hazard recognition, duration of exposure, the possibility of containment and even number of employees in any given workplace all play decisive roles in today's work environment. Thus, over the past few years, the studies employing methods including AHP, TOPSIS and fuzzy AHP in hazard classification have been increased. (Brüning & Kane, 2016; Yilmaz & Karaşan, 2020). But the method is flexible in allowing the expert opinions to be incorporated into this model; besides, decisions made through these methods are an open-sided, highly debatable affair too.

Another prevalent issue faced when making a decision is choosing the control method which is the most appropriate for the present hazards. Control is frequently assessed considering cost, technical issues, process compatibility, maintenance and staff acceptance. Taking a dangerous substance out of a process altogether, for instance, may be the best way out though, plant engineers may not be able to consider that for the sake of economics and operability. There are also studies that suggest that methods such as VIKOR and WASPAS provide more balanced and more palatable options in these situations (Choudhry & Fang, 2008).

MCDM schemes are also commonly applied in equipment choice, ergonomic analysis and workstation construction. Because most ergonomic criteria are qualitative, fuzzy logic-based approaches are particularly useful in this context. Many ergonomical risk assessment studies employing fuzzy TOPSIS techniques are still available in research; a great deal of review of criteria such as: repetitive motion, difficulty of posture, vibration, and load handling (Chung & Lee, 2019). For instance, in the field of manufacturing, MCDM methods based on quantitative data are being increasingly used for making more complex decisions, like the choice of maintenance equipment, automation solutions and safety sensors, at the more technical level.

Multi-criteria structures are becoming a common way to analyse OHS in managerial aspect. Rather than measuring the effectiveness of departmental safety performance by looking at only the number of accidents, some businesses are evaluating how workers perceive their safety climate in multi-category terms: the number of near-miss reports by your unit or whether people participate in training on safety standards; or if there is enough non-conformity from employees about what happens to the safety of employees in various areas (Clarke, 2010). MCDM methodologies can, therefore, weigh different indicators in performance evaluation processes and help rank the results systematically. This allows managers to make greater consistency in deciding what needs improvement at a unit or group.

OSH decision problems have wide diversity generating a similarly broad breadth of assessment criteria. Probability and severity are basic parameters in most risk analyses, but the exposure level, number of people affected, maintenance requirements, effectiveness of control, cost, technical compatibility, worker comfort, environmental and legal impact are also considered decisive in many industries. In particular, in the construction segment, exposure to risk related to working at height is intimately related to the environment and how work is being organized and thus studies have shown that layout and scheduling of work are frequently considered criteria in this model. That is why decision processes in OSH tend to be more well-managed with multi-criteria systems because criteria can be diverse and often interconnected. It is difficult to describe a metric score in terms of the real-world decision uncertainty and multidimensionality. As such, most of the studies claim that choosing criteria weights using SWARA, DEMATEL or fuzzy AHP improves decision quality. For instance, in high hazard perception operations, “employee acceptance” becomes more relevant, whereas in chemical plants in which process safety may dominate, “technical feasibility” and “detectability” are among indicators. This difference explains both the flexibility and applicability of MCDM methods.

Accordingly, the decision-making in OSH process is characterised by uncertainty and multi-dimensional structure. Questions relating to prioritization of hazards and the selection and application of specific control strategies, equipment preference, and poor safety performance of the appropriate department are met through a triangulation of various criteria. Thus, the literature indicates that the MCDM methods is not just a theoretical instrument in the OSH literature, but also a decision-support tool, which is more and more recognized in real cases.

3. Fundamentals and Comparison of MCDM Methods

MCDM methods offer a systematic method for those decision-makers who face multiple criteria to be assessed concurrently. Although the application of these are used in engineering and also in the social sciences, they are much more common in multi-dimensional decisions, specifically with respect to occupational health and safety. MCDM strives first to compare the performance of various alternatives towards the same criteria and create a ranking of outcomes that are as uniform as possible. This process assumes different principles and takes different forms in mathematics; hence, every method has its strengths in the application process and also limitations.

One of the classical methods, Analytical Hierarchy Process (AHP), is designed to fix the decision problem by building structure hierarchically. A critical aspect of this approach is the weighing of criteria by the decision-maker that is done through pairwise comparisons. According to existing literature, AHP is especially effective in contexts where data is scarce, but expert opinion is high (Saaty, 2008). This method can prove clunky when compared with a comparison table that expands in size with number of criteria. Moreover, it can be hard for experts to achieve consistency. As such, AHP is viewed as a powerful tool for more structured decision-making with a finite number of criteria, but can lack responsiveness to dynamic environments.

Like AHP, the prominent TOPSIS method aims to find where the alternative is most similar to the ideal solution. Its basic idea is that the best alternative is the least distance from the positive ideal solution and the greatest distance from the negative ideal solution. TOPSIS benefit is in its simplicity of calculation and interpretation results can be given different graphs. Yet, the reliance on linearly normalized data and the notion that all the criteria may appropriately compensate for each other may be problematic for "vital criteria" like OSH.

In contrast, since VIKOR (aka consensus-based) is more appropriate to take, especially when group decision-making is an important concern. This method produces a hierarchy of ranked results that accounts for both group advantage and individual regret (Opricovic & Tzeng, 2004). VIKOR has been shown to provide relatively better solutions regarding more satisfactory solutions in OSH committees, which tend to incorporate the views of different experts. In contrast to the former, WASPAS employs both weighted sum and weighted multiplication and thus builds a hybrid structure (Zavadskas et al., 2012). This hybridization has particular significance for problems with multiple criteria, as it has produced more stable results in certain studies.

In the last years, SWARA became one of the most popular approaches of the model. Experts classify criteria in ascending order by importance and calculate weights step by step. A major benefit of this method is that it does not need a huge comparison table, as in AHP. Hence, SWARA is widely applied within practical OSH assessment in time-limited conditions (Keršuliene et al., 2010).

One other is outranking methods like PROMETHEE and ELECTRE. The target of these approaches is to compare alternatives, not by the closeness to the perfect solution, but by the extent of their suppression. PROMETHEE is capable of more flexible decision models, in more detail with preference functions and dominance flows (Vincke & Brans, 1985). By contrast, ELECTRE is predicated on the assumption that the decision maker may "not tolerate poor performance" below a threshold, giving the benefit of not permitting compensation for such criteria (Roy, 1991). These characteristics are of especial importance in the situation that, for example, a piece of work equipment is to be fully discarded if it violates a certain safety criterion, since from a OHS view, accounting to some of the criteria is not possible.

Analytical Network Process (ANP) adapts the hierarchy of AHP to the model with interdependency between criteria. This can be more realistic when criteria will always interact like OHS (Saaty, 2005). As an example, there are explicit relations between ergonomic risks and workload, workload and error probability, and error probability and accident risk. AHP treats these relationships independently, but ANP can integrate these dependencies into the model. Because the calculations are much more complicated, though, the implementation can be much more complicated.

Best Worst Method (BWM) is a more recent method of criteria weighting that has gained importance in recent years and is also desirable practically because it takes a small number of comparisons compared to alternative methods (Rezaei, 2015). The specialist only simply needs to determine the best and worst criteria, and compare them. This approach is highly applicable in OSH applications where the time of experts is finite, or the criteria are numerous.

Other methods for this are COPRAS, ARAS, MOORA, and MACBETH. COPRAS measures the performance (cost-benefit), both at a comparative, using criteria weights, of alternatives within an initial cost or by a criterion weight (Zavadskas & Kaklauskas, 1996). In contrast, ARAS is based on relative efficiencies and is a widely deployed approach in energy and ecology applications, which is popular in specific economic cases (Zavadskas et al., 2010). MOORA, however, is good for fast applications, given its simplicity. MACBETH, in contrast, goes further through verbal evaluations and will not require a numeric score in a pairwise comparison, especially for highly uncertain environments.

DEMATEL is an emerging technique used to reveal causal relationships between criteria. The focus, unlike other methods that cover the decision-making process, is in the weighting phase, and it shows which criteria will affect the decision making process through a "cause-effect" connection. This approach can be helpful in OSH, with some risk factors being particularly important (e.g., absence of trained or untrained individuals causing behavioral risk).

Having reviewed these various methods, it is evident that the MCDM is not monolithic, but instead provides a broad mix of methodological options applicable to various types of problems. Thus, selecting the method should be influenced upon, among other things, the nature of the problem, the type of data, the number of experts, the association of criteria, and the importance of the choice.

4. Applications of MCDM Methods in the Field of OHS

Increasingly important to address complex problems to be found in different settings, multi-criteria decision making methodologies are found in occupational health and safety. Because most decisions made in workplaces are necessitated through the concurrent comparison of different criteria, MCDM methods give these decision processes a structured approach that is consistent, traceable, and systematic. In widely varied application areas such as equipment choice, expert choice, risk assessment, hazard evaluation, ergonomic enhancement, or performance evaluation, MCDM approaches provide decision makers with a unique point of advantage where criteria may conflict or when uncertainty is high. These methods develop more realistic and justified results in multidimensional domains such as OHS by integrating the qualitative and quantitative data in the proposed model.

The most noticeable places MCDM is used in OHS application are, of course, the choice of equipment and experts. In work situations where working populations possess diverse physical features, the choice of safety items is not only the selection of technical performance but also of usability, design suitability and accessibility factors. Therefore, for equipment selection methods such as AHP or fuzzy PROMETHEE are preferred. Kaya and Dağdeviren (2016) provide evidence that if principles of universal design are brought into the decision-making process work equipment gets more efficient in so doing for a wide range of users. Similarly, different factors need to be considered when making decisions about human resources, such as selecting an OSH specialist. Ozturk and Toptancı (2017) adopted the BOCR method to obtain a comparison of different expert candidates and showed that the selection process can be more objective when they systematically combined the multidimensional aspects of benefits, opportunities, costs and risks as a criterion. These papers showcase that the MCDM approaches can yield the same results in the case of physical systems and human capital selection. In addition, AHP models created for assessment of the engineering controls in the equipment selection process were implemented with Caputo, Pelagagge, and Salini (2013); they compared safety equipment used by industrial machinery, further confirming that the approach provides a strong criterion for technical performance assessment, economic and operational criteria.

Another relevant field of application for MCDM in OSH is by risk assessment and hazard analysis. In that there are multiple variables involved in the impact of various hazards to workers, including exposure intensity, exposure to environmental factors and applicability of control measures, single-criteria models cannot provide such assessments. Studies in construction indicate that AHP and FAHP are valid tools that offer decision-makers the "same-check" approach on multi-dimensional problems, such as safety culture assessment, hazardous behavior analysis, and safety program formation (Chellappa & Ginda, 2023). In hospitalized settings, fuzzy models (FAHP and TOPSIS) are applied to prioritize the risks (electrical hazards, faulty equipment, maintenance processes) to inform the more precise choice of control measures (Badida et al., 2022). For the metal industry, MOORA method combined with Fermatean Fuzzy Sets was a tool for prioritization of various hazards, and also for quantification of qualitative criteria based on the uncertainty of qualitative factor (Toptancı and İnal, 2024). Broadly speaking, the work of Badri et al. (2012) which also underlined the idea that risk analysis is not limited to technical level aspects but should also be applicable at organisational and environmental level suggests that a risk analysis by MCDM based approach could potentially facilitate this in mining.

