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An Interval Valued Pythagorean Fuzzy AHP–TOPSIS Integrated Model for Ergonomic Assessment of Setup Process under SMED

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Abstract: Single-minute exchange of dies (SMED) is one of the most significant lean tools which reduces the required time for setup operations. The consideration of appropriate ergonomic interferences during the SMED implementation improves working conditions, productivity, and flexibility. The SMED literature has an opportunity for expansion with ergonomic assessment. Moreover, ergonomic assessment studies have various limitations in terms of a broad hierarchy of ergonomic factors and their weighting. Therefore, this study enriches the literature by providing the ergonomic assessment of the setup process through integrating multi-criteria decision-making (MCDM) into SMED. In this context, a wide hierarchy of ergonomic risk factors is compiled for ergonomic assessment. The Interval Valued Pythagorean Fuzzy Analytic Hierarchy Process (IVPF-AHP) method is used to determine the weights of factors. Then, Fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is used to prioritize setup tasks in terms of ergonomic factors by using the Interval Valued Pythagorean Fuzzy Sets (IVPFSs). The proposed model was validated by applying it to a real-life manufacturing system in the white goods supplier industry. The application results justify the proposed model with a setup time reduction of 58% and an ergonomic improvement of 19%.

Keywords: SMED; ergonomics; human factors; Pythagorean fuzzy numbers; AHP; TOPSIS

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1. Introduction

The setup time is defined as the period between the end of the last product generated and the first product manufactured in the next batch [1]. Lean production entails setup time reduction to meet customer requirements effectively in a short period of lead time. Setup time reduction is an effective way of shortening lead time with small batches [2]. Single-minute exchange of die (SMED) methodology is used to reduce setup time within lean manufacturing [3,4]. SMED was developed by Shingo [5] at Toyota [6]. SMED is a lean tool that increases quality and machine availability while reducing scrap, rework, and inventory. The idea of this method depends on performing many setup activities while machine is running as much as possible and simplifying the remaining actions with a smooth production flow [7]. The positive impacts of lean production on working conditions and worker well-being are proven [8]. The same effect is valid for the contributions of SMED to human factors and ergonomics. Shortening the setup time within SMED implementation creates an opportunity for interference with occupational accidents, injuries, and work-related musculoskeletal disorders (MSDs), due to the lack of continuous improvements, loss of flexibility, and low efficiency. The European Agency for Safety and Health at Work (EU-OSHA) has addressed that work-related MSDs affect millions of workers and cost employers billions of euros throughout Europe. For conventional SMED, the primary purpose of evaluating setup activities is the reduction of costs by shortening their times. However, in addition to shortening setup time, ergonomically addressing setup activities is an important issue for action plans. Therefore, the aim of this study is to reduce the required time for setup tasks and improve working conditions by providing an approach including IVPF-AHP–TOPSIS integrated model and SMED.

There is a symbiotic relationship between worker satisfaction and organizational performance [9]. This relationship is grounded in human–machine symbiosis that has some benefits, such as human well-being, manufacturing flexibility, as well as human and machine capacity development [10]. Worker requirements and health directly affect the success of SMED activities in the sense of sustainability and efficiency. Moreover, the harmonization of the conflicting ergonomic and economic objectives should be ensured for both human and efficiency aspects [11]. Thus, a human-centric approach to conventional SMED requires new attention [6]. For this purpose, ergonomics should be addressed to design a setup process that optimizes the workers' well-being and the overall performance of the setup organization. Operators are exposed to different levels of risk when performing setup tasks that have different characteristics. The evaluation of each setup task with respect to ergonomic risk factors is a separate and unique problem that needs to be resolved using comprehensive risk assessment methods. In case of detecting serious level ergonomic risk of some setup tasks, suggestions can be implemented as soon as possible.

According to the EU-OSHA, various risk factors including physical and biomechanical factors, organizational and psychosocial factors, and individual factors cause work-related MSDs and disabilities. Likewise, the exposure levels to ergonomic risk of setup tasks may vary according to physical, cognitive, and organizational ergonomic factors. For instance, while a setup task may have a catastrophic level of risk related to physical factors, another task may have a high level of risk related to cognitive factors such as mental fatigue. Therefore, the broad hierarchy of ergonomic risk factors provides the basis for a holistic method for reducing or even eliminating any ergonomic risks that may occur during a changeover process. Additionally, the aforementioned risk factors can cover different industries and research areas.

Conventional ergonomic risk assessment methods handle all risk factors with at the same weight. According to Ahmadi et al. [12], the most important ergonomic risk factors are posture, force, and repetition. The biomechanical, anatomic, and physiologic effects of risk factors on the body are different in cases of prolonged exposure to awkward posture, poor environmental conditions, improper work safety, and high mental fatigue. For example, there is a difference between effects on the neck and elbow during awkward postures where both the neck and elbow are flexion. The fact that the risk of neck flexion may be more dangerous than that of elbow flexion is neglected in conventional methods. Therefore, the importance coefficient of the risk factors should be considered in ergonomic assessment.

Ergonomic assessment of the setup process is a difficult and complicated process; various criteria, some of which may conflict and compete, should be considered, and thus prioritization of setup tasks with their improvement actions for the manufacturing system can be regarded as an MCDM problem. Manufacturers should assess workers' health and working environment well and quickly be able to improve setup conditions. Since the assessment process consists of mostly subjective judgments of observers or workers, this process contains vagueness and uncertainty. Hence, MCDM methods are effective tools for evaluating and prioritization of setup tasks with respect to a generic view of criteria. Moreover, integrated MCDM methods with fuzzy sets have a strong ability to express information vagueness and impreciseness of the setup process.

Considering the aforementioned observations about the setup time process and ergonomics, integrating the human factors into SMED is quite limited in the current literature. There is no published study considering the ergonomic assessment of the setup process with MCDM methods. With this motivation, this study integrates fuzzy hybrid MCDM methodology and SMED to regularize the setup process from both human and economic aspects. Within the hybrid MCDM methodology, firstly, the weights of risk factors are determined by AHP and then setup tasks are evaluated with respect to predetermined risk factors considering their weights by TOPSIS. TOPSIS is one of the most used MCDM methodologies, and it is convenient to use and has many real world applications [13]. Due to the uncertainty of the ergonomic assessment of the setup process, the evaluation of criteria and alternatives becomes more realistic by using IVPF. Therefore, the IVPFSs have a strong ability to eliminate vagueness and uncertainty in the ergonomic assessment of the setup process caused using net values in AHP and TOPSIS. After the first ergonomic assessment of the setup process, the steps of SMED are performed to reduce the required setup time by improving setup tasks. Then, the improved setup tasks are evaluated by the proposed MCDM model to show the effects of suggestions on the ergonomic condition of the setup process. Consequently, all improved setup tasks are scheduled. The proposed model is validated via an application in white goods supplier industry.

The main advantage of the proposed model is to handle two distinct problems: setup time reduction and a workplace design based on workers' requirements. Thanks to the proposed model, decision-makers have the opportunity to discover and solve more fundamental problems in the setup process. Clear guidance is provided so that decision-makers can differentiate among risk factors, namely, posture, technical factors, work elements, work environment, worker characteristics, safety, and organizational factors. Moreover, this model has flexibility for being applied to various industries.

The rest of this paper is structured as follows. Section 2 presents the literature review. The proposed integrated methodology is introduced in Section 3. The application of the proposed methodology is presented in Section 4. In Section 5, the results and implications are given. Finally, conclusions are presented in Section 6.

2. Literature Review

The overall productivity of any production system may heavily increase with SMED. Therefore, this method has been attracted recently within manufacturing systems [14]. It has been extensively implemented in various industries such as food [15], the Polyvinyl Chloride (PVC) industry [7], automotive [16], plastic injection mold [17], oil and gas [18], electronics assembly [19], producing aluminium profiles [20], barrel making industry [21], and the textile industry [22]. Additionally, some authors have performed literature reviews regarding SMED. A comprehensive literature review was conducted by da Silva and Godinho Filho [1]. Papers have been reviewed with respect to categories, areas, research methods, lean tools, implementation, results, and countries. Godina et al. [14] demonstrated that case studies represent 72.8% of the total and most of studies were published between 2012 and 2017.

SMED is combined with different techniques by adapting to the requirements of the production process and the business itself in previous studies. Lozano et al. [15] benefited from MTBF (mean time between failures) and MTTR (mean time to repair such failure) to evaluate and improve the implementation of SMED-based methodology. Almomani et al. [7] incorporated MCDM techniques for the third implementation phase of conventional SMED to select the best setup technology among available alternatives considering cost, energy, facility layout, safety, life, quality, and maintenance factors. Junior et al. [18] proposed a novel SMED based on a practical application of strategies such as improvements by ECRS (eliminate, combine, reduce, and simplify), standardized work (SW), and OEE (overall equipment effectiveness). They revealed that setup time reduction was promoted with the case study in an oil and gas company.

Simplifying and improving operational setup activities are mostly made by improvements based on machines and the sequence of setup tasks [20]. Since a well-organized workplace will make operations easier for operators, ergonomics and safety issues should be considered in SMED. The consideration of operators has been successfully integrated into SMED in different studies. Fonda and Meneghetti [6] introduced human-centric SMED (H-SMED) to reduce overall setup time. The main difference in H-SMED is to put the human factors in the center of the setup improvement attempts. H-SMED is implemented in eyewear manufacturing. Thanks to H-SMED, operators are exposed to lower levels of fatigue and physical stress when performing the changeover process. Afonso et al. [23]

focused on the setup operations of a molding machine from an ergonomic aspect. They applied distinct ergonomic methods for each critical task because of different inputs and outputs. Boran and Ekincioglu [20] integrated the Sue Rodgers muscle fatigue assessment method into the SMED method to reduce setup time of activities in a factory producing aluminium profiles. They also applied the grey-based Taguchi method to activities unimprovable by this method. Brito et al. [24] integrated ergonomics into SMED to improve the ergonomic conditions of workers and reduce setup time. Cakmakci and Karasu [17] proposed SMED and MTM (method time measurements) integration to focus on the body movement of operators during internal setup activities. This method is applied to rims manufacturing for lorries and midi trucks. Ulutas [25] handled operators' safety and ergonomic principles during SMED implementation in the styrofoam manufacturing process. Yazici et al. [26] implemented SMED-fuzzy FMEA model in the plastic injection molding to prevent problems causing further extension of setup time for internal activities that cannot be converted into external ones. Unfortunately, the aforementioned studies lack a focus on the overall perspective in the context of ergonomics. However, the ergonomic aspect is divided broadly into three domains: physical, cognitive, and organizational ergonomics [27]. Physical ergonomics includes human anatomy and relevant factors. Cognitive ergonomics are related to mental processes and workload. Organizational ergonomics concerns work design, working duration, and teamwork factors.

Setup activities may involve many risks that can affect the operators throughout the changeover process. Therefore, a comprehensive setup activities-based risk assessment for operators is required. In an ergonomic risk assessment, experts evaluate exposure to workplace risk factors for work-related musculoskeletal disorders by measuring various risk factors [28,29]. In the literature, various ergonomic risk assessment approaches are proposed. Conventional ergonomic risk assessment methods employ both different body parts and work elements to determine the risk level. These methods and the risk factors used are summarized in Table 1.

Table 1. Input variables of ergonomic risk assessment methods.

Methods [1]	Body Parts	Work Elements	Ref.
REBA	Neck, Trunk, Arm, Wrist	Force/external load, coupling, muscle activity	[30]
RULA	Upper arms, lower arms, wrist, neck, trunk, legs	Muscle function, Force/external load	[31]
OWAS	Back, arms, legs, head	Load	[32]
OCRA	General posture	Frequency, duration, repetitiveness, recovery period	[33]
EAWS	Postures	Action forces, manual material handling, whole-body risk factors and repetitive loads of the upper limbs	[34]
QEC	Back, shoulder/arm, wrist/hand, neck	Load weight, duration, frequency	[29]

[1] REBA: Rapid Entire Body Assessment, RULA: Rapid Upper Limb Assessment, OWAS: Ovako Working Posture Analyzing System, OCRA: Occupational Repetitive Action, EAWS: The European Assembly Worksheet, QEC: Quick Exposure Check.

Ergonomic risk assessment methods have limitations in focusing on a series of different risk factor types. Since there are different and conflicting ergonomic risk criteria in setup activities, classic ergonomic risk assessment methods cannot be sufficient. In such a situation, the evaluation and prioritization activities are performed using an MCDM approach, which is a branch of operation research and a systematic procedure of decision-making in complex problems [35]. Additionally, these methods are applied observationally, including in assessments of the observer or worker [28]. Since they are insufficient in the quantification of imprecise and subjective linguistic expressions, fuzzy MCDM methods are suggested [36]. Several articles exist to select the best ergonomic solution considering risk criteria and production performance. Gul et al. [35] weighted five risk parameters and prioritized 12 hazard types in each department of a hospital by applying the Fuzzy Analytic Hierarchy Process and the fuzzy Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) respectively. Li and Zhu [37] performed risk analysis of human error concerning user experience of interactive systems using Failure Mode and Effect Analysis (FMEA). Then, TOPSIS is used to prioritize the risk factors of the error. Ahmadi et al. [12] presented an approach to prioritize the measure of the ergonomic checkpoints using Analytic Network Process (ANP) and Fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) methods. They compared the risk factors of the solutions with respect to five ergonomic risk criteria in an assembly and packaging industry. Rossi et al. [38] implemented AHP with the aim of choosing the optimal alternative for material handling from the ergonomic and production points of view. A detailed literature review was performed to construct the hierarchy that includes a goal and three levels of risk criteria. However, they have not employed the fuzzy logic. Another study dealing with ergonomic risk assessment for manual material handling systems was proposed by Delice and Can [28]. They determined workers who are exposed to the highest ergonomic risk level considering two criteria sets as lifting-related and human-related criteria with multi-objective optimization.

Based on a comprehensive literature review, a comparison of the existing studies and the proposed study in terms of various aspects is summarized in Table 2. The proposed study differs from the existing studies in the relevant literature. Additionally, the following research gaps have been observed:

1. The harmonization of the conflicting ergonomic and economic objectives is still underrepresented in conventional SMED approaches;
2. The literature of conventional ergonomic assessment methods has a limitation of considering and weighting risk factors in a holistic manner;
3. MCDM implementations related to ergonomic assessment have not been performed for the setup process;
4. Extending IVPF-AHP with IVPF-TOPSIS has not been proposed to solve an ergonomic assessment problem.

Table 2. The comparison of the existing studies and the proposed study.

Aspects	**[7,16,18,19,21,22]**	**[6,17,20,23–26]**	**[29–34]**	**[12,28,35,37,38]**	**The Proposed Study**
Broad hierarchy of ergonomic factors	-	-	-	- (Except [12,38])	✓
Weighting the ergonomic factors	-	- (Except [26])	-	✓	✓
Handling both ergonomic and economic aspect	-	✓	-	- (Except [38])	✓
Ergonomic assessment method	-	✓	✓	✓	✓
Use of SMED	✓	✓	-	-	✓
Use of MCDM	-	-	-	✓	✓

This study contributes to the relevant literature by integrating a hybrid MCDM technique into a SMED tool so that setup tasks can be evaluated according to ergonomic risk factors and setup time can be reduced. A hybrid MCDM method consisting of AHP and TOPSIS under IVPFSs is combined under SMED approach for the first time. Ergonomic risk criteria are extended to reveal a more comprehensive and sensitive risk evaluation model.

3. The Proposed Model

The proposed model incorporates MCDM methods into the conventional SMED model to provide a more sensitive analysis balancing both setup time reduction and ergonomic attributes. The flow of the proposed model is given in Figure 1. It will be meaningful to emphasize critical points within the proposed model. The proposed model is initiated by identifying the current state of the setup process. The ergonomic perspective is addressed for ergonomic exposure assessment of the overall process in the second step. Ergonomic assessment is performed by the integration of IVPF-AHP (for weighting ergonomic factors) and IVPF-TOPSIS (for evaluating setup tasks). The aforementioned step is the core of this study in terms of contribution to the relevant literature. Then, the classic steps of SMED are included to provide improvement for the future state of the setup process (Step 3.1 and Step 3.2). After, Step 2.3 is reactivated for the future state in Step 4. Finally, the improved schedule including the sequence of setup tasks and their revised time requirements is determined in Step 5.

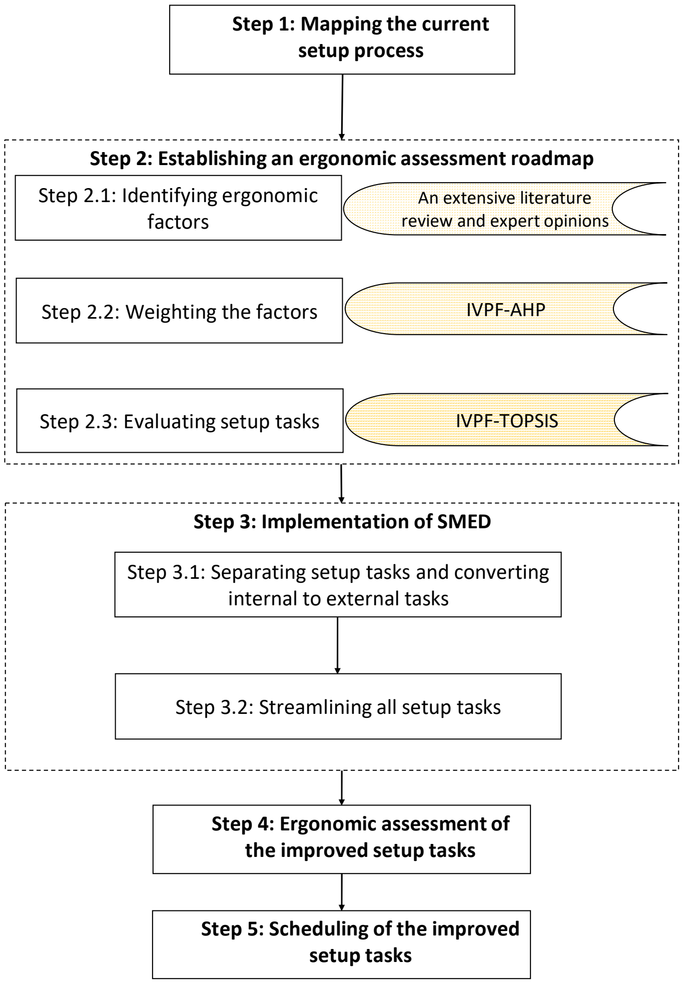


Figure 1. The proposed integrated SMED-fuzzy MCDM procedure.

Step 1: Mapping the current setup process.

The goal of this step is to present all setup activities performed. Line supervisors and operators can be involved in gathering information and data about the setup process in this step. The process is recorded to state setup tasks, their time, and sequence by performing time and motion studies [39].

Step 2: Establishing an ergonomic assessment roadmap.

This step is proceeded to improve the working condition by reducing non-ergonomic conditions of the setup process. Therefore, MCDM is employed to assess and prioritize setup tasks with respect to ergonomic factors. A higher score makes the setup task serious with respect to ergonomics and suggestions for mitigation and prevention deserve the highest priority.