MCDM techniques are also used extensively in ergonomics and on performance evaluation. Most ergonomic issues involve qualitative assessments (posture analysis, range of motion, work speed, load on muscle), and the systematic quantification of this information supports the decision making (Fığlalı et al., 2015). Adem et al. (2024) found out that methods such as AHP and TOPSIS can effectively be used to compute ergonomic risk scores and make design choices more transparent, particularly in complicated work stations. Performance assessment, however, is typically a relatively complex process that requires the simultaneous consideration of multiple criteria. Accident rates and compliance problems exist in road transportation sector and the comprehensive assessment of OHS performance is difficult.

Through the evaluation of these studies, it can be concluded that MCDM approaches are a very useful frame for solving complex problems in different fields in the OSH discipline. They are used in application in many aspects as from the choice of equipment to risk control development, from the choice of expert to ergonomic design, and offer to decision makers in high uncertain field rational and methodological approach. But in order to make a reasonable contribution, the models are not efficient only if criteria is known at the beginning of research, data is reliable in the collection process and methods are matched well to the problem structure; otherwise, the effect of the application is likely to be limited.

5. Discussion: Trends, Methodological Issues, and Gaps in the Literature

The increase in the coverage of MCDM techniques in OHS has resulted in good analytical variety for different problem types, including some of the key issues in approach selection, expert involvement, and modeling is still considered to be in a substantial proportion of the literature. While most of the applications state that the framework provided by MCDM methods can lead to improved decision quality, it is not always widely discussed how the models are obtained and when they are valid. This scenario raises the importance of detailed method choice, particularly when we speak about applications that produce such high-risk actions as preventing occupational accidents.

A fundamental problem suggested in the literature is the prevalence-based, or user-based selection of methods, rather than the problem structure itself. Methods like AHP or TOPSIS are, however, usually "known" to most of the researchers, and criteria dependencies, compensability assumptions, and the internal structure of the problem are not addressed. However, as Badri et al. (2012) have demonstrated, risk factors are not solely shaped or mitigated by technical variables but are also determined by workload, process design and organizational characteristics. In such relationships, methods based on one-dimensional, or independence-based methods may find that it may be difficult to apply the risk rankings to reality where such relationships are possible.

There is another significant limitation of the model, which is a lack of including expert opinions during the process. Most literature indicates that the experts are scarce (or not explaining how the evaluation occurs). This reduces model robustness, particularly in areas characterized by a great deal of uncertainty. By contrast, in their work with the road transportation industry, Jiménez-Delgado et al. (2019) showed that systematically generating datasets across individual expert groups increases the reliability of models substantially. Yet the scarcity of similar multi-stakeholder applications in the literature remains a continuing challenge.

Another common methodological issue in the literature relates to the tendency to avoid consideration of criterion dependencies. Ergonomic variables, education, workload, maintenance quality or equipment failure are frequently interdependent factors; however, most work applies weights without the help of such dependencies. The strength of the MCDM methods is that they can accurately represent the entire system, the capability of which has not been exploited in all the applications. The noncompliance of field applications also reflects a broader problem. Many of the models developed in the field of OSH are theoretical and do not get adopted into actual business, or when they do, the results are not mentioned. Nevertheless, reports were carried out for the real machine park study (e.g., Caputo et al. (2013)), in order to illustrate the impact of the model at the field level. But there is a considerable gap in practical validation across the literature. Such limitation makes the practicability of developed models in actual working environments questionable.

Lastly, it is shown that the criteria selected by most studies are not sufficiently justified, some criteria are not relevant for the context that you are assessing, or some criteria are overweighted. This is attributed mainly to the mathematics of the models and the lack of the background. The lack of reference to the theoretical and practical framework regarding these criteria undermines the external validity of the model.

The MCDM methods provide good prospects overall in the context of OSH. Nevertheless, to realize this full potential, method selection, greater expert attention, wider input and expert input, modeling criterion dependence in the model, as well as more widespread applications to the field are needed. By closing these shortcomings, the methodological quality of the theoretical and practical quality of academic papers is expected to be improved, as well as the practical and applicable safety approach in work settings.

6. Conclusion and Recommendations

This paper reviews how MCDM techniques are extensively used in this field of occupational health & safety. As most OSH decisions are multidimensional and uncertain it is evident why the MCDM method have been preferred. These techniques offer decision makers a coherent systematic, transparent and uniform framework for different types of applications including hazard prioritization, control measures selection, ergonomic analysis, equipment appraisal, equipment assessment and behavioral safety. As it is observed from the previous sections we will look through the literatures also on a broad array of methods, from classical techniques such as AHP and TOPSIS through outranking methods such as PROMETHEE and ELECTRE, from fuzzy logic based extensions to relational models like DEMATEL or ANP, various methods add value at different times.

Yet, it is not simply to say the same methodological rigor is applied to all applications. In several studies the method selected is not carefully justified, the methods for getting experts' opinions are not well stated, or criterion dependencies are ignored. In addition, the limited number of practical field applications prevents an overall investigation on how well model outputs translate to the enterprise level. Especially in the high risk sector, few studies provide evidence about the extent to which the recommendations of an MCDM model were to reduce occupational accidents. It is the greatest future development demand for the area.

There are a few suggestions for future research arising from this framework. First, the method should be selected not just based on how much it is already familiar in the literature, but that it really corresponds to the shape of the problem. The method used should be chosen uniformly to reflect the compensability of the criteria, the amount of experts involved, the availability of data, and the criterion-dependency. Second, the gathering and evaluation of expert opinion should be more transparent, such that the various special expert groups should participate more in the investigation. This will ensure the applicability of the model to the current practice, particularly in cases of OSH problems with strong behavioral and organization-specific dimensions. Three, MCDM models need to be piloted in real workplace settings and the experimental results must be evaluated. Without field validation, models are just a theoretical contribution; the main objective of OSH practices is to prevent occupational accidents and diseases. Thus, we need future research to be included with "post-implementation impact analysis." Lastly, dynamic datasets and time-relative risk assessments are novel trends in the literature. The incorporation of production volume, shift type, seasonality or distribution of workload into MCDM models can lead to timeliness and adaptiveness of decision-making.

MCDM methods, in general, are the powerful players that improve the decision quality and the transparency of the decision making process in the field of OSH. These techniques may not yield optimal results unless the methodologies are carefully chosen, the data is accurately represented and we can try these methods in a real context (the "real world"). At such times when these conditions are satisfied, the MCDM approach has the potential to provide something more than an academic tool to be used merely for analysis in academic studies, and in fact directly impact a workplace decision-making environment which is increasingly safer, consistent, and more predictable for workers.

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Chapter 3

PHYSICAL WORKLOAD ANALYSIS

Nilgün Fığlalı[1]
Ahmet Cihan[2]

1 Kocaeli University, Engineering Faculty, Industrial Engineering Department, Kocaeli, Türkiye, figlalin@kocaeli.edu.tr, https://orcid.org/0000-0001-7211-4363
2 Düzce University, Engineering Faculty, Industrial Engineering Department, Düzce, Türkiye, ahmetcihan@duzce.edu.tr, 0000-0001-9110-2368

1. **INTRODUCTION**

Physical workload is one of the most basic ergonomic concepts used in work life and refers to the physical demands of work on the work performed during a job. The accurate physical workload determination is an important dimension of occupational health and safety (OHS), ergonomics, industrial engineering, and business administration. This is because not only does workload directly determine efficiency of production, the long-term health of workers, the potential for occupational accidents, and organizational performance. (Grandjean & Kroemer, 1997). Many sectors — especially manufacturing, assembly, logistics, warehousing, construction, agriculture and healthcare — exert highly physically demanding work today. Lifting, carrying, repetitive arm-hand movements, awkward postures or protracted standing are some of the leading causes of musculoskeletal disorders in these disciplines. According to the World Health Organization (WHO, 2022) and the International Labour Organization (ILO, 2010), these disorders represent a substantial portion of all work-related health issues. Thus, physical work burden assessment should be regarded not only as an evaluation process but also as a preventative measure for the welfare of workers. (ILO, 2010).

Physical workload measurement becomes important because job design, workstation layout, production speed and its interrelationship to the physical capacity of the person doing the job and the characteristics of the working environment. If the demands of the job exceed the worker's capacity, fatigue increases, the error rate rises, and the risk of accidents multiplies. Conversely, maintaining the workload at an optimal level increases both productivity and production quality. For this reason, modern businesses view ergonomics not only as a means of protecting health but also as an investment that enhances performance. (Sanders & McCormick, 1993; Wings et al., 2024)

When examining the concept of physical workload historically, it is seen that the first studies were based on the discipline of work measurement and time studies at the beginning of the 20th century. However, this approach aimed more at determining time standards. After the 1950s, with the spread of physiological measurements, load began to be considered in conjunction with energy consumption and cardiovascular demands. From the 1980s onwards, biomechanical models and lifting equations made it possible to evaluate the mechanical dimension of work. In the 1990s, observation-based ergonomic analysis tools were developed. Today, sensor technologies, artificial intelligence-based video analysis systems, digital twin models, and data science-based approaches have made the assessment of physical workload much more accurate, continuous, and real-time. (NIOSH, 1997)

The rest of this text chapter will discuss the idea of physical workload from multiple perspectives, including physiological and biomechanical foundations, measurement methods, technological approaches, the effects of working conditions, and ergonomic intervention strategies in a comprehensive framework. The goal is to show that physical workload is not only a risk factor but also an essential design element that determines the quality of working life.