Step 2.1: Identifying ergonomic factors.

The proposed model involves various ergonomic factors that affect the setup process. As a result of an extensive literature review, ergonomic factors are compiled within two levels, as can be seen in Figure 2. The first level consists of seven main criteria: namely, posture, technical factors, working environment, worker characteristics, work elements, safety, and organizational factors. There are 37 sub-criteria at the bottom of the hierarchy.

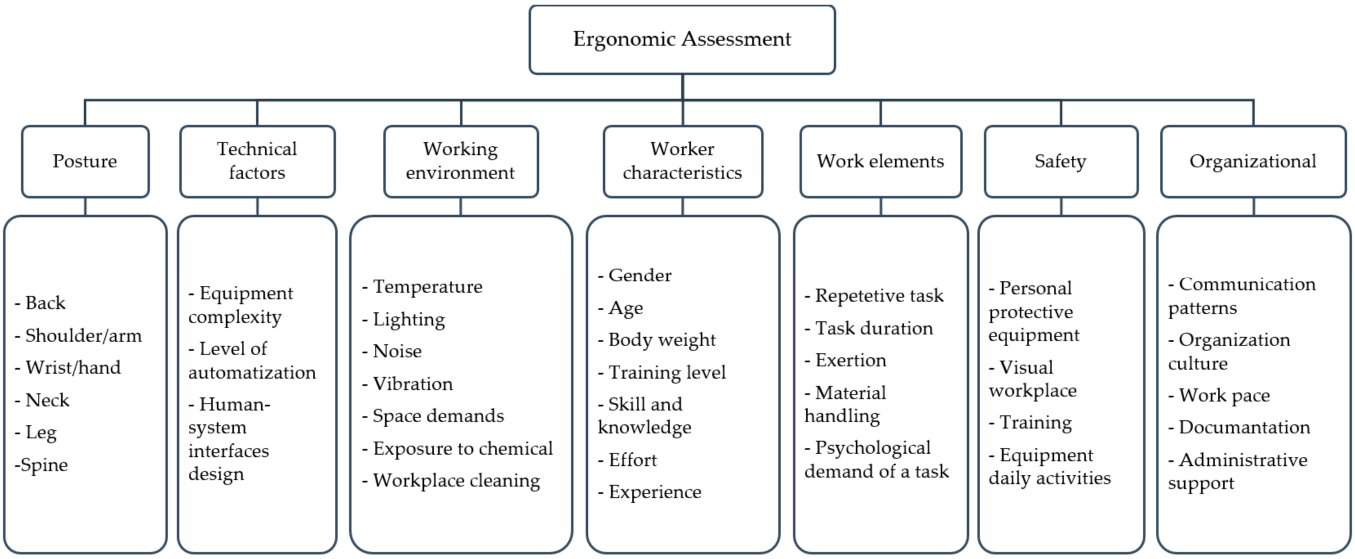


Figure 2. The structure of criteria associated with ergonomic.

Sub-criteria that directly affect the ergonomic risk level logically represent the main criteria of the hierarchy. Changeover processes, as in most business systems, have risk factors such as human aspects and relevant technical factors, as well as environmental, organizational and task characteristics. Therefore, a holistic perspective is necessary to understand the nature of the setup process and to eliminate its risk factors. Comprehensive research is carried out to identify risk factors that can influence the ergonomic risk. In this context, each sub-criteria are provided and defined in Table 3.

Table 3. Summary of ergonomic risk factors.

Risk Factor	Reference	Description	Ergonomic Assessment Method
Posture			
Back	[29]	A part of trunk	QEC
Shoulder/arm, Wrist/hand	[29]	Upper limb	QEC
Neck	[20]	A part of head	MFA [1] and SMED
Leg	[20]	Lower limbs	MFA [1] and SMED
Spine	[30]	A part of trunk	REBA
Technical factors			
Equipment complexity	[40]	Complexity of their technologies that the organization uses to achieve its mission	FAHP
Level of automation	[41]	Separation between operators and the work; if it is increased, operators control system with physically less and mentally more demanding	-
Human–machine interface	[41,42]	Manual handling of function keys, pushbuttons, switches, and valvesequipment obsolescence/conservation	AHP and Fuzzy Logic

Table 3. *Cont.*

Risk Factor	Reference	Description	Ergonomic Assessment Method
Working Environment			
Temperature	[43]	Exposure to temperature	Review
Lighting		To be maintained in a range depending on the type of work being carried out	Review
Noise	[43]	Limits for noise pressure accumulated by workers	Review
Vibration	Expert view	Duration of exposure to whole body vibration and hand-arm vibration	-
Space demands	[42]	Physical constraints of workspace	AHP and Fuzzy Logic
Exposure to chemical	[44]	Exposure to hazards chemicals in the workplace	Chebyshev goal program
Workplace cleaning	[42]	Disposing the litter and waste and cleaning surfaces, equipment regularly	AHP and Fuzzy Logic
Worker characteristics			
Gender	[45]	Demographic characteristic, indicates men or women worker	Questionnaire
Age	[45]	Demographic characteristic,	Questionnaire
Body weight	Expert view	Worker's mass or weight	-
Education	Expert view	Educational stages	-
Skill and knowledge	[46,47]	Proficiency at following a given method	Fuzzy Logic, Integer Programming
Effort	[46]	The will to work	Fuzzy Logic
Experience	Expert view	Duty period	-
Work elements			
Repetitive task	[43]	The number of repetitions of the same job	Review
Task duration	[48]	The difference between the final and start time of a task	NIOSH [2] and OCRA
Exertion	[48]	Force necessary to perform a task	NIOSH [2] and OCRA
Material handling system	[49]	Handling system of the product or work in process in the system	Fuzzy MCDM
Psychological demand of a task	[49]	Interpersonal relationships, psychological resilience	Fuzzy MCDM
Safety			
Personal protective equipment	[12]	To minimize exposure to hazards	ANP and Fuzzy DEMATEL
Visual workplace	Expert view	Graphic designs to facilitate attention, understand system, risks and dangers, operations' start-up, control, and interruption	-
Training	[40]	Specific information and recommendations on how to implement the risk assessment	FAHP
Equipment daily activities	Expert view	Responsibility of operator on cleaning, lubricating and tightening of their equipment	-
Organizational factors			
Communication patterns	[12,50]	Communications channels, coordination between departments, shifts and interpersonal communication and understanding	ANP and Fuzzy DEMATEL, Review
Organizational culture	[51]	The pattern of values and norms that guide employees' behaviour	Questionnaire
Work pace	[40]	Break times	FAHP
Documentation	[15,40]	Communicable materials to explain and continue for the system	- FAHP
Administrative support	[15]	Administrative control system to minimize exposure to hazards	-

[1] MFA: Muscle Fatigue Assessment, [2] NIOSH: National Institute for Occupational Safety and Health.

Awkward or prolonged situations can increase risk factors for work-related MSDs since the load on body parts increases with greater flexion, extension, hyperextension, lateral bending, or axial twisting [29,43]. So, there is a link between workers' posture and risks of injuries. Risk factors of posture are divided into six body segments: back, shoulder/arm, wrist/hand, neck, leg, and spine. The reliability of ergonomic risk assessment methods highly depends on the correct determination of the joint angles for the body parts at different postures [52].

Technical factors in work systems should ensure adequate response to human capabilities and limitations [41]. Therefore, their potential effects on ergonomic risk are not neglected [53].

Working environment is important for workers when performing a task. Temperature, lighting, noise, and vibration level required may vary according to tasks. Therefore, the risk levels on setup tasks also differ.

Worker strain for a particular task is not the same for all workers [47]. Individual characteristics such as age, gender, and diversity can make a difference in how workers perform in their task [53]. Considerable variations may occur in the exposure level to risk among workers [45]. It is demonstrated that the women can be at higher risk than men for a particular task. Therefore, individual difference factors should be considered when assessing risk factors.

Physical and cognitive capability of workers depends on undertaking physical and mental work elements, respectively [41]. There is strong evidence that a slight change in the level of any work elements affects the ergonomic risk [36]. Workers' exposure to risk varies according to the physical workload of a task. For instance, if a task is highly repetitive and has a short duration, workers may barely focus on their attention for that task [47]. Therefore, their exposure level to risk is likely to be high. Moreover, as can be seen in Table 1, most of the conventional ergonomic assessment methods include these factors as the main criteria.

Safety and organizational factors affect the ergonomic risk level of tasks [50]. High organizational well-being leads to productive workers and improved working conditions. A safe working environment ensures workers' well-being and health.

Step 2.2: Weighting the risk factors.

The effects of each risk factor may differ to determine the risk levels of tasks. Therefore, the weights of these main and sub-risk factors should be determined. For this purpose, IVPF-AHP method is employed. This step is addressed for the difference in weights among risk factors.

Atanassov [54] propose extension of ordinary fuzzy sets and Intuitionistic Fuzzy sets (IFSs). Then, Yager [55] improves IFS2 as Pythagorean fuzzy sets (PFSs). PFSs accomplish the duality property of IFSs and examines an evaluation of membership degree and non-membership degree. In case of $(\sqrt{3/2})^2 + (1/2)^2 \leq 1$ and $\sqrt{3/2} + 1/2 \geq 1$, IFSs cannot define this situation. PFSs as a new generalization of IFSs and FSs utilize successfully corresponding case [56].

Definition 1. *Let a set X be a universe. A PFS P is an object having the form [57,58]:*

$$P = \left\{ \left\langle x, P\left(\mu_{P(x)}, v_{P(x)}\right) \right\rangle \middle| x \in X \right\}, \tag{1}$$

where $\mu_{P(x)} : X \to [0,1]$ *shows the degree of membership and* $v_{P(x)} : X \to [0,1]$ *shows the degree of non-membership of the element* $x \in X$ *to P, respectively, and, for every* $x \in X$*, it holds:*

$$0 \leq {\mu_{P(x)}}^2 + {v_{P(x)}}^2 \leq 1, \tag{2}$$

For any PFS and $x \in$, $\pi_{P(x)} = \sqrt{1 - \mu_{P(x)}^2 - v_{P(x)}^2}$ *defines the degree of indeterminacy of x to P.*

Definition 2. *An IVPFS A can be defined in X as [59,60].*

$$A = \{\langle x[\mu_{A_L}(x), \mu_{A_U}(x)], [v_{A_L}(x), v_{A_U}(x)]\rangle; x \in X\}, \tag{3}$$

where

$$0 \leq \mu_{A_L}(x), \mu_{A_U}(x), v_{A_L}(x), v_{A_U}(x) \leq 1, \text{ and } \left(\mu_{A_L}(x)\right)^2 + \left(v_{A_L}(x)\right)^2 \leq 1 \ \ x \in X, \tag{4}$$

Similar to PFSs, the degree of indeterminacy is calculated

$$\pi_A(x) = [\pi_{A_L}(x), \pi_{A_U}(x)] = \left[\sqrt{1 - (\mu_{A_U}(x))^2 - (v_{A_U}(x))^2}, \sqrt{1 - (\mu_{A_L}(x))^2 - (v_{A_L}(x))^2}\right], \tag{5}$$

Definition 3. *The score* ($\mathbb{S}^\circ$) *and normalized score* ($\mathbb{S}^*$) *functions for IVPF number* $\alpha = ([\mu_{A_L}, \mu_{A_U}], [v_{A_L}, v_{A_u}])$ *are given below* [61]:

$$\mathbb{S}^\circ(\alpha) = \frac{(\mu_{A_L})^2 + (\mu_{A_U})^2 - (v_{A_L})^2 - (v_{A_u})^2}{2}, \tag{6}$$

$$\mathbb{S}^*(\alpha) = \frac{1}{2}(\mathbb{S}^\circ(\alpha) + 1), \tag{7}$$

Definition 4. *The distance measure between two IVPF numbers* $\alpha = ([\mu_{A_L}, \mu_{A_U}], [v_{A_L}, v_{A_u}])$ and $b = ([\mu_{B_L}, \mu_{B_U}], [v_{B_L}, v_{B_u}])$ *can be defined as follows* [62].

$$d(\alpha, b) = \frac{1}{4}\left(\begin{array}{c} \left|\mu^2_{A_L} - \mu^2_{B_L}\right| + \left|\mu^2_{A_U} - \mu^2_{B_U}\right| + \left|v^2_{A_L} - v^2_{B_L}\right| \\ + \left|v^2_{A_U} - v^2_{B_U}\right| + \left|\pi^2_{A_L} - \pi^2_{B_L}\right| + \left|\pi^2_{A_U} - \pi^2_{B_U}\right| \end{array} \right), \tag{8}$$

After determining the fuzzy set, AHP determines the weights of criteria by performing pair-wise comparison between criteria [63]. Definition of IVPF is used to present the real case of problems as it involves the uncertainty in linguistic judgments. However, crisp AHP cannot compute this situation. The application steps of IVPF-AHP are given below:

Step 2.2.1. Compromised pairwise comparison matrix $R = (r_{ik})_{m \times m}$ with respect to criteria is constructed using the linguistic terms and their abbreviations given in Table 4.

Table 4. Weighting scale for the IVPF-AHP.

Linguistic Terms	IVPF Numbers			
	μ_L	μ_U	v_L	v_U
Extremely Low Importance—ELI	0.00	0.00	0.90	1.00
Very Low Importance—VLI	0.10	0.20	0.80	0.90
Low Importance—LI	0.20	0.35	0.65	0.80
Below Average Importance—BAI	0.35	0.45	0.55	0.65
Equal Importance—EI	0.45	0.55	0.45	0.55
Above Average Importance—AAI	0.55	0.65	0.35	0.45
High Importance—HI	0.65	0.80	0.20	0.35
Very High Importance—VHI	0.80	0.90	0.10	0.20
Extremely High Importance—EHI	0.90	1.00	0.00	0.00

Step 2.2.2: The differences matrix $D = (d_{ik})_{m \times m}$ is determined between lower and upper values of the membership and non-membership functions based on Equations (9) and (10):

$$d_{ikL} = \mu^2_{ikL} - \vartheta^2_{ikU}, \tag{9}$$

$$d_{ikU} = \mu^2_{ikU} - \vartheta^2_{ikL}, \tag{10}$$

where m is the number of criteria.

Step 2.2.3: The interval multiplicative matrix $S = (s_{ik})_{m\times m}$ is determined based on Equations (11) and (12):

$$s_{ikL} = \sqrt{1000^{d_{ik_L}}}, \tag{11}$$

$$s_{ikU} = \sqrt{1000^{d_{ik_L}}}, \tag{12}$$

Step 2.2.4: The determinacy value $\tau = (\tau_{ik})_{m\times m}$ of the r_{ik} is calculated based on Equation (13):

$$\tau_{ik} = 1 - \left(\mu^2_{ikU} - \mu^2_{ikL}\right) - \left(v^2_{ikU} - v^2_{ikL}\right), \tag{13}$$

Step 2.2.5: The determinacy degrees with $S = (s_{ik})_{m\times m}$ matrix for obtaining the matrix of weights, $T = (t_{ik})_{m\times m}$ is multiplied according to Equation (14):

$$t_{ik} = \left(\frac{s_{ikL} + s_{ikU}}{2}\right)\tau_{ik}, \tag{14}$$

Step 2.2.6: The normalized priority weights w_i is calculated based on Equation (15):

$$w_i = \left(\frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{ik}}\right)\tau_{ik}, \tag{15}$$

Step 2.3: Evaluating setup tasks.

Each setup task may have different characteristics and occurrence of one or more risks. Therefore, the evaluation of each defined ergonomic risk factor for every setup task is performed by decision-makers. The TOPSIS methodology is applied under IVPFSs to prioritize setup tasks. TOPSIS methodology considers both positive-ideal and negative-ideal solutions in decision-making [64,65]. TOPSIS outshines with computational simplicity and flexibility to integrate with different areas. The application steps of IVPF-TOPSIS are given in the following steps.

Step 2.3.1: IVPF number-based decision matrix $R = \left(C_j(x_i)\right)_{m\times n}$ is computed using the linguistic terms given in Table 5 [66], where n is the number of alternatives. $C_j = (j = 1, 2, \ldots, m)_{m\times n}$ and $x_i(i = 1, 2, \ldots, m)_{m\times n}$ represent values of criteria and alternatives.

Table 5. Linguistic terms to evaluate setup tasks.

Linguistic Terms	IVPF Number			
	μ_L	μ_U	v_L	v_U
No relation—NO	0	0	1	1
Extremely Low—EL	0.03	0.16	0.74	0.87
Very Low—VL	0.12	0.25	0.5	0.78
Low—L	0.21	0.34	0.56	0.69
Medium Low—ML	0.3	0.43	0.47	0.6
Middle—M	0.38	0.51	0.38	0.51
Medium High—MH	0.47	0.6	0.3	0.43
High—H	0.56	0.69	0.21	0.34
Very High—VH	0.65	0.78	0.12	0.25
Extremely High—EH	0.74	0.87	0.03	0.16

Step 2.3.2: The positive ideal points (A^+) and negative ideal points (A^-) are defined based on normalized score function:

$$\mathrm{A}^+ = \left(\left[\left\{\max_i \mu_{ijL}\left(\widetilde{P}^*\right), \max_i \mu_{ijU}\left(\widetilde{P}^*\right)\right\}\right], \left[\left\{\min_i v_{ijL}\left(\widetilde{P}^*\right), \min_i V_{ijU}\left(\widetilde{P}^*\right)\right\}\right]\right)_{1xn} \tag{16}$$

$$\mathrm{A}^- = \left(\left[\left\{\min_i \mu_{ijL}\left(\widetilde{P}^*\right), \min_i \mu_{ijU}\left(\widetilde{P}^*\right)\right\}\right], \left[\left\{\max_i v_{ijL}\left(\widetilde{P}^*\right), \max_i V_{ijU}\left(\widetilde{P}^*\right)\right\}\right]\right)_{1xn} \tag{17}$$

Step 2.3.3: The weighted distances from A^+ and A^- are computed with respect to criteria weights for alternatives:

$$D\left(A_i, \mathrm{A}^+\right) = \Sigma_{j=1}^{n} w_j \left[d\left(A_i, \mathrm{A}^+\right)\right], \tag{18}$$

$$D\left(A_i, \mathrm{A}^-\right) = \Sigma_{j=1}^{n} w_j \left[d\left(A_i, \mathrm{A}^-\right)\right], \tag{19}$$

Step 2.3.4. The closeness coefficient is calculated for each alternative as follows:

$$F_i = \frac{D\left(A_i, \mathrm{A}^-\right)}{D\left(A_i, \mathrm{A}^+\right) + D\left(A_i, \mathrm{A}^-\right)}, \tag{20}$$

Step 2.3.5. The alternatives are ranked in the descending order. In this study, we determine the riskiest task with the highest F_i value.

Step 3: Implementation of SMED.

SMED makes it possible to execute equipment setup in a single-digit number of minutes so that good performances in a changeover process can be achieved [39]. Conventional SMED steps developed by Shingo [5] are implemented under this step and detailed explanations are given in the following sub-steps.