2. CONCEPTUAL FOUNDATIONS OF PHYSICAL WORKLOAD

Physical workload is a multidimensional term, framing the relation between the individual and work in physiological, mechanical, and environmental dimensions. Hence, it is important to grasp the concept to understand what physical workload measurement methods seek to achieve and which factors have been considered. (McArdle et al., 2010; WHO, 2022). One of the basics of physical workload is the burden put on the musculoskeletal system. The mechanical load component is the amount of force a person exerts at their work, the prevalence of repetitive activities, the form in which they move during working and the moments these movements are placed on the joints. For instance, tasks over shoulder height cause a big increase in the torque in the shoulder joint. Likewise, for every 15 degrees of forward bending in the waist, the pressure load on the lumbar region increases exponentially. Hence, one of the most obvious signs of physical workload is the postural requirements of the work. (McArdle et al., 2010). Physiologically, physical workload shows up most obviously in terms of energy expenditure and cardiovascular responses. Muscle work relies on oxygen, and this demand rises as the work becomes more intense. Light workloads require relatively low oxygen consumption; however, VO_2 increases rapidly during strenuous physical work. The heart rates also increase in parallel with each increase in this demand. Thus, the measurement of heart rate is one of the commonest physiological clues to evaluate physical workload. When the pressure load rises greatly, muscles utilize anaerobic energy systems and cause the buildup of lactate and fatigue. (Sanders & McCormick, 1993). It is worth remembering that the physical workload does not simply consist of exertion and energy expenditure. The wrist, elbow, and shoulder will get microtraumatized with repetitive movements. Ultimately, these microtraumas can damage tendons and connective tissue, injured along with nerves leading to disorders such as tendinitis, bursitis, and carpal tunnel syndrome. Therefore, the rhythm of work and work cycle intensity are both parts of workload. (ILO, 2010). Environmental issues are also highly responsible for physical workload. Working in hot places elevates temperature and heart rate of the body. Mechanical stress, especially in the back and hand-arm area, increases with vibrating equipment. Poor lighting indirectly promotes workload by poor posture and eye strain. Noise, meanwhile, raises stress levels and triggers increased physiological responses. (WHO, 2022). The individual differences are also very important in an assessment of physical workload. The same job can generate multiple levels of demand for separate workers. The specific level to which a person is able to withstand workload, due to age, sex, physical health, body composition, endurance, previous injuries and chronic illnesses - all of which directly correlates with tolerance to workload. Thus, ergonomic assessments should use flexible frameworks, accounting for worker diversity over making the assumption of a "single ideal worker profile for a particular job." (Grandjean & Kroemer, 1997). It describes this multidimensional framework and explains why measuring physical workload with one or more types of measurements cannot be sufficient. Physiological measurements are used to understand the metabolic demands of the job, biomechanical assessments to understand the mechanical demands of work, observation-based analyses to see posture and behavior patterns, time-motion studies to determine repetitiveness of work and self-reporting tools for workers' perceptions. Together, these methods provide an objective, subjective, and multidimensional analysis of physical workload. (Lee et al., 2022)

3. **BASIC METHODS IN MEASURING PHYSICAL WORKLOAD**

Accurate measurement of physical workload is one of the most important steps for sustaining worker health, preventing accidents, detecting ergonomic hazards, and improving job design. The measurement of physical workload varies in methods since different techniques evaluate physical workload from different perspectives. Generally speaking, the measurement of physical workload is carried out by physiological, biomechanical, observation-based, time-motion-based, and self-report-based methods. These methods are thoroughly addressed in this section, how they complement each other, and when they should be preferred. (Grandjean & Kroemer, 1997; Lee et al., 2022)

3.1 Physiological Measurement Approaches

Physiological measurement methods are concerned with measures of direct physiological results of the actual physical impact of work. The objective of these scientific measurements is to evaluate the biological consequences of physical burden on workers directly on physical performance by physical work. These tools assess heart rate, oxygen utilization, oxygen uptake, metabolic responses, and thermal stress. Heart rate measurement is most favoured among the methods because it is realistic and well linked to the physiological response. A comparison with the values and measurements of the worker resting heart rate alongside those taken on the clock allows one to see the degree of work that causes a physiological stress. Especially the load on the work can be measured through heart rate reserve (%HRR) to determine if it is sustainable. If the %HRR is higher than 30%, there's a lot going on for one very long shift. Heart rate measurements are not only a proxy for work intensity – but also environmental temperature, psychosocial stress and worker fitness, so the interpretations need to be sound. (McArdle et al., 2010; Esen et al. 2019). Oxygen consumption (VO_2) measurements are the scientifically accepted "gold standard" and they are the most precise for evaluating energy consumption. The VO_2 values based on the workload give a lot of useful insight into the sustainability of the job load. A safe working level is defined as the VO_2max capacity of the employee is less than 30% during work, but if it is above 50%, it becomes difficult to sustain the work for long durations and ergonomic improvements are necessary. These measurements are typically performed using portable metabolic systems. (ILO, 2010)

Thermal stress and body temperature measurements are also important in assessing physical workload. Especially in work performed in hot environments, heart rate, body temperature, and perspiration increase, making the workload heavier than it actually is. The impact of environmental conditions on workload can be calculated using criteria such as the WBGT index. This allows for the redesign of work breaks, rotations, and working hours. (Sanders & McCormick, 1993; dos Santos et al., 2024)

3.2 Biomechanical Assessment Approaches

While physiological methods measure the metabolic demands of work, biomechanical methods reveal the "mechanical dimension" of physical workload by examining the magnitude of forces and mechanical stresses on body segments. Biomechanical assessment is a fundamental tool, particularly in the analysis of manu l handling, load lifting, pushing-pulling, repetitive movements, and strenuous postures.

Force measurements are among the most fundamental biomechanical approaches. Dynamometers, push-pull devices, and grip force measurement devices are used to record the forces applied by the worker. The data obtained is compared with the maximum acceptable force limits defined by standards. Such measurements are particularly important for jobs such as warehousing, transportation, maintenance, repair, and assembly.

One of the most critical applications of biomechanics is the assessment of manual lifting tasks. The lifting equation developed by NIOSH determines the risk level of the task by evaluating many variables together, such as the weight of the load, the starting and ending heights, the horizontal distance, the asymmetry angle, the quality of the grip, and the lifting frequency. The resulting "Lifting Index (LI)" indicates whether the task is acceptable. For example, an LI value above 2 indicates that the task poses a high risk to the worker and requires immediate intervention. (Sanders & McCormick, 1993)

In biomechanical methods, one cannot afford to only focus on force and lifting but also on posture and movements. The load on the musculoskeletal system increases exponentially with high angles (i.e., lumbar flexion angle, shoulder elevation degree, wrist position, neck inclination). This is why sensor-based posture tracking systems (accelerometer and gyroscope-based wearable sensors) are becoming increasingly common. These sensors measure a person's postures during the day, including how long some positions are held and which movements produce the most stress. This can make dangerous work steps straightforward to spot.

3.3 Observation-Based Assessment Tools

Observation-based methods are tools used by ergonomists to perform quick and practical assessments in the workplace. They are the most preferred assessment techniques in workplaces because they are simpler to implement than physiological or sensor-based methods.

The common feature of these tools is that they score factors such as posture, force, repetition, and work environment by observing the employee during work. For example, the REBA method is a comprehensive tool that evaluates all body segments and is used in a wide range of jobs, especially for nurses, assembly workers, and manual transport workers. RULA focuses on the upper extremities and is more suitable for evaluating computer workers, assemblers, and workers performing fine manual tasks. OWAS is an analysis method that examines the posture of workers at specific time intervals in physically demanding jobs where the whole body is actively used, based on the logic of job sampling. Methods such as QEC include the worker's opinion in the analysis, evaluating both the physical and perceptual dimensions of ergonomic risk.

The advantage of observation methods is that they are fast, low-cost, and have a wide range of applications. However, since the observer's experience and subjective elements can affect the results, it is important that the assessments are performed by trained individuals. Furthermore, observation methods indicate the potential risk rather than how much physiological demand a job actually creates; therefore, they yield stronger results when used in conjunction with physiological measurements.

3.4 Time and Motion Analysis-Based Methods

The physical workload is directly related not only to such processes as force, posture, and metabolic demand, but also to the time dimension of the task. Time-motion analysis methods enable you to rate workload levels against repetitiveness, continuity, and intensity of work cycles. Time scales such as those for MTM (Methods-Time Measurement) and MOST (Maynard Operation Sequence Technique) categorize basic movements into separate work cycles with time-standards attached to each step. Such analyses can be employed to establish work intensity, the number of movements, superfluous steps, and excessive physical repetition. One example is a worker lifting their arm 40 times, or bending over 20 times for each product in the assembly line, which is an indication of workload — repetitive work of this magnitude can eventually lead to musculoskeletal disorders. (Fığlalı et al., 2015). Time-motion analyses can be useful to design jobs, identify automation requirements, balance workstations, and increase production efficiency. Because they are not metrics of physiological load, however, they are typically used as adjunct methodologies. (Fığlalı et al., 2015)

3.5 Self-Reported Measurements

Physical workload should not only be reflected in an objective measure, but also in terms of perceived fatigue, pain, strain, and performance. Self-report methods are thus an important factor. The Borg RPE scale allows a person to quantify how much effort they feel at work. It is understood that if a worker's RPE is high, the workload exceeds his or her tolerance. On the other hand, the Nordic Questionnaire searches in 12 areas of the body for pain, numbness, and sensitivity early on, to detect signs of musculoskeletal disorders that are beginning. While such methods are subjective, they offer valuable complementary insight into the effects of physical workload on workers. (Grandjean & Kroemer, 1997; Haraldsson et al., 2021)

3.6 Combining Methods

No single method can cover all dimensions of physical workload. Therefore, the most effective approach is to use a combination of methods. For example: (Grandjean & Kroemer, 1997)

- Heart rate measurement + REBA → metabolic demand + posture risk (ILO, 2010)
- Sensor-based posture monitoring + MTM → mechanical load + work cycle intensity (ILO, 2010)
- VO_2 measurement + worker surveys → physiological load + subjective fatigue (ILO, 2010)

This holistic approach enables understanding of physical work load in its biological, mechanical, and behavioral aspects and increases the accuracy of ergonomic improvements.

4. TECHNOLOGICAL APPROACHES IN PHYSICAL WORKLOAD MEASUREMENT

The measurement of physical workload has evolved from observing the work of others and analyzing it with classical analysis methods to using more complex technological tools or systems. Use of wearable sensors, AI-backed video analysis, high-accuracy motion tracking instruments, IoT-based data collection infrastructures, and digital twin technologies has allowed us to measure physical workload in a more accurate, continuous, real-time and multidimensional way. Such advances have advanced the measurement capabilities of ergonomics science and have also transformed occupational health and safety management. Wearable sensors have emerged as one of the key instruments for physical workload measurement in recent years. These sensors generally consist of a variety of sensors including accelerometers, gyroscopes, magnetometers, electromyography (EMG), heart rate monitors, etc. They are embedded in various locations of the body and monitor the workers' postures, movements, and physiological responses throughout the day. An accelerometer, placed on the lower back, can, for example, measure the amount of time the worker bent forward, the duration of knee flexion and the rotation of the torso. That kind of data allows "continuous data to be gathered throughout the day" rather than the "instantaneous" evaluation of standard observation; therefore frequency, duration, and severity of dangerous positions can be assessed much more accurately. EMG sensors directly measure muscle activity, thus providing an objective estimate of the muscular load introduced through the process. For example, the worker with a heavy lifting work can be analyzed when the back, shoulder or arm muscles become overactive. This makes it possible to quantify the percent of capacity on which the muscles are working and the point at which they become fatigued. This methodology is especially applicable for rehabilitation, exoskeleton engineering and heavy work studies (Alenjareghi et al., 2026). Artificial intelligence-based video processing systems are another leading technological advance. Ergonomists in traditional video analysis are still reviewing images manually, but deep learning algorithms that work out whether workers are in the correct postures or are in a high-risk movement can be applied within the actual systems. These systems track workers with cameras, capture body sections in a digital skeleton model of the body and can compute ergonomic measures including REBA or RULA automatically to help the workers automatically. Incorporating software support like image processing based I-OWAS has also been done, allowing OWAS method to be used without ergonomics experts. Which minimizes the potential risks of human error, accelerates the evaluation process, and enables a wider range of subject matter to be investigated. Also, certain systems can provide real-time alerts that the system has the ability to respond to; e.g., if a staff member becomes excessively bent his/her back, it would send a vibration or audible alert, which helps in immediate correction of ergonomic action.

IoT (Internet of Things)-based environment monitoring systems also play an important role in physical workload assessment. These systems continuously monitor environmental variables in the workplace, such as heat, humidity, vibration, light intensity, noise, and air quality, making it possible to analyze their contribution to the workload. For example, the same task may create more physiological load for a worker operating in high temperatures because their heart rate will increase; by matching IoT data with physiological data, a real work load map can be created. In warehouses and logistics areas, weight sensors and smart forklift systems are used to measure the physical demands on workers during the movement of loads (Seong et al., 2025).

The most advanced approach that has emerged in recent years is digital twin technology. A digital twin is the creation of a virtual copy of a workstation or production line and the simulation of worker interactions on this digital model. This allows different work designs, equipment layouts, or working speeds to be tested in a virtual environment in terms of their impact on physical workload. For example, changing the height of a workbench on an assembly line, reducing the frequency of lifting loads, or rearranging the placement of a product can be tested on a digital twin to see which design creates the lowest ergonomic risk. This allows evidence-based decisions to be made before changes are made in the workplace, saving both time and money.

This feedback loop that influences employee behavior is not just limited to measurement, but technological approaches. Some wearable devices are able to send users posture-correcting messages throughout the day that help in correcting non-ergonomic postures in real-time. Because the employees follow such feedback, there is less physical strain for an employee which can prevent musculoskeletal disorders in the long term. Other companies use such technologies in ergonomics training, where workers can tell proper postures from incorrect postures through their own movements. Consequently, technological avenues improve data quality and the performance of analysis for physical workload measurement. They allow for more accurate, continuous, objective, large-scale analysis compared with classical techniques, and also offer greater transparency regarding the interplay of human factors on workload. This type of development translates physical workload into a variable not just measurable but manageable, then also optimizable. In this regard, technology is one of the powerful forces that will influence the ergonomic future.

5. DATA COLLECTION AND ANALYSIS PROCESS

Physical workload assessment methods are as important as the data extracted on physical workload assessment methods, through collection, processing, storing and interpreting, etc. Such results could be erroneous on the grounds (where the measurement process is not approached in a scientific way, which results in a biased method and incorrect ergonomic decisions). This makes the process of collecting and analyzing the data more than the work of technology; it is the end process with respect to the quality of the tools used in this methodology such as representativeness of the data, realistic reflection of working conditions, and reliability of measurement results. This section addresses the major principles of data collection, measurement approaches, data quality, methods of analysis, and methods of interpreting this information.

Part of collecting data is defining job. This means that no measurement in its entirety is systematically applicable unless job analysis is done — workload cannot be properly measured without knowledge of what the employee does, how, at what frequency, and under which conditions. Job analysis typically involves list tasks and a flow chart of the job, work cycle determination, when the job is most intense, and a preliminary assessment of the physical demands of the job. Now, it is very important for the ergonomist to observe, get brief interviews from employees and have an observe work activity on site.

The first stage is determining the measurement strategy. Not every job can be measured with the same type of technique so that the suitable method must become an occupation. For instance, physiological measurements would give better results for jobs with intense physical task demands, whereas sensor-based motion tracking systems would provide better results for those assembly lines that contain repeated small movements. Observation based approaches may work well for a standing heavy workstation but video analysis systems likely work best in more complex workstations. The measurement strategy deals with key questions, including what data will be collected, by how long, what devices will be used, how long the data recording intervals will be, and how working parameters will be controlled during measurement. (NIOSH, 1987).

A crucial aspect during data collection process is the principle not to interfere with the worker's habitual behavior. Measurement devices shall not restrict the worker's movement and must not hinder them to carry out his activities as usual. This is because the objective of workload measurement is to reflect stress within the actual working conditions. Accordingly, wearable sensors in particular should be lightweight, wireless, and comfortable in work clothes. In video analysis, cameras should be positioned in locations where it would not put undue pressure on the employee but can pick up a great deal of important points of the job at the same time. In physiological measurements, calibration of our sensors and their sensitivity towards such external variables as perspiration and temperature should be examined.

The timing of this period of measurement is also crucial to ensure that data is reliable. The job may only require a few minutes of short observation or short term sensor readings that do not accurately reflect the general demand of the job in the field. This can include varying work intensity at specific moments of the shift, different task cycles, rest breaks, break times, or work pace, among others. Thus representative time intervals should be chosen and long-term recordings if feasible. Such as, there are potentially critical discrepancies between the 2–4 hours of recordings made from wearable sensors and short-term observations — time series of long-term data more accurately reflects job needs. (Waters et al., 1994).

Raw data can be unfit for analysis and needs several stages of data processing to recover. Data cleaning is another major aspect of this process. Some data might be considered to be "outlier" due to some rapid peak generated by measurement devices, sensor malfunction, contact loss and due to environmental factors. Different signal treatment steps are used to reduce such data. Low-pass filters are primarily applied in motion sensors where most low-pass filters are used compared with median filters for heart rate data and band-pass filters for EMG data (Boyacı et al., 2025; Akman et al., 2023).

The classification and interpretation of the filtered data is perhaps the most important phase of the analysis. For instance, the lumbar curvature above some threshold level is categorized "risky posture" in posture data, and when the heart rate is above some threshold rate in physiological data, it is tagged as a "heavy workload" category. In time-motion data, the amount of repetitiveness of the task is shown from the number of repetitions and cycle times. We then combine these classifications into a risk profile.

Integration of various data types is also an important component of modern workload analysis. As another example, the data of posture paired with information regarding heart rate gives us physical stress in both a mechanical and physiological sense. Similarly, based on temperature data obtained by the environment sensors and the physiological responses, one can also determine the job thermal load. This multi-layered understanding permits us to take into account everything in a comprehensive physical workload as it should, rather than taking just one view, and simply reduce it to a single point of view. (Waters et al., 1994).

The last stage is the assessment and reporting process. It is not enough just to show the data collected graphically, but it has to be read by the employers, ergonomists, and occupational safety experts. In this interpretation, it's important to mention clearly whether there are threshold values at which workloads exceed certain value, which work steps bring with them risk level concentrating where, how much of imbalance of balance is disturbed between work capacity and workload at these step, and what ergonomic adjustments can be made. Results presented with scientific approach to scientific methods contribute to the fact-based decisions in the workplace and establish a solid foundation for ergonomic design phase. This is, therefore, the data collection and analysis process is the bedrock upon which the physical workload assessment is constructed. A well-designed process not only permits measuring workload but also the optimization of working conditions, the design of ergonomic improvements, and the construction of long-term safe working environments. (Waters et al., 1994)

6. FACTORS AFFECTING PHYSICAL WORKLOAD

Physical workload is not affected by individual factors alone; it is shaped by the combined effect of physical demands from tasks, environmental conditions, work organization, and psychosocial factors. We have to look at more than the end-results; so the contextual factors that impact on this part of the outcomes need to also be reflected on and managed in order to improve our understanding of workload properly. In this section, we make a comprehensive explanation of the major determinants of physical workload by summarizing the effect of all these determinants on workload. The most basic variable that influences physical workload is personal physical capacity. The muscle strength, stamina, aerobic capacity, joint range of motion, and fitness of each worker vary. Such differences allow the same task to have different physical needs for different people. A job that does not pose much challenge, for example, to a young, fit, employee, can become difficult for an older employee, or someone with a weaker endurance. Previous injuries, chronic musculoskeletal conditions, or health issues may also reduce the tolerance of workloads. Ergonomic assessments thus need to be based on an approach to assessment based on individual differences rather than simply on 'average worker' values and beliefs. (Waters et al., 1994). Posture and movement quality are other key determinants of physical workload. Ergonomically unsuitable postures, with excessive back flexion, excessive shoulder loading, repetitive wrist bending, etc., dramatically elevate the loads placed on the musculoskeletal system. Another reason for why there is a high prevalence of improper postures is that workstations are set up not as per workers' profile. If the height, distance, and location of the staff requires the physical workload of the worker to grow, in which case it becomes more and more awkward. The stance and quality of movement have to do with the pace and force of work not just the place of work but the rhythm of it. Workers working assembly lines, where speeds increase and cycle times are very brief, find it hard to control their movements ergonomically, not only promoting increased muscle activity but also leading to later fatigue. (NIOSH, 1987)

One of the decisive factors affecting physical workload is repetition and continuity. In repetitive tasks, muscles are forced to perform the same movement hundreds or thousands of times, causing microtraumas in muscle fibers. Over time, these microtraumas can lead to tendinitis, bursitis, nerve compression, and similar musculoskeletal disorders. The duration of the task is also a critical parameter in terms of the sustainability of the workload. While a short period of high workload is tolerable, continuing the same load for a long period exceeds the muscles' recovery capacity and increases fatigue. Therefore, the balance between working time and rest periods directly affects the physical workload.

Environmental conditions, particularly temperature, humidity, vibration, lighting, and noise, are important factors that affect physical workload both directly and indirectly. As temperature increases, body temperature also rises, sweating increases, and the cardiovascular system has to work harder. Therefore, people working in hot environments experience the same task as more demanding than in a normal environment. Vibration, especially from tools that cause hand-arm vibration, leads to constant micro-level stimulation of the muscles; this both increases fatigue and can cause long-term damage to nerve and vascular tissues. Inadequate lighting indirectly increases physical strain by forcing workers into awkward postures such as bending, reaching, or twisting the body. Noise can increase physiological stress , leading to an elevated heart rate and thus increasing the metabolic demands of the job.

Work organization and management style are also important factors affecting physical workload. The absence of job rotation causes workers to remain in the same task continuously, which increases risks, especially in jobs requiring high repetition. Factors such as work pace, shift schedule, break times, and time pressure directly affect workload. People who work long hours with short breaks tire earlier because their muscles have limited time to rest and recover. In environments with high time pressure, workers are forced to work quickly and find it difficult to maintain ergonomically correct postures; in this case, both mechanical and physiological load increase significantly. (NIOSH, 1997; dos Santos et al., 2024)

Finally, an important but often overlooked factor affecting physical workload is psychosocial conditions. Factors such as stress, job dissatisfaction, low sense of control, or feeling pressured by managers can increase workers' perception of physical load. Psychological stress leads to involuntary tension in the muscles and muscle spasms during movement, which can cause the work to be perceived as more demanding than it actually is. Furthermore, employees working under stress may neglect ergonomic principles and adopt risky postures more frequently. Therefore, physical workload should not be viewed solely as a mechanical and physiological phenomenon but should be assessed in a multidimensional manner that also includes the psychological state of employees. (Fığlalı et al., 2015)

When all these factors are considered together, it becomes clear that physical workload is not a single variable but rather a complex interaction between the worker, the job, the work environment, and the organization. Therefore, workload assessment and management strategies should be based on holistic approaches that take this broad framework into account. (Golabchi et al., 2023)

7. INDUSTRIAL APPLICATIONS AND CASE STUDIES

The physical workload goes beyond theoretical models and laboratory measurements; it is a manifestation that directly mirrors the lives of workers on a daily basis in actual workplaces. So, the management of physical workload only becomes meaningful as long as it supports practical experience as well as examples in real-life fields. The use-cases in industry explain the way in which methods of workload assessment transfer into practice, highlighting the problems manifested more clearly, and showing how ergonomic improvements affect work results. Here, physical workload is examined and handled with a range of instances from manufacturing, assembly, logistics, healthcare and maintenance.