Step 3.1: Separating setup tasks and converting internal to external tasks.

This step is initiated by distinguishing internal and external setup tasks using tools such as check lists and function checks. Internal setup tasks are performed only while the machine is stopped. External ones are performed while the machine is running. Tools and components should be ready ahead of time before starting setup tasks and the replaced parts should be back in the storage area after running the machine. After the classification, the aim is to increase, as much as possible, the number of setup tasks that can be carried out externally. In addition, it is appropriate to make the adjustments in the tool assembly settings, if possible, in the external time. Obviously, the machine must not be stopped just to use the machine table.

Step 3.2: Streamlining all setup activities.

Improvements are handled by evaluating both the internal and external activities in this step [5]. Action plans for shortening the setup time are common attempts for this purpose. Especially, setup tasks with high risk levels can be elaborated on to improve working conditions. Numerous lean tools and techniques contributing to improving the setup process are suggested. Setup workers can be employed to reduce setup time [67]. Two or more operators may perform the setup task in parallel. In addition, waste such as walking, transporting, and relocating by a single operator can be eliminated by using the tool kit area. Visual management during the setup process is ensured by colour and digital coding distinguishing similar components. Technical modifications, training within industry, and standardization can be counted as alternative solutions for streamlining activities [23,68]. Mechanizations should be established to shorten the transition time from one mould to another. Multi-process and feeding systems save time for internal and external tasks such as disassembly, transportation, and loading by performing sequential operations in a mould or equipment.

Step 4: Ergonomic assessment of the improved setup tasks.

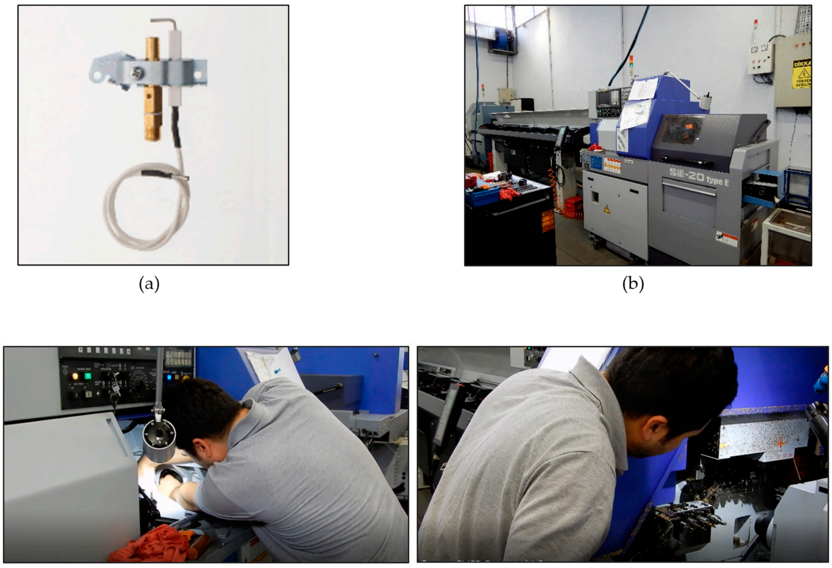
The third step of the proposed model is an ergonomic assessment of setup tasks after regularizations of the setup process and implementation of suggestions. The positive or negative ergonomic impacts of suggestions on setup tasks are obtained by employing this step. The SMED implementation phase is investigated according to whether it is sufficient on the basis of setup tasks. Appropriate interventions are made for non-ergonomic work conditions. If the setup process is optimal, the final step of scheduling can be executed.

Step 5: Scheduling of the improved setup tasks.

A scheduling methodology for setup tasks should not be developed unless the analysis of the setup process is performed. Therefore, scheduling is the last complementary step in the proposed methodology. It is the scheduling of when the machines will go into the setup process and the planning of which task will be performed during the setup process. Freeing of additional workers for parallel tasks, keeping special tools ready, availability of material handling vehicles when requested, and waiting times in the setup process are critical elements of this step. There are two types of setup time: sequence-independent and sequence-dependent setup time. Since sequence-dependent setup time which grounds on both the task to be processed and the immediately preceding task, it is one of the most considerable issues to be considered when reducing setup time. After scheduling, it will be useful to prepare equipment and tool requirements lists supported by market research and the determination of total cost for SMED application. In this list, the tool item, quantity, and position should be stated.

4. Application

The proposed approach was applied for the goods supplier industry. The company was established in Turkey as a manufacturer and supplier of piezo igniters. The products consist of eight main groups: Pilot Group, Electrode, Thermocouple, Electrical Igniters, Battery Igniter, Piezo Igniter, Gas Nozzle, and Microswitch. In this study, the setup process analysis of the gas safety valve part, the component of the source gas heater thermocouple pilot group product family, was handled in the CNC Swiss-type machining (Figure 3).



(a) (b) (c) (d)

Figure 3. (**a**) Source gas heater thermocouple pilot group, (**b**) Swiss-type CNC, (**c**) checking tool chuck, and (**d**) counting samples.

4.1. Step 1-Mapping Current Setup Process

In the first main stage of the proposed model, the time and motion study were performed to examine the setup process. Videos of complete setup process were recorded two times, including different shifts. Several meaningful screenshot pictures of the setup process video are shown in Figure 3 to illustrate the setup process more clearly. Regular informal observations and dialogues with the operators and production supervisor contributed to the analysis. Thus, the complete setup task list for the current state, along with their descriptions and time is presented in Table 6.

Table 6. Setup process analysis.

Machine: SB20E				Previous Part: YV-05-10			Next Part: AK-04-43
Task No.	Description	For Current State		Task No.	Description	For Current State	
		Time	Task Type			Time	Task Type
T-1	Bring the tool car	1.5	Internal	T-17	Remove the upper housing cover from the tool carriage and install it	0.5	Internal
T-2	Search workpiece and bring it near to machine	0.5	Internal	T-18	Disassembly guide bush	0.2	Internal
T-3	Change the jaws	3	Internal	T-19	Clean and lubricate guide bush nut	0.6	Internal
T-4	Place the back chocks	0.5	Internal	T-20	Clean fixed guide bush	1	Internal
T-5	Tighten the wedges and attach the cover with 2 screws	2.6	Internal	T-21	Disassembly the collet casings	0.6	Internal
T-6	Clean the stand	1.7	Internal	T-22	Change ejection pin	4.4	Internal
T-7	Remove the main spindle (head 1) cover	0.6	Internal	T-23	Adjust of collet for Head 2	2.2	Internal
T-8	Bring tools to the operation area	0.5	Internal	T-24	Disassembly the previous cutting tool	3	Internal
T-9	Search and bring copper wedges	0.5	Internal	T-25	Clamp and reset cutting tool	5	Internal
T-10	Clean and lubricate main spindle	2.5	Internal	T-26	Reset the tool	0.5	Internal
T-11	Clean the sleeve on the tool car	0.7	Internal	T-27	Clean with air and check tool chuck	1.5	Internal
T-12	Bring and place lubricate closer with the stand	1.0	Internal	T-28	13 samples count and program revision	37.2	Internal
T-13	Assembly and clean the spindle, sleeve, and collet	1.5	Internal	T-29	Connect side hole of the drill bit	5.8	Internal
T-14	Search for the workpiece and bring it to the stand	0.4	Internal	T-30	Take rear tool	1	Internal
T-15	Install the spindle, sleeve and collet	1.5	Internal	T-31	Connect and reset rear tool	17	Internal
T-16	Adjust the tightness and position of the Head 1 collet	3.7	Internal	T-32	5 samples count and program revision	34	Internal
Total required time for current state of setup process: *137.2 min*							

Recorded videos were examined to determine the time for each setup task time and to map the current state. The setup process was decomposed into 32 setup tasks. The total duration of the setup process was 137.2 min with one operator.

4.2. Step 2-Establishing the Ergonomic Assessment Roadmap

In the second step, the integrated IVPF-AHP and IVPF-TOPSIS method was applied to examine the potential ergonomic risk score of setup activities. As a result of an extensive literature review, ergonomic risk factors are presented in Section 2. The remainder flow of the proposed procedure is explained in the following subsections.

4.2.1. Weighting the Risk Factors

Five experts were consulted as decision-makers to determine weights of ergonomic risk factors. The first expert is the chief labour inspector who is in charge of examining labour laws and standards. The second, third, and fourth experts are occupational health and safety specialists who inspect working environments, design preventative programs for worker safety, examine incidents and identify causes, and train workers for emergencies. The last expert is an academic who has scientific expertise in ergonomics. As a result of the surveys conducted by meeting with the experts, their evaluations for the criteria are obtained.

The opinions from the experts were used to evaluate the main and sub-risk criteria. For this purpose, linguistic terms given in Table 4 were used to compare criteria. Therefore, pairwise comparison matrices were structured for both main and sub-risk factors by each expert. As an example, the pairwise comparison matrix for the main risk factors by Expert-3 is presented in Table 7. The pairwise comparison matrix for the sub-risk criteria of C1-Posture main criterion was constructed according to the opinions from by Expert-2 is presented in Table 8. In Table 9, the pairwise comparison matrix for the sub-risk factors of the C7-Organizational main criterion for Expert-1 is presented. Other evaluations cannot be presented in this study due to page limitation.

Table 7. Pairwise comparison matrix for main risk factors constructed by Expert-3.