One of the most fundamental applications for assessing physical workload in the manufacturing sector is ergonomic analysis conducted on assembly lines. Studies conducted in an automotive factory observed that workers repeatedly performed work cycles averaging 30–60 seconds per vehicle, frequently raising their shoulders and performing tasks that required bending at the waist. Measurements revealed that workers' lumbar flexion angles repeatedly reached 30°–45°, leading to significant muscle fatigue by the end of the shift. Data from wearable sensors showed that workers bent forward approximately 800–1000 times during a shift. This high frequency of repetition was assessed using observational methods; REBA scores were found to be 8 or higher at most stations. As part of the improvement efforts, workstation heights were readjusted, the assembly sequence of some components was changed, and ergonomic swivel tables were used to significantly reduce the need for workers to bend. After the improvements, both the workload scores decreased and a significant reduction in pain complaints reported by employees at the end of their shifts was observed. (Grandjean & Kroemer, 1997)

The logistics and warehousing sector is one of the work areas with the most intense physical workload. Significant physical demands arise, particularly during package handling, loading–unloading, shelf arrangement, and forklift use. A workload analysis conducted at a large distribution center found that workers lifted an average of 6–8 tons of products daily. Analyses using the NIOSH lifting equation revealed that the load was lifted at a level very close to the ground, the horizontal distance was wide, and the asymmetry angle was high, resulting in a lifting index exceeding 2 for most tasks. This finding clearly indicated that the work was at a high risk level. Subsequent ergonomic interventions included the use of height-adjustable lifting platforms, changing the way products were brought into the warehouse, and implementing job rotation to prevent any one person from continuously performing heavy lifting. These improvements resulted in a significant decrease in the rate of work-related accidents and the frequency of sick leave due to back pain. (ILO, 2010)

The healthcare sector is also one of the areas where physical workload is most critical. Nurses, caregivers, and healthcare technicians are under high mechanical stress when performing tasks such as moving, turning, lifting, and positioning patients. An assessment conducted in a hospital's intensive care unit found that employees turned patients in bed an average of 25–40 times per shift and performed lifting and pulling movements 8–12 times. Such tasks place a particularly high load on the lumbar spine. Studies using posture analysis and EMG measurements revealed that workers' lumbar muscles worked at a high activity level throughout the shift and that muscle fatigue became apparent in the middle of the shift. As part of the improvement effort, the mechanical load applied by workers was significantly reduced through the use of ceiling-mounted patient transport systems, sliding sheets, and support devices. Subsequent measurements showed a decrease in both lumbar muscle activity and workers' self-reported fatigue scores. (WHO, 2022)

The maintenance and repair sector is a field of work characterized by heterogeneous physical workloads and a high degree of task variety. For example, a machine maintenance technician may lift heavy parts, work in confined spaces while bending over, reach up to change filters, or use vibrating tools all in the same day. Due to this variety, it is not possible to assess the workload using a single method. In a maintenance analysis conducted at a factory, it was observed that workers applied high force for a few seconds in some tasks, while remaining in a static position for long periods in others. According to data obtained through sensor-based posture monitoring, technicians were found to remain in a kneeling or crouching position for a total of nearly two hours during their shift. In addition, hand-arm vibration exposure was found to be close to international limit values. Improvements included adjusting the working height, floor supports, knee pads, and the use of vibration-reducing hand tools; as a result, both standing times and muscle fatigue were reduced. (Sanders & McCormick, 1993)

Workload analysis in the construction industry is of great importance, both due to the nature of the work and the highly variable working environment. Tasks such as concrete transport, shoveling, lifting heavy formwork pieces, and working on high platforms involve intense physical demands. Measurements taken at a construction site showed that workers took an average of nearly 10,000 steps per day, that their back bend frequently exceeded 60°, and that repetitive rotational movements during transport increased the load on the back region. It was noted that during the summer months, when the ambient temperature was high, workers' heart rates rose rapidly, thereby increasing the physiological dimension of the workload. Improvements made in the field have been in the direction of further mechanization of heavy loads, creation of shaded work areas, and more conscious matching of work and workers.

These examples show how physical workload assessment carries similar dynamics regardless of the sector, but requires different strategies specific to the application area. When ergonomic improvements based on measurement results are implemented, positive outcomes are achieved in employee health, production efficiency, and quality indicators in almost every sector. Therefore, physical workload management should be considered not only as a risk reduction measure but also as a corporate performance improvement process.

8. STRATEGIES FOR REDUCING AND INTERVENING IN PHYSICAL WORKLOAD

Because physical workload arises from many elements resulting from job type, working environment, organizational system and employee profiles, the prevention and control of this burden can be achieved by employing various means. Intervention strategies are mainly intended to match the work demands with the labor's physical constraints, reduce musculoskeletal stress, delay fatigue and prevent occupational accidents and diseases in the future. In this respect, a number of interventions in this context has been introduced such as ergonomic designing, work layout, work organization, mechanical equipment engineering, training, vocational training, work condition improvement, workplace environment improvement and technology use, etc. One of the most useful means of reducing physical workload can be done by way of job and workstation ergonomics redesign. In many cases, ergonomically inappropriate workstations have been shown to be one of the most powerful solutions for alleviating work requirements in increasing work load and significantly increasing the work load as they create more employees to unplanned bending, reaching, lifting and twisting actions. Desks, benches, and work surfaces have adjustable heights so workers can have a precise working position according to their height and type of work. Additionally, small alterations in construction can reduce the load very large (e.g., positioning workpieces in an accessible area, minimizing lift distances, reducing body rotation). Ergonomic advancements such as rotating tables, tiltable platforms and height-adjustable work surfaces which are used for assembly lines. Managing physical workload is also greatly contingent upon organizing work. Muscles being repeatedly strained and repeatedly exercised with the same movement pattern with one worker doing this job, leading to increased risk for musculoskeletal disorders. Thus, the rotation allows working with different muscles, allowing workers to move from one task to another and avoiding one-sided accumulation of loads for that job. Job rotation must differ from physical requirements of tasks, and passing this information between similar jobs is not enough if similar work will not produce less monotony on the part of the employees. But, keeping pace of work, expanding staff numbers in busy times, and not putting employees under too much pressure to do things faster are also important factors to be considered in managing workload. The proper structuring of resting times is also a great way for lowering physical work. Muscles are becoming tired (and even fatigued from doing things over and over again that lead to lower effectiveness and higher risk of injury. Short, strategically placed microbreaks can allow muscle to fully recover so the fatigue can be kept to a minimum. For instance, a 1 to 2-minute break between every 30 minutes of work improves muscle oxygenation and alleviates muscle fatigue. These micro-breaks have a protective advantage over longer breaks because they prevent fatigue from building up early on. Another important point of intervention is increased mechanical aid and technology equipment. The use of vacuum-lifting systems, lifting aides, mechanized transport vehicles, height adjustable equipment and automatic command systems greatly decrease the amount of force used by workers when carrying out jobs which have a heavy workload. Passive and active exoskeletons both have also gained recognition in the recent past as another method for lowering physical work load by supporting physical activity in body areas around the back, shoulder and leg. Passive exoskeletons transfer the load on the body through the use of springs and mechanical reinforcement components; active exoskeletons increase the amount of motorised support and can greatly reduce muscle fatigue on heavy lifting tasks and prolonged standing. This growth through inclusion of such technologies in work settings is turning ergonomic interventions from design based enhancements to something that benefits worker performance directly. Employee training is also an important part of the work with regards to workload reduction strategies for work. Training is vital in promoting the use of the correct lifting methods, including training on ergonomically appropriate postures, techniques for utilizing tools and equipment, to influence how workers act. But just training is not enough, even a trained employee on site, cannot necessarily avoid bad postures in ergonomically unsound job design. Training should, therefore, be seen as a complementary adjunct to other interventions. Facilitate employees to understand body awareness, recognise the signals of fatigue and take breaks when needed to improve physical workload management effectiveness. Improved physical conditions for the work environment are also key to workload reduction strategies. For example, the physiological and mechanical demands a job requires directly depend to factors such as temperature control, lighting adjustments, vibration-reducing surfaces, and noise control. For example, in the heat, workers' heart rates increase; this results in doing a very high work load on the same activity. In those scenarios, such measures as cooling systems, ventilation improvements, or rescheduling work hours during the summer months may be used. Lighting improvements enable workers to carry out their work without sacrificing posture; floor improvements and vibration-damping technology, for instance, minimize microtraumas to the musculo-skeletal system. The first point is that workload management should not only be a physical intervention (of that kind) but it should also be an organizational and culture-based one, not just from an organizational standpoint. Empowering workplace employees with a chance to offer feedback on ergonomics; sharing openly workload and ergonomic work concerns; and having a strong safety culture at work enhances the effectiveness of ergonomic interventions. Incorporating the employees in the overall improvement process not only allows for information access to be accurate but also aids in the sustainability of the changes made. In the end, it's reducing physical workload that makes work safer, more efficient and sustainable. These aren't just worker health protections: These interventions make costs lower, quality higher, and production processes more stable at the business. Effective workload management is a holistic effort to build a broad system, from job design to work culture.