	Posture	Technical Factors	Working Environment	Worker Characteristics	Work Elements	Safety	Organizational
Posture	EI	EI	EI	AAI	HI	VHI	VHI
Technical factors	EI	EI	EI	EI	AAI	AAI	HI
Working environment	EI	EI	EI	EI	AAI	AAI	HI
Worker characteristics	BAI	EI	EI	EI	EI	AAI	HI
Work elements	LI	BAI	BAI	EI	EI	AAI	HI
Safety	VLI	BAI	BAI	BAI	BAI	EI	AAI
Organizational	VLI	LI	LI	LI	LI	BAI	EI

Extremely Low Importance—ELI; Very Low Importance—VLI; Low Importance—LI; Below Average Importance—BAI; Equal Importance—EI; Above Average Importance—AAI; High Importance—HI; Very High Importance—VHI; Extremely High Importance—EHI.

Table 8. Pairwise comparison matrix for C1-Posture constructed by Expert-2.

	Back	Shoulder/Arm	Wrist/Hand	Neck	Leg	Spine
Back	EI	EI	AAI	EI	EI	BAI
Shoulder/arm	EI	EI	HI	EI	EI	LI
Wrist/hand	BAI	LI	EI	ELI	BAI	ELI
Neck	EI	EI	CHI	EI	HI	EI
Leg	EI	EI	AAI	LI	EI	EI
Spine	AAI	HI	CHI	EI	EI	EI

Table 9. Pairwise comparison matrix for C7-Organizational constructed by Expert-1.

	Communication Patterns	Organizational Culture	Work Pace	Documentation	Administrative Support
Communication patterns	EI	EI	AAI	LI	AAI
Organization culture	EI	EI	AAI	LI	AAI
Work pace	BAI	BAI	EI	LI	HI
Documentation	HI	HI	HI	EI	CHI
Administrative support	BAI	BAI	LI	ELI	EI

First, all matrices were tested for consistency for each expert. For this purpose, Consistency Ratio (CR) was calculated for each matrix. After all the matrices were regarded as consistent (CR < 0.1), the weight calculation process was started. Then, the weights of the main risks were calculated by applying steps of IVPF-AHP and given in Table 10 for each expert.

Table 10. The weights of main risk factors for each expert.

	Expert-1	Expert-2	Expert-3	Expert-4	Expert-5	Aggregated Scores	Rank
Posture	0.280	0.182	0.376	0.189	0.318	0.269	1
Technical factors	0.077	0.118	0.147	0.103	0.039	0.097	5
Working environment	0.168	0.155	0.147	0.143	0.183	0.159	4
Worker characteristics	0.043	0.173	0.129	0.083	0.036	0.093	6
Work elements	0.105	0.164	0.114	0.239	0.289	0.182	2
Safety	0.303	0.136	0.060	0.165	0.117	0.156	3
Organizational	0.023	0.073	0.028	0.078	0.018	0.044	7

According to the weights given in Table 10, "posture" is the most important main factor for ergonomic risk assessment according to Expert-2, Expert-3, and Expert-5. Furthermore, it was determined as the second most important factors for other experts. Organization was determined as the least important risk factor for all experts.

After determining main risk factor weights, the same steps were repeated for sub-criteria and sub-criteria weights were determined for each expert, as given in Table 11.

Table 11. Sub-risks weights for each expert, the final weight, and rank.

Sub-Criteria	Expert-1	Expert-2	Expert-3	Expert-4	Expert-5	Final Weight	Rank
Back	0.079	0.125	0.260	0.063	0.069	**0.034**	**12**
Shoulder/arm	0.135	0.129	0.237	0.054	0.063	**0.035**	**10**
Wrist/hand	0.022	0.038	0.208	0.031	0.033	**0.020**	**17**
Neck	0.458	0.239	0.122	0.297	0.416	**0.069**	**1**
Leg	0.068	0.116	0.102	0.070	0.063	**0.020**	**16**
Spine	0.238	0.353	0.071	0.486	0.355	**0.061**	**2**
Equipment complexity	0.777	0.777	0.777	0.613	0.613	**0.075**	**3**
Level of automatization	0.074	0.074	0.074	0.181	0.181	**0.011**	**29**
Human-system interfaces design	0.149	0.149	0.149	0.206	0.206	**0.017**	**22**
Temperature	0.157	0.088	0.235	0.412	0.379	**0.039**	**9**
Lighting	0.119	0.080	0.110	0.054	0.062	**0.017**	**24**
Noise	0.038	0.048	0.064	0.088	0.156	**0.017**	**26**
Vibration	0.072	0.077	0.240	0.090	0.084	**0.013**	**19**
Space demands	0.032	0.031	0.070	0.045	0.052	**0.007**	**31**
Exposure to chemical	0.533	0.619	0.260	0.295	0.246	**0.054**	**5**
Workplace cleaning	0.050	0.056	0.022	0.016	0.020	**0.005**	**34**
Gender	0.014	0.047	0.021	0.042	0.071	**0.007**	**37**
Age	0.074	0.042	0.017	0.049	0.033	**0.012**	**36**
Body weight	0.206	0.071	0.057	0.038	0.035	**0.009**	**33**
Education level	0.370	0.256	0.390	0.228	0.341	**0.022**	**15**
Skill and knowledge	0.064	0.114	0.198	0.395	0.205	**0.017**	**18**
Effort	0.190	0.313	0.149	0.018	0.020	**0.018**	**20**
Experience	0.082	0.157	0.168	0.231	0.294	**0.014**	**21**
Repetitive task	0.035	0.558	0.299	0.055	0.073	**0.032**	**14**
Task duration	0.273	0.257	0.270	0.101	0.156	**0.034**	**13**
Exertion (force load)	0.561	0.109	0.228	0.171	0.218	**0.042**	**8**
Material handling	0.111	0.051	0.143	0.079	0.081	**0.016**	**23**
Psychological demand of a task	0.019	0.025	0.060	0.593	0.473	**0.055**	**6**
Personal protective equipment	0.339	0.379	0.468	0.489	0.526	**0.072**	**4**
Visual workplace	0.339	0.379	0.403	0.121	0.104	**0.045**	**7**
Training	0.259	0.135	0.072	0.269	0.291	**0.039**	**11**
Equipment daily activities	0.064	0.108	0.058	0.121	0.079	**0.015**	**25**
Communication patterns	0.106	0.479	0.380	0.056	0.121	**0.013**	**28**
Organization culture	0.106	0.230	0.249	0.222	0.245	**0.012**	**30**
Work pace	0.113	0.134	0.162	0.462	0.373	**0.016**	**27**
Documentation	0.637	0.090	0.124	0.078	0.131	**0.009**	**32**
Administrative support	0.038	0.068	0.085	0.182	0.131	**0.006**	**35**

The priority score of each sub-risk factors was determined by multiplying the sub-risk factor weight with the weight of the related main factor for each expert. Then, the sub-risk factor weights were aggregated considering the reputations (weights) of experts. The weight of each expert was assumed to be equal. As a result, the final weights and rank are shown in bold font in the seventh and eighth columns of Table 11.

The results obtained for the weights reveal that the most important main risk factor was determined as “posture”. Risk for body parts appears as a criterion the importance of which is calculated at a higher rank in work-related musculoskeletal disorders. A link between workers’ posture and risks of injuries is obvious. Prolonged exposure to awkward posture has more adverse biomechanical, anatomic, and physiologic effects on the body parts compared to the other main criteria. The results also exhibit that “neck” was found as the most important factor considering sub-criteria evaluation. The sub-criteria, “spine”, is a part of the posture main criteria. The consequences of neck and spine awkward situations are more dangerous than other risks. Moreover, industrial system workers are barely aware of awkward neck and spine positions. On the other hand, yielding the main criteria under “organizational factors” with the least importance, it can be interpreted that critical effects of communication patterns, organizational culture, work pace, documentation, and administrative support are not encountered in the decision process regarding the assessment of ergonomic risk.

4.2.2. Evaluating the Setup Tasks

The steps of IVPF-TOPSIS were applied and ergonomic risk scores were calculated for each setup task. Each setup task involves different levels of risk related to seven main ergonomic risk factors. Their levels are represented as linguistic terms and their corresponding IVPF numbers are given in Table 5. Since each setup task does not include all risk factors, on the basis of reviews of the research team and production supervisor, the new scale “no relation” is included in the table. For instance, task 5 (Tighten the wedges and attach the cover with 2 screws) has an extremely high-risk level related to wrist/hand, neck, spine, and lighting; middle risk level related to visual workplace and communication patterns; and it does not involve risk for exposure to chemical factors. The consolidated task evaluation matrix was created based on expert opinions as given in Table 12 for the current state. The modified Delphi method was used to consolidate the expert opinions [69]. It presents practical and easy use ways to aggregate opinions from multiple experts. In this method, experts can express their opinions such as written, e-mail, discussion, and feedback. The method basically consists of five main steps. In the first step, anonymous experts are selected based on their experience and skills. Then the questionnaire is posed to experts for the first time. If there is no consensus, then the questionnaire is asked to experts for the second time as a third step of the method. In the fourth step, questionnaire is posed to experts for the third time. Lastly, opinions from experts are integrated to reach a consolidated decision. Consequently, the results of the first ergonomic risk assessment of setup tasks are given in Table 13.

According to the risk scores, the setup task with the highest risk score during the current working environment is the T-28 task. This setup task was followed by T-32 and T-27 tasks, respectively. The setup task with the lowest risk score is T-2. T-28 setup task is one of the core tasks for the changeover process performing with the highest processing time compared to other tasks. On the other hand, T-2 is an external setup task performed at the beginning of the changeover process with lower processing time. Additionally, when the results were shared with the experts, they claimed that the processing time may affect the risk of the setup task. Therefore, it can be articulated that the ranking obtained based on these facts is plausible.

Table 12. Consolidated task evaluation matrix.

	C11	C12	C13	C14	C15	C16	C21	C22	C23	C31	C32	C33	C34	C35	C36	C37	C41	C42	C43	C44	C45	C46	C47	C51	C52	C53	C54	C55	C61	C62	C63	C64	C71	C72	C73	C74	C75
T-1	VH	VH	EH	VH	VH	VH	MH	M	NO	H	H	MH	H	VH	L	H	VL	H	VL	VL	H	H	MH	H	H	EH	EH	EL	M	VH	H	EL	M	EL	VH	H	NO
T-2	MH	MH	VH	MH	M	MH	MH	H	NO	H	EH	M	M	EH	NO	H	NO	EL	NO	L	M	MH	H	MH	MH	L	VH	ML	ML	EH	H	ML	EL	EL	H	H	NO
T-3	VH	VH	EH	EH	ML	EH	H	H	H	VH	EH	MH	VL	H	NO	VH	EL	VL	EL	ML	MH	H	H	VH	VH	H	M	MH	VH	M	H	EL	M	EL	H	VH	EL
T-4	VH	VH	EH	EH	ML	EH	H	H	H	VH	EH	MH	VL	H	NO	VH	EL	VL	EL	ML	MH	H	H	VH	VH	H	M	MH	VH	M	H	EL	M	EL	H	VH	EL
T-5	H	H	EH	EH	ML	EH	H	H	H	VH	EH	MH	MH	H	NO	VH	EL	VL	EL	ML	MH	H	H	VH	VH	H	M	MH	VH	M	H	EL	M	EL	H	VH	EL
T-6	H	H	H	H	VL	H	EH	L	NO	H	VH	M	L	VH	H	EH	L	ML	L	MH	H	MH	VH	MH	MH	MH	EH	VL	H	H	M	VH	MH	EL	MH	H	VH
T-7	MH	MH	H	H	VL	H	VL	ML	NO	VH	H	M	MH	H	NO	H	EL	VL	EL	MH	MH	H	H	H	H	H	EH	L	H	M	H	EL	M	NO	H	VH	EL
T-8	H	VH	MH	H	VH	H	VL	VH	NO	VH	VH	MH	H	VH	NO	H	EL	VL	EL	VL	M	MH	VH	M	M	H	EH	VL	H	VH	M	VH	EL	NO	VH	H	NO
T-9	H	VH	MH	H	VH	H	VL	VH	NO	VH	EH	MH	H	VH	NO	H	ML	ML	ML	VL	M	MH	VH	M	M	VH	EH	VL	H	VH	M	VH	EL	NO	VH	H	NO
T-10	VH	VH	H	H	VH	H	EH	H	NO	VH	H	MH	VL	MH	H	EH	L	ML	L	ML	M	MH	VH	MH	MH	H	H	VL	VH	VH	H	VH	MH	L	H	VH	VH
T-11	H	VH	MH	M	MH	M	EL	H	NO	H	H	M	VL	H	H	EH	L	ML	L	VL	M	MH	VH	MH	MH	H	EH	VL	H	VH	M	VH	MH	NO	VH	VH	VH
T-12	VH	EH	MH	H	VH	H	EL	H	NO	VH	H	VL	H	VH	NO	H	ML	M	ML	EL	ML	MH	L	MH	MH	VH	EH	VL	M	VH	M	VH	EL	NO	H	VH	NO
T-13	VH	VH	VH	H	VH	H	EH	H	MH	H	H	M	VL	VH	H	EH	ML	M	ML	MH	M	MH	MH	MH	MH	H	VH	VL	H	VH	M	VH	MH	L	VH	VH	VH
T-14	MH	H	MH	H	VH	H	EL	H	NO	VH	H	VL	H	VH	NO	H	MH	H	MH	L	M	MH	MH	MH	MH	MH	EH	VL	H	VH	M	VH	EL	NO	VH	H	NO
T-15	M	M	VH	H	M	H	H	VH	H	H	EH	M	L	MH	NO	H	ML	M	ML	H	MH	H	VH	VH	VH	H	M	MH	H	M	VH	EL	M	NO	H	VH	EL
T-16	M	M	VH	EH	VH	EH	VH	VH	H	VH	VH	MH	L	M	NO	H	MH	H	MH	H	H	H	VH	VH	VH	H	M	M	VH	M	VH	EL	M	NO	H	VH	EL
T-17	MH	H	H	VH	H	VH	H	VH	H	VH	MH	VL	L	M	NO	MH	MH	H	MH	H	MH	H	VH	VH	VH	VH	EH	M	H	M	VH	EL	M	NO	H	VH	EL
T-18	VH	VH	VH	VH	MH	H	VH	VH	H	VH	VH	M	H	VH	NO	M	L	ML	L	H	MH	H	VH	H	H	VH	L	M	H	VH	VH	EL	M	NO	H	VH	EL
T-19	VH	VH	VH	VH	MH	H	VH	H	NO	H	H	M	VL	VH	H	EH	ML	M	ML	L	MH	H	VH	H	H	VH	L	M	H	VH	VH	VH	MH	NO	VH	VH	VH
T-20	H	H	VH	M	MH	M	H	MH	NO	H	H	M	VL	VH	H	EH	ML	M	ML	L	M	MH	H	H	H	MH	VL	L	H	VH	M	VH	MH	L	VH	VH	VH
T-21	EH	EH	VH	VH	H	VH	VH	H	H	VH	VH	M	H	VH	NO	M	ML	M	ML	MH	M	VH	EH	H	H	H	L	L	H	H	VH	L	M	NO	VH	VH	EL
T-22	EH	EH	VH	VH	H	VH	VH	H	H	VH	VH	MH	H	VH	NO	H	NO	EL	NO	MH	H	VH	EH	VH	VH	VH	H	M	L	H	VH	L	M	NO	H	VH	EL
T-23	MH	MH	VH	EH	VH	EH	VH	EH	H	H	VH	MH	L	H	NO	H	NO	EL	NO	H	VH	VH	EH	VH	VH	VH	L	H	L	VH	VH	L	M	NO	H	VH	EL
T-24	MH	MH	VH	VH	H	VH	H	H	H	H	H	H	L	VH	NO	M	ML	M	ML	H	MH	H	VH	H	H	VH	L	H	VH	VH	VH	L	M	NO	H	VH	EL
T-25	MH	MH	VH	VH	H	VH	H	VH	H	H	VH	H	L	VH	NO	M	ML	M	ML	MH	H	H	VH	H	H	H	L	H	VH	VH	H	L	M	NO	H	VH	EL
T-26	ML	ML	VH	VH	H	VH	VH	VH	H	H	VH	H	L	H	NO	M	NO	EL	NO	H	MH	VH	EH	VH	VH	H	L	VH	H	VH	VH	L	M	NO	H	VH	EL
T-27	MH	MH	H	VH	H	VH	VH	VH	VH	VH	VH	EH	EH	H	H	EH	VL	L	VL	ML	MH	MH	H	H	EH	H	VH	L	EH	MH	VH	VH	MH	L	H	VH	VH
T-28	VH	VH	H	VH	H	VH	EH	VH	H	VH	VH	H	VH	VH	NO	VH	L	ML	L	H	VH	VH	EH	EH	EH	VH	H	VH	EH	VH	VH	MH	MH	M	VH	H	H
T-29	H	H	VH	VH	MH	H	H	VH	H	VH	H	L	L	VH	NO	M	EL	VL	EL	M	MH	MH	H	VH	VH	H	L	H	VH	H	H	L	M	NO	H	M	EL
T-30	EH	VH	VH	H	VH	H	VL	MH	NO	VH	VH	VL	VL	VH	NO	M	ML	M	ML	VL	M	M	MH	H	H	MH	H	M	H	H	H	L	EL	NO	H	M	NO
T-31	EH	VH	VH	VH	MH	H	VH	MH	H	VH	VH	L	L	H	NO	M	L	ML	L	MH	MH	MH	H	VH	VH	H	L	H	VH	VH	H	L	M	NO	H	H	EL
T-32	VH	VH	H	VH	H	VH	EH	VH	H	VH	VH	H	VH	H	NO	VH	L	ML	L	H	VH	VH	EH	EH	EH	VH	H	VH	EH	VH	VH	MH	MH	L	VH	VH	VH

Table 13. The results of the first ergonomic risk assessment of setup tasks.

Task	Time	Type	Score	Rank	Task	Time	Type	Score	Rank
T-1	1.5	External	0.624	21	T-17	0.5	Internal	0.628	20
T-2	0.5	External	0.472	32	T-18	0.2	Internal	0.651	14
T-3	3	Internal	0.654	12	T-19	0.6	Internal	0.705	4
T-4	0.5	Internal	0.654	13	T-20	1	Internal	0.595	23
T-5	2.6	Internal	0.650	15	T-21	0.6	Internal	0.660	7
T-6	0.2	Internal	0.638	18	T-22	4.4	Internal	0.659	9
T-7	0.6	Internal	0.490	29	T-23	2.2	Internal	0.656	11
T-8	0.5	Internal	0.499	28	T-24	3	Internal	0.646	16
T-9	0.5	Internal	0.513	27	T-25	5	Internal	0.637	19
T-10	0.5	Internal	0.694	6	T-26	0.5	Internal	0.639	17
T-11	0.7	Internal	0.540	25	T-27	1	Internal	0.763	3
T-12	1	Internal	0.478	31	T-28	37.2	Internal	0.796	1
T-13	1.5	Internal	0.697	5	T-29	5.8	Internal	0.618	22
T-14	0.4	Internal	0.483	30	T-30	1	Internal	0.518	26
T-15	1.5	Internal	0.588	24	T-31	17	Internal	0.659	10
T-16	3.7	Internal	0.660	8	T-32	34	Internal	0.794	2
Total risk score for the current state of setup process: *19.96*									

4.3. Step 3-Implementation of SMED

After an ergonomic assessment of the current setup process, the conventional SMED steps (Steps 3.1 and 3.2) can be applied according to the suggestions given in Table 14. These suggestions are explained in the following paragraphs. After the implementation of Step 3, the updated time and type of setup tasks are given in Table 14.