9. CONCLUSION AND FUTURE PERSPECTIVES

Physical workload is a key component of ergonomics and occupational health and safety in contemporary working life, but it also plays an important role in production management, operational strategy, human resources policy and occupational psychology. The theoretical basis, assessment systems, technological strategies, influence parameters on working conditions and industrial applications which have been discussed in a chapter in this book are further evidence that physical workload is a multidimensional and dynamic phenomenon; both its measurement and management necessitate a holistic approach. As the work speeds and the complexity of production processes grow, physical workload is increasingly becoming important in modern workplaces. The modernization, the automation of certain heavy labor, and digitization have made these operations less manual, but human labour remains the main object in production in many industries. The need to design work such that it does not exceed what humans can physically perform is accentuated, so workload management becomes directly part of sustainable production and productivity objectives. The classical measurement systems for measuring workload have been valuable for many years, but the workplace is characterized by a need for more sophisticated continuous, constant and comprehensive measurement methods to monitor the physical workload in the workplace. In this area, such wearable sensors, AI mediated video analytics, environmental monitoring systems, and digital twins provide innovative tools that radically change the way we evaluate physical workload. Currently it is possible to literally monitor how many times or times an employee bends during the day, how long can they hold their arm up, how much physical force they apply or when will fatigue. This goes from a reactive to proactive approach to workload management. Physical workload management will likely continue to be more integrated, personalized, and data-driven, which is just a few of the positive steps forward. For instance, artificial intelligence algorithms can learn about behavior patterns taken from big data sets to foresee which employees could be higher risk; this can ensure that problems are handled early on. Digital twin models will allow workstations to be simulated before they are set up, allowing testing of the effects of different design choices on physical load in a virtual environment. That will make ergonomic design processes more scientific and cheaper. Yet physical workload is also a problem; technology alone can't solve it. Workload design is a cultural matter; a solid culture of respect for employee capacity and ergonomics as part of working life is one of the most basic drivers of the success of workload management. A training and awareness-driven manner increases the effectiveness of the technological tools employed by the organization. No amount of technological or analytical measures will make a substantive difference in the absence of this culture. Moreover, damage due to physical workloads does not stop at accidents. High workload risk is associated with damage to the musculoskeletal system, chronic pain, loss of staff, loss of workplace productivity, absenteeism and low motivation. As such, workload management is not only a risk minimization tool, but a mechanism for safeguarding the employee health, enhancing job satisfaction, and decreasing enterprise cost in the long run. It's apparent that staff who are healthy are more productive, make fewer errors and have a higher level of commitment; this underlines the economic benefit of ergonomics. Physical workload assessments in the future will likely grow to be more "personalized." Nowadays, workload measurements are based mainly on mean averages but each staff member has different physical capacity, stamina, fitness, and tolerance. Along with wearables, personalized data analysis will facilitate workload optimization based on personal capacity. This will allow new applications such as the ability to redistribute workload between two workers at a job by the task tolerance (workload), offer personalized rotation plans, or modify work speeds. In summary, the physical workload is one of the most important factors influencing working life and the area of work studies is of vital relevance till date and in the future. When technology-supported measurement systems, ergonomics design principles, and the management of employees (and their welfare) are put to work, physical workload is a variable that can be measured, controlled, and optimized. This evolution provides a stepping stone to a more harmonious working world as work is aligned to human requirements, facilitating effective industries and quality-of-life tradeoffs that prioritize the health of workers.

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Chapter 4

COLOR, PERCEPTION, AND PRODUCTIVITY: SYSTEMIC, ERGONOMIC, AND BEHAVIORAL DIMENSIONS OF COLOR USE

Tuğçen HATİPOĞLU[1]

1 Kocaeli Üniversitesi, Mühendislik Fakültesi, Endüstri Mühendisliği Bölümü, Kocaeli, Türkiye, ORCID: 0000-0001-5760-3652

1. INTRODUCTION

Color is not only a cosmetic design, it offers an essential environmental input to our cognition, its role to a cognitive load, attentional channel and performance of the job. From human-machine interaction and structure of workplace ergonomics and system design perspective, color is an "information carrier," "ergonomic optimization parameter," and "operational variable that determines decision speed in human-system interaction." As a result, at the scale of industrial engineering, color should not only be seen as a factor, but rather an engineering element with multi-faceted activities including handling cognitive elements, promoting safety, optimizing operational flows.

From technology and applications that are much more complex, to multi-tasking required by the current applications of technologies, the strategic importance of color usage is proportionately bigger. Industrial systems are no longer confined to a physical system, but are very complicated socio-technical systems which are governed by the perceptual capability of the operator, controlling the disruption and situational awareness. In that context, the color has a major position within the system to be the "perceptual regulator" that encodes the information, discriminates among categories, places emphasis and directs the operator to respond quickly.

This is most apparent in those high-cognitive-load workplaces. For example:

• As a control room operator, when viewing 8–12 monitor screens at the same time, color helps in establishing visual hierarchy, differentiating critical alerts from others, and reducing reaction time to information when there is limited time. The classifying alarms, warnings and information in color reduces false alarm rates.

• Labels on the production lines using color take some cognitive load out of assembly sequencing, material sorting, quality control points, and debugging processes, therefore reducing the operator's error rate by 27–48%. This effect is particularly salient for limiting visual vagueness and reinforcing standardization in repetitive activities.

• Zoning of storage units and logistics centers by color will decrease picking time by 10–15%, through rapid identification of product categories. Color acts as a signal to the brain, which aids in enhancing spatial memory and optimized route selection.

• The color environment has a profound impact on employee mood, mental resilience, stress level and attention sustainability in the corporate workplace, call center, creative work environments. Warm color palettes can have a greater burst of energy and reactivity in real time, while cool colors have a more favorable effect on tasks that require patience and focus.

The research here is based on a synthesis conceptualization based on combining the chromatic literatures on color and the principles of industrial engineering. Color is not an aesthetics issue, it can be a control for the systems, human-machine relationship and work performance of the systems.

Accordingly, the objective of this paper was to explore the application of color along four main lines:

1. On a systemic basis – how the color impacts the large-scale processes, the layout structures, the visual management techniques and safety of the work.

2. Ergonomic dimension – color-contrast relationships, visual comfort, legibility, perceptual discrimination, and error minimization.

3. Behavioral dimension – How does it induce a motivational behavior change in an employee or employees who are affected in their emotional control, risk perception, and task strategy.

4. Cognitive dimension – How it impacts attention control, short-term memory, visual search efficiency, decision-making speed, and cognitive load.

In line with this concept, this work design proposes a conceptual model for an exploratory investigation of the effect of color parameters such as saturation, brightness, contrast, color hierarchy, saturation balance, area density and light-color interaction on working outcomes. It shows that color is not only aesthetic-induced but also contributes directly to performance, safety, efficiency, and to perceptual ergonomics-related values which are key outcomes in the performance study. This broader perspective would add new layers in academia and to the industry, which in turn give scope for a more systematic, measurable, and design-oriented view of how we approach color for industrial engineering.

2. THE LITERATURE VIEW

2.1 Color Science

The science of color combines many aspects of physics, physiology, psychophysics, and cognitive psychology to offer an in-depth treatment on how color is produced, experienced, and interpreted by people in interaction with the human and physical environment. From an industrial engineering perspective, knowledge of color theory is essential so as to realize the proper visual communication, lower perceptual errors, and provide human cognition-related work environments. The rest of the paper presents a detailed review of the scientific origins of color perception and representation that includes the physical aspects of light, the biological aspects of sight, and the psychology of colour perception.

Color arises through the action of electromagnetic radiation with the human visual system. Light, in the nanometer (nm) region, occupies a narrow band of the electromagnetic spectrum. The region between 380–740 nm is visible, in visual terms corresponds to the wavelengths that human photoreceptors can actually read.

Short wavelengths (400–500 nm) conjure perceptions of blue and violet, mid-range wavelengths (500–600 nm) are greens and yellows, and longer wavelengths (600–700+ nm) generate perceptions of orange and red.The physical properties of light relevant to color science include:

- **Wavelength**: Determines the hue perceived.
- **Amplitude**: Influences brightness or luminance.
- **Spectral composition**: Determines the quality of the color stimulus (pure vs. mixed).

Colors play a critical role in accuracy in industrial environments, where lighting conditions such as correlated color temperature (CCT), spectral distribution, and luminance uniformity significantly affect color-based tasks. To this end, the physical foundations of light are the first building block of color science.

The human eye and brain can recognize colors due to biological processes. The retina, located at the back of the eye, has two basic types of photoreceptors: rods and cones. Rods provide low-light vision without being used to perceive color, and cones allow chromatic discrimination in normal light.

In general human beings have three classes of cones: S-cones, M-cones and L-cones at short, medium and long wavelengths respectively. This trichromatic structure is the physiological underpinning which the Young–Helmholtz trichromatic theory, which is one of the most basic color vision theories has used.

The visual signal processed by these cones is given to the cells known as ganglion, namely, the opponent-process pathways involved in encoding color contrasts as red–green versus blue–yellow. Such a mechanism underlies the Hering Opponent Process Theory and accounts for phenomena such as afterimages and colour constancy.

The biological limitations of the visual system — particularly, contrast sensitivity, visual fatigue, and age-related decrements in color discrimination — are major considerations for color designing in applied contexts such as monitoring control rooms and high precision assembly.

Psychophysics bridges the gap between physical stimuli and psychological experience. Several standardized models quantify how humans experience color:

- **CIE 1931 RGB and XYZ color spaces** introduced quantitative mappings between wavelengths and perceived colors, enabling reproducible color measurement.

- **CIE L*a*b*** and **L*u*v*** models account for perceptual uniformity—ensuring that equal numerical changes correspond to equal perceptual differences.

- The concept of **just noticeable difference (JND)** defines the smallest detectable variation between two color stimuli.

These models are used in industrial engineering to aid with color-coded displays, interface optimization, safety signage design, and quality control in manufacturing. Psychophysical models rely on perceptual thresholds to ensure that critical information is distinguishable under real working conditions.

Color is not only a purely biological or physical matter but also has cognitive and emotional associations that are important. Research about color in environmental psychology showed that it influences mood regulation, attention allocation, memory performance, and decision-making strategies. Colors act as pre-attentive cues; those cues direct visual search within milliseconds without it being processed consciously.

Some of the basic cognitive concepts are:

- Color–attention interaction: Warm colors capture immediate attention; cool colors support sustained focus.

- Color memory effects: high-contrast color schemes maximize recall of visual information.

- Semantic linkages: Colors are semantically linked based on conventions (that is, red signifying danger; green signifying go; blue signifying stability) specific to the context of culture or task.

From a perspective of industrial engineering, it certainly is very relevant to recognize this psychological aspect of the science of color while preparing panels of control, dashboards, hazard warning systems, or spatial zoning systems.

Theoretical backgrounds of color science in general view color as a multidimensional phenomenon with functional implications for systems design. In human–system interaction:

- The physical theory explains how light conditions need to be handled.

- The physiological theory describes the limits of human color discrimination.

· The psychophysical models quantify the thresholds for perceptual accuracy.

· Cognitive principles explain how color modulates attention and decision-making.

These theoretical underpinnings of color science serve to suggest that color is not strictly a discretionary aesthetic matter: color is an interdependent construct informed by physics, biology, cognition, and psychology. So yes — it is why the industrial engineering world simply cannot consider color as a beauty decision alone, i.e., aesthetic decision. In this case, color should be considered a design metric impacting performance, safety, cognitive burden, and human reliability - some results can be measured.

This understanding will improve the accuracy of using color in designing work systems, safety management, ergonomic systems optimization, and human–machine interaction. It is the scientifically validated understanding which lends itself well to how the visual environment is intended to reinforce the limits of human perception, and help maximize performance, decrease errors, and increase operator well-being.

3. COLOR AND HUMAN PERCEPTION: THREE CORE MECHANISMS

The colour influences the way humans perceive, organise and react to visual information as colour operates as a highly efficient cue to the environment which shapes how individuals process information. On a higher level, colour influences the perception of objects and information in the brain in a range of visual ways through three main processes: perceptual segregation, cognitive categorisation and attentional guidance. These processes operate in parallel and interactively, which permit the colour solution to help diminish cognitive load, speed up processing and assist in the response towards high visual demands. The theory derives from decades of empirical research on visual neuroscience, cognitive psychology, and human factors engineering.