Table 14. Future state of the setup process.

Task No.	Suggestion	For Future State		Task No.	Suggestion	For Future State	
		Time	Task Type			Time	Task Type
T-1	Tool car design	1.5	External	T-17	Placing closer cover kit belonging to the stand	0.3	Internal
T-2	Tool car design	0.5	External	T-18	Keep spare guide bush nut and remove	0.2	Internal
T-3	Parallel operator (PO)	1.5	Internal	T-19	Keep spare fixed nut and remove and PO	0.6	Internal
T-4	PO	0.3	Internal	T-20	Place closer with cleaning kit belonging to the stand and PO	0.7	Internal
T-5	Bench tool pocket	2	Internal	T-21	PO	0.3	Internal
T-6	AM application and PO	0.2	External	T-22	Set code for pin set and place in the tool car	3.4	Internal
T-7	Avoiding manual disassembly and PO	0.5	Internal	T-23	Avoiding manual adjustment using Torque meter and PO	1	Internal
T-8	Waist bag	-	Eliminated	T-24	Standard work methodology	2.9	Internal
T-9	Increase the number of wedges	0.2	Internal	T-25	Standard work methodology	4	Internal
T-10	AM application and PO	0.3	External	T-26	Standard work methodology	0.5	Internal
T-11	Place closer with spare hive	0.3	Internal	T-27	With AM and PO	1	External
T-12	Place closer with lubricate belonging to the stand	1.0	Internal	T-28	Reduce sample count to 5 with standardized work charts	12	Internal
T-13	Place closer with cleaning kit belonging to the stand	1	Internal	T-29	5S	5	Internal
T-14	Bring required material in the crate to the stand while previous batch is being processed and PO	0.4	External	T-30	Prepare tool ahead of time and PO	1	External
T-15	PO	1	Internal	T-31	Standardized work charts	9	Internal
T-16	5S studies decrease search for tool kit	2	Internal	T-32	Reduce sample count to 3 with standardized work charts	10	Internal
Total required time for future state of setup process: *57.9 min*							

4.3.1. Separating Setup Activities and Converting Internal Activities to External Activities

In this step, 7 out of 32 internal tasks are converted to external tasks employing some suggestions. Task 1 and 2 were classified as external in Table 14 at the future state. Cleaning, lubricating and tightening tasks (T-6, T-10, and T-27) needs to be completed within 5.7 min at the current state. These tasks were completely transformed into external tasks within the framework of Autonomous Maintenance that is based on operators' responsibilities of daily cleaning, lubricating, and tightening activities on their equipment. AM application was consolidated with standardization, visual management, scheduling, and layout operations so that daily maintenance activities cannot interrupt machine working. T-14 and T-30 are transformed into an external task using the preliminary phase. Step 3.1 ensures the reduction of the total required time for completing all internal setup tasks by 4.9 min even if the implementation of Step 3.2 is not initiated.

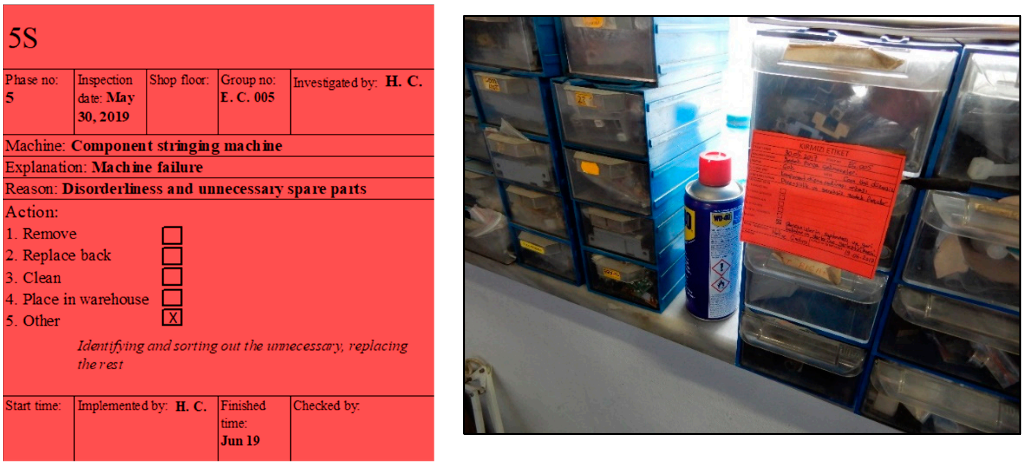
4.3.2. Streamlining All Setup Activities

This is the last stage of conventional SMED. It includes improvements in all setup activities by redesigning, standardizing setup activities, and eliminating non value-added activities to smooth task processing and reduce their setup time. Corresponding suggestions for setup tasks are presented in Table 14.

To avoid time spent when looking for tools, some solutions were suggested, such as bench tool pockets for T-5, waist bag for T-8, dedicated lubricant to the equipment for T-12 and T-13, and cleaning kits for T-20. A kit tool car belonging to the stand (Figure 4) was designed and placed closer to the machine for T-17. Therefore, the tools have fixed positions.

Figure 4. Cover kit belonging to the stand.

Additionally, 5S provides an effective workplace organization with visual control [70]. Red tag applications were executed to classify, order, and clean tools for T-16. The required time was reduced from 3.7 to 2 min by resolving the tool search via the red label. The illustrated red tag in Figure 5 was used by authorized technicians to visualize problems. Then, problems were eliminated and all red tags were recorded. Moreover, implementing 5S for drills and bringing the drill bits to the operation area reduced the setup time of T-29 to 5 from 5.8 min.



(**a**) (**b**)

Figure 5. (**a**) Red tag template and (**b**) application area.

Based on the standardized work charts, setup task time was reduced and changes were easily monitored and new operators were quickly adapted. Pure standardized work in its final form must also include three different elements to qualify as standardized work. Those three elements are take time, work sequence, and standard work in process (SWIP). A standardized work chart created for the preliminary phase for the sampling tasks (T-28 or T-32) is given in Figure 6. This chart visualized an optimized walking path with a reduction in walk time by dividing the setup task into a minor step. Since intervening in offset values and program values are realized simultaneously, redundant front and back samples were obtained at the current state. Thanks to the standardized work charts created for the preliminary phase of the samples collecting setup task, the number of front and back samples obtained was reduced and the required time for these setup tasks (T-28 and T-32) was reduced to 22 from 71.2 min.

Standardized Work Combination Table					Plant:	Product:
Date:			Approved By:		Area:	
By:					Process:	
					Shift:	Takt Time:
					Volume:	Cycle Time:
No	Minor Steps	Man Time	Auto Time	Walk Time		
1	Pick up sample 1	1.6				
2	Connect cutter tool 1	1.6				
3	Load part 1	1.6				
4	Connect cutter tool 2	1.5				
5	Load part 2	1.5				
6	Reset cutter tools and drill bit	1				
7	Pack in pallet	1				

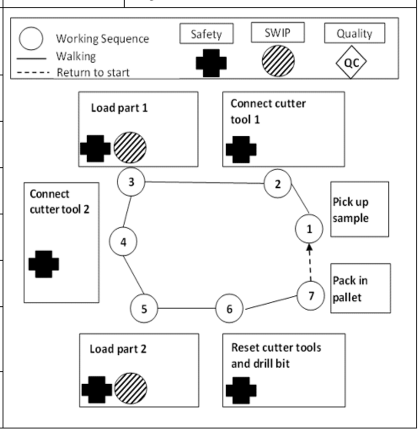


Figure 6. Standardized work chart for preliminary of collect samples setup task.

Parallel operators are suggested for T-3, T-4, T-6, T-7, T-10, T-14, T-15, T-19, T-20, T-21, T-23, T-27, and T-30 so that the required time can be reduced or some internal tasks can be converted to external when possible. Operator 2 was employed to perform separate tasks simultaneously with Operator 1 for reducing the required time of T-3, T-4, and T-21. On the other hand, T-6, T-10, T-14, T-27, and T-30 were performed by Operator 2 as external tasks. The performing time of each worker is illustrated in Step 5 using Gantt Chart.

Some suggestions are related to technical solutions to avoid manual clamping and fastening. For instance, a torque meter is suggested to avoid manual adjustment for T-23. For T-7, some tool parts can be designed to avoid manual removal of head 1.

4.4. Step 4-Ergonomic Assessment of the Improved Setup Process

The final step of the proposed model is the ergonomic assessment of the improved setup tasks. After reducing setup time and implementing suggestions, the risk factors of improved setup task were evaluated by the same experts. The experts used the same linguistics terms (Table 5) in the sub-criteria evaluation matrix. The entire matrix of this assessment is excluded from this study due to space limitation (see Supplementary Materials). The ergonomic risk assessment results obtained using MCDM for the future state of the setup process are presented in Table 15.

Table 15. The results of the second ergonomic assessment of setup tasks.

Task	Time	Type	Score	Rank	Task	Time	Type	Score	Rank
T-1	1	External	0.624	4	T-17	0.3	Internal	0.481	21
T-2	0.5	External	0.472	23	T-18	-	Eliminated	0.651	3
T-3	2.8	Internal	0.426	26	T-19	-	Eliminated	0.705	1
T-4	0.3	Internal