3.1. Perceptual Segregation: Color as a Mechanism for Visual Differentiation

Perceptual segregation refers to the visualization process of separating an element from its environment, which is critical for object detection, visual orientation and quick decision-making. Segmentation in colour is highly potent in this respect, as colour is processed at an early stage of the visual pathway, independently of form or motion (Livingstone & Hubel, 1988). Special channels exist in the human visual cortex for colour-opponent processing where quick discrimination through chromatic contrast is facilitated (Gegenfurtner & Kiper, 2003).

Colour can increase figure-to-ground isolation by allowing a target to stand out against the background. The faintest color difference or even slight change in saturation can set up strong perceptual contours and allow observers to more accurately see and recognize stimuli (Treisman, 1991). In industrial and operational applications, this system is important for discrimination of control elements, identification of hazards or in detecting anomalies in the highly cluttered information environment. Studies in visual search show that color-determined targets "pop out" preattentively, suggesting detection that is much quicker than shape- or texture-based cues (Wolfe & Horowitz, 2004).

Therefore, colour emerges as an affordable and high-bandwidth form of information that improves operational safety and minimises the risk of misperception, especially at high-density communication or time constraints.

3.2. Cognitive Categorization: Reducing Mental Load Through Color-Based Grouping

Color not only plays an aesthetic role in the perceptual space, it further promotes cognition by facilitating coding of perceptual elements. Categorization of cognitive information is the process of organizing stimuli into meaningful clusters, resulting in less information overload and a faster approach to information retrieval (Rosch, 2024). Colour is one of the most primitive and easiest dimensions we humans categorize stimuli based on their relatively intuitive nature which is partially attributed to its close correlation with semantic information and environmental regularities (Regier & Kay, 2009).

Color-based categorization decreases the scale of visual scenes as it permits observers to consider multiple items as a single concept unit. For instance, if any of the products in the same category, (process stage, hazard or workflow) share the same color, users would be able to use colors as shorthand for higher level information. This minimizes the need for ongoing analysis, and cognitive load which is consistent with cognitive load theory (Sweller, 2011).

Color classes in industrial engineering use of design are visual schemas that frame user requirements, enhance organizational predictability and reduce chance of error. Cognitive experiments in human–computer interaction demonstrated that color displays can improve learning speed, improve accuracy and speed up task completion compared with monochromatic ones. Color serves, at its most elemental, as a cognitive scaffold that breaks up information into manageable units and serves both novice and expert information users where decisions are complex.

3.3. Attentional Guidance: Directing Focus Toward Priority Information

Color does more than divide and group visual data: It drives attention. Attentional steering: It is a process by which some visual features attract (or direct) attentional resources to particular spatial locations or object properties (Itti & Koch, 2001). Color has been recognized as one of the best attentional cues owing to its superior discriminability, emotive significance, and the ability to signal urgency or importance (Nothdurft, 2000). Attention can be shaped bottom-up (stimulus-driven) as well as top-down (goal-driven). Color works well in both modes too.

- **Bottom-up:** Highly saturated or contrasting colors automatically attract attention through saliency-map mechanisms in the visual cortex (Itti & Koch, 2001).

- **Top-down:** Users can be trained to associate specific colors with task priorities, such as warnings, system states, or workflow stages. This enables faster attentional shifts and improves situational awareness in high-stakes environments such as manufacturing, healthcare, control rooms, and transportation systems.

Research into warning design indicates that red–yellow combinations produce faster reactions and stronger hazard perception compared with other color pairs (Wogalter & Vigilante, 2006). Likewise, in complex monitoring environments color cues help to reduce missed alerts and enable more accurate threat detection (Yantis & Egeth, 1999).

Through attentional guidance, color functions not merely as a passive property but as an active regulator of human–system interaction.

4. ENVIRONMENTAL IMPACTS OF COLOR USE

Color stands for systematic perceptual contexts where people appraise freshness, safety, focus, calmness, and spatial comfort. In many different places this influences one's experience on affective as well as cognitive and motivational levels which support a significant role played by color in human-environment interaction (Küller, Ballal, Laike, Mikellides & Tonello, 2006). Based on the Mehrabian–Russell (M–R) Emotional Valence Model (Mehrabian & Russell, 1974), the most important theory highlights the emotional role of colors within a physical environment. The structure suggests affective responses through a set of three psychological properties: Pleasure, Arousal, and Dominance (PAD). And how you feel affects whether you approach or avoid a certain environment. Color—a by far one of the most immediate and preattentively processed environmental features—has definite effect on the three PAD dimensions.

4.1. Pleasure: The Affective Tone of Color Atmospheres

It was indicated by the literature that low saturation and cooler colors, notably blue and green colours, are positively associated with pleasantness ratings and lower psychological irritability as well as higher perceived environmental quality (Ou, Luo, Woodcock, & Wright, 2004). Colors linked to both characteristics tend toward calmness, stability, and restoration, all supporting aspects of the attention restoration theory, which postulates that providing mental resources through a naturalistic stimulus is beneficial to cognition (Kaplan & Kaplan, 1989). In organisational settings, high-pleasure colour environments positively influence emotional comfort, in addition to reduced psychological stress and subjective well-being (Küller et al., 2009). For instance, some organizations also exhibit cool and desaturated colours as parts of the workplace, which is said to increase the level of calm and relaxation for employees, leading to greater resilience when it comes to mentally exerting performance on particular activities. However, red or orange have relatively lower pleasure scores as well, which is mostly perceived to be a cue of impatience, alertness, as well as possibly overstimulation. These relationships show that how to adapt color schemes to suit the desired emotional & perceptual goals of the workspace.

4.2. Arousal: Color-Induced Activation and Alertness

The dimension of "arousal" includes the degree of activation or physiological alertness evoked by stimuli in the environment. Color has long been a significant determinant of arousal. Warm colors, in particular red and orange, have consistently been linked to higher arousal responses (manifested as an automatic increase in heart rate, increased levels of activation of one's cortex, and increased vigilance) (Kaya & Epps, 2004).

Due to the degree of arousal, blue and green colors offer less arousal than warm colors; they help to maintain concentration and inhibit cognitive fatigue during prolonged attention tasks (Wexner, 1954; Stone, 2003). This makes them particularly appropriate for environments that stress clarity, strength, and limited distractions — the control room, the analysis station and the office, for example. Arousal thus serves as an intermediary mechanism in which color regulates performance, attention and task engagement. Finally, a relationship between color and arousal in the task–color fit paradigm is crucial. While high-risk operational environments with immediate reaction to cues like these might show a corresponding positive impact through arousal colors to performance, in cognitively taxing or repetitive tasks, such colors also can amplify stress or attentional overload. From this, the arousal dimension within the M–R model supports a need for strategies that design color according to the cognitive demands of the work environment.

4.3. Dominance: Sense of Control, Spatial Influence, and Behavioral Regulation

The third dimension, "dominance," is a person's notion of their status or control in an environment. More recently, with relatively less study than pleasure or arousal, dominance has been associated with environmental characteristics that constrain or empower peoples perceived autonomy. The color affects dominance mainly by its interaction with spatial perception and cognitive structure. (e.g., darker tones and warm tones that are highly saturated could make one feel like one was being forced in order to feel control, subsequently reducing dominance effect on the other side of the scale (Valdez & Mehrabian, 1994). Light, desaturated colors—particularly pastels and neutrals—researchers have found a positive correlation with larger perceived space and room for interpretation, increasing feelings of control. This effect is consistent with architectural psychology findings that lighter spaces are perceived to be more manageable and less oppressive (Flynn, &Spencer, 1977).

In industrial contexts such as control rooms and supervisory workstations, where hierarchically structured control systems exist, dominance-related color effects on environments also become pertinent. A workspace that supports the perception that one can exert dominance can raise decision confidence, reduce stress reactions, and bolster the ability of an operator to sustain situational awareness.

4.4. Integrating Color's Environmental Effects in Work Environments

The PAD (Pleasure, Arousal, Dominance) model shows how colors can influence our behavior.

Empirical Proof of Impact Research applying the PAD model in work settings has empirically confirmed that the color atmosphere truly makes a difference in several key areas:

Firstly perception of Safety: Enhancing environmental safety awareness and hazard perception (Küller et al., 2006).

Cognitive Recovery: Sustaining attention recovery, especially during long and demanding monitoring tasks (Stone, 2003).

Emotional Resilience: Regulating stress in high-pressure environments (Küller et al., 2009).

Lastly motivation: Influencing motivational levels (Ou et al., 2004).

Given to the fact that, color acts as a systemic environmental cue that shapes both how we think and feel. Therefore, integrating color into the workplace should be seen as a science-based engineering decision. It is not a matter of design aesthetics.

5. COGNITIVE ERGONOMICS AND LOAD THEORIES

Color is a major design variable from an ergonomics point of view since it influences encoding, processing, and retrieval of information within complex task environments. Cognitive Load Theory (Sweller, 1988) claims that human working memory is limited and can be overloaded, especially with instructional and operational information in which the organization isn't ideal. In this vein, color aims to diminish extraneous cognitive load by visually separating information components, emphasizing structural relationships, and decreasing the need for effortful visual search. Correct color coding has been shown to speed up information processing and improve schema acquisition by lowering attentional and time demands on task-related cues (de Crook & van Merriënboer, 2007). Color also has a performance benefit by modifying how cognitive capacity is shared across perceptual channels according to the Multiple Resource Theory (Wickens, 2002). Color is processed pre-attentively in the visual system of the brain, reducing competition between processing channels and improving parallel encoding, thus improving monitoring performance in visually dense industrial environments. In multimedia learning studies, the Signaling Effect has also been extensively studied to identify the color cues that orient attention to high-priority elements and improve the efficiency of information selection and organization (Mayer, 2005; Jamet, 2014). As the "visual pointer," color improves attentional coherence and lessens cognitive fragmentation, in particular within multi-step tasks or time constraints. These theoretical perspectives together indicate that color is not only decorative but also a cognitive-ergonomic device, which leads to processing efficiency, less cognitive load, and increased efficiency in task performance in demanding workplaces. Colors are also useful in working posture analysis studies using a video camera. By dressing the employee in different colored clothes, cameras containing sensors in the RGB color space are enabled to distinguish the employee's arms, body and legs (Fığlalı et al., 2015).

6. COLOR AND SAFETY MANAGEMENT

Color is an important feature of industrial safety mechanisms serving as an alert or pre-awareness to the hazard and decision support under time constraint. International standards like ANSI Z535, OSHA 1910.145, and ISO 3864 have standardized safety-tone color codes including red for immediate danger, yellow for caution, and the color green for safety or permissible conditions, which refer to the universal perceptual significance of chromatic signals in a dangerous environment (ANSI, 2011; ISO, 2011). It has been demonstrated from empirical work that incorrect interpretation of color-based signage results in the greater likely occurrence of accidents; in fact, misconstrual or badly designed, or visually ambiguous safety signs are responsible for around 60% of industrial accidents, frequently due to poor contrast, inappropriate color saturation, or to an excess of other visual signs on the sight (Wogalter & Leonard, 1999; Drury and Dempsey, 2021). Studies of human factors show that red stimuli promote arousal and greater threat detection on the one hand, and yellow increases anticipatory vigilance, correlating color-emotion mappings with hazard messaging needs (Elliot et al., 2007). Incorrect and inconsistent use of these colors can also lead to disordered attentional processing, slow reaction time and cognitive burden and, consequently, inhibit situational awareness—a major safety performance factor in an industrial environment (Lehto & Landry, 2012). Therefore, the performance management of safety is not just a matter of regulatory compliance, but also relies also on the use of perceptual ergonomics to realize that color operates as an unambiguous, intuitive, and hierarchically determined safety cue in complex work systems.

7. SYSTEMIC DIMENSION OF COLOR USE FROM AN INDUSTRIAL ENGINEERING PERSPECTIVE

In the realm of industrial engineering, it is evidently argued that the systemic use of color is instrumental in the creation of workflow efficiency, transparency and coherence of process and control, that is the core of an industrial organization's system in complex, sociotechnical systems. Color acts as a tool used as a visual control system serving to regulate uniform communication between processes, the physical environment and human–machine interfaces. In a lean production setting, for instance, color-coded kanban cards, floor markings, and workflow boundaries function like external cognitive supports in facilitating the elimination of ambiguity and instructing a worker on which work to start or finish based on no direct instruction (Kirjnen, 2007; Galsworth, 2017). At the system level, color improves process visibility, a core principle in industrial visual factory design, by visually making states, categories and priorities detectable and therefore improving system controllability overall (Greif, 2017). Human factors and ergonomic studies indicate that well-designed color coding minimizes search time, improves decision accuracy, and increases situational awareness in high-complexity environments such as control rooms and manufacturing cells (Wickens et al., 2021). Furthermore, the systemic color schemes can be helpful to safety management since systemic color schemes make the hazard communication structures of hazard communication in a single and consistent way over linguistic and cultural communication framework, as required in multinational industrial operations (ISO 3864-1:2011). At the systemic level of analysis, color is thus not only an aesthetic accoutrement but a strategic operational variable that organizes human behavior, communicates system condition information, and improves the uniformity and efficiency of industrial activities.

7.1 Human–Machine Interaction (HMI) Design and Color

Color is an important element of human–machine interaction (HMI) that serves as an informative and perceptual cue that improves the usability, safety, and effectiveness of the system. This is particularly helpful in advanced HMI scenarios composed of control rooms, process monitoring interfaces, and industrial dashboards that introduce operators to multiple visual cues simultaneously. With the use of color strategically, visual differentiation provides rapid insight to critical alerts, operational status, and system hierarchy (Wickens, 2008). Color is an important cue with relevance to the attention of the user because it draws attention to high-priority information, decreasing the potential for the user to overlook and improving situational awareness. Similarly, color coding reduces cognitive load by grouping similar parts of a system together, eliminating the need for additional cognitive resources spent processing information (Sweller, 2011). Additionally, applying color needs to be ergonomic, due to the potential for visual fatigue as well as inappropriate contrasts or saturation leading to misinterpretations or delayed response times (Healey & Enns, 2011). Increasingly, design guidance on HMI design follows standardized color conventions for the color of alarms (red), warnings (yellow), and normal operation (green), aiming to align operator's expectations and perceptual processing capabilities, to reduce errors, and to maximize system efficiency. Accordingly, color theory application in HMI systems becomes more than a decorative feature but a practical tool for better human–system performance in high-risk industrial/technology environments. It has been proven to have very significant advantages to operator action and response times when deployed in data-hungry environments (control rooms, process monitors, dashboards, etc.) with respect to color usage. Color coding accelerates the detection of salient alarms by around 40% and leads to improved accuracy of decision making under high cognitive load (Healey & Enns, 2011). Specifically, red and other high-salience colors, usually used in relation to critical or high-priority alerts, can result in 0.3–0.5-second faster decision-making for quickly identifying critical alarms as compared to low-salience signaling or non-colored cues (Wickens, 2008). These temporal benefits are critical in dynamic industrial contexts where a fraction of a second of input can be a matter of survival at each level of the system. Therefore, color is not only used as a visual embellishment, but also as a perceptual amplifier that enhances attention allocation and curtails the likelihood of overlooking alarms.

7.2. Color Coding in Production Lines and Logistics Systems

In recent years, color coding has become an important tool for visual management in the modern manufacturing and logistics industry to provide a direct input on improving process transparency, error reduction, and operational efficiency. Visual management in lean production processes is dependent on the color-coded signals, labeling, and color markers for visualizing workflow status and priority information. For example, colored Kanban cards enable visualization and lead-time reduction, because operators can immediately determine material requirements, i.e., stock replenishment requirements or production bottlenecks in the flow (Krijnen, 2007). Color coding also shows how lean principles are translating directly into reduced waste at the shop floor level by providing immediate and thorough display of process information for sound decision making. For TPM (Total Productive Maintenance) or self-maintenance strategies, color-coding machine zones or maintenance areas could be used to assist in better tracking machine operation and fault detection. Tagging colors over important parts, points of lubrication, or safety zones, in order to identify their urgency, allow the operator to visually rank the priority maintenance operation by its need, and make visible the performance improvement. Such a visual differentiation, as seen in the study below, reduces detection times for machine faults by 22%, driving both greater uptime with equipment and less unplanned downtime (Rother & Shook, 2003). The importance of color coding extends from manufacturing lines and the warehouse and logistics world. Color-coded shelving or aisle markings helps the decision of where to store items. This visual stratification has not only taken into account warehouse workers but also improves the speed of operation. In the literature, racks made from colored lines have been shown to improve picking speeds, reducing picking times by 10–15%, and up to 30% fewer misplacement errors occurred (Frazelle, 2002). This is especially applicable to large product distribution centers which require a direct separation between storage spaces for efficiency and reducing mistakes. Color coding in production and logistics is an economically highly recommended intervention that takes advantage of the human perceptual function for optimizing system performance. For example, color coding, by linking environmental signals and operator requirements, promotes awareness, simplifies the operational process, and reduces errors in several industrial environments. The findings of this study demonstrate that color should be systematically applicated in engineering as a tool for visual control and as an ergonomic design element.

8. ERGONOMIC DIMENSIONS OF COLOR USE

8.1. Visual Ergonomics

Color plays a crucial role in the practice of visual ergonomics in industries, workplaces, and other settings, where it is directly relevant to clarity, visual comfort, and work execution. An ideal contrast ratio is 4.5:1 between the foreground and background for clarity, which is recommended to optimize readability and alleviate visual burden (Kirkpatrick, 2018). Bad color decisions might give rise to visual fatigue – visual blur, headache, and lack of ability to concentrate on any task for long periods (Healey & Enns, 2011). Bad color combinations not only reduce performance but also aggravate cognitive load, as operators have to constantly piece together relevant information in poor visual conditions. Color is not just the common term of legibility: color is an attentional beacon. Based on the complex operation modes of control rooms and manufacturing stations, the colors guide the operator toward the appropriate instruments, indications, or warning signs. The most effective visual scanning is achievable, and good situational awareness. Pre-attentive processing allows information to be processed by the operator without conscious deliberation; this is an important process for limiting error and improving decision-making (Wickens, 2008) and is one of the ways color design within display interfaces helps in this sense. In turn, improper use of color and too much color could flood the sensory channels, impede attention, and cause an interruptive effect on awareness and monitoring performance. We must come to a realization that ergonomic design colors which are a factor in our comfort are as important to the cognitive efficiency and safety of interactions between human and machine as they are to the comfort factor.

9. BEHAVIORAL DIMENSIONS OF COLOR USE

9.1 Nudge Theory and Color

The importance of color in production organization cannot be underestimated. This scope can be accessed in detail through the foundations of Nudge Theory (Suter, 2008). For example, in the workplace, color highlights points to which we should direct our attention: a button marked red might mean "Check this" or "Pay attention," which provides stimulation even without prompts. Visual pathways with these responses reduce thinking, thus facilitating faster and healthier responses to cues, even in high-stress and multitasking situations (Keller et al., 2011).

9.2 Decision-Making and Risk Perception

Color also has a measurable impact on decision-making behaviours and risk perception. High-salience colours such as red are consistently associated with heightened arousal and heightened attention to potential hazards, thus amplifying risk perception (Elliot et al., 2007).By contrast, cooler colours like blue support analytical reasoning and cognitive control, promoting a deliberative and methodical approach to problem-solving (Mehta & Zhu, 2009). Color effects on this behavior demonstrate that when color schemes are chosen carefully in work surroundings, it can be beneficial not only for cognitive performance but also for safety outcomes through the matching of visual cues with desired psychological and behavioral responses from workers.

10. DISCUSSION AND CONCLUSION

The current study has shown that color may have multidimensional effects on the work performance on an industrial and operational scale. In line with a multidimensional framework, the proposed framework highlights the systemic, ergonomic, behavioral and cognitive levels in a new engineering-based fashion, which directly associates color parameters— including saturation, brightness and contrast— with cognitive load, attention allocation and operator performance. In production lines, warehouses and control areas, color coding has been found to improve workflow visibility, reduce error and speed up task completion. For example, colored Kanban cards can optimize visual control of processes and process clarity, and color-coded machine zones in Total Productive Maintenance (TPM) programs reduce fault detection times by up to 22% (Rother & Shook, 2003). Likewise, in logistics systems color-coded shelving reduces picking time by 10–15% and location errors by about 30% (Frazelle, 2002).

Ergonomically speaking, color contrast and color selection prevent visual fatigue, improve legibility, and aid in attention control, thus translating directly to human performance in highly intricate environments (Healey & Enns, 2011; Wickens, 2008). The behavioral impacts are no less dramatic: color acts as a gentle touch, leading workers to what actions, affecting perception of risk, and improving and speeding up decision making accuracy. Ranging from red colors increase risk awareness through high salience while blue colors permit analytical reasoning and focus through cooler pigments (Elliot et al., 2007; Mehta & Zhu, 2009). When color coding is applied in human-machine interface (HMI) such principle is applicable for quick detection of the alarm detection, heightened awareness of the environment, reduced error detection etc. with up to 40% increase in the key alarm recognition (Healey & Enns, 2011). Collectively, these results suggest that using color strategically as an element of the design, construction, and use of industrial plant in the manufacturing and operation of industrial machinery suggests a cost-effective, efficient and high-impact usage of the use of colour in colour in the design, construction and operation with cost efficiency the implementation of a colour strategy. By increasing the environmental inputs relating to human perceptual, cognitive and behavioral resources, color theory facilitates system efficiency and safety and operator safety and performance based on the optimization of an environmental stimuli with regards to human perception and learning. It is emphasised by the recommended framework that use of colour is seen as essential not only the aesthetic factor but also as an important tool in the optimization of productivity, safety, and cognitive ergonomics and that the employment of colour is the most important factor in modern production and control systems.

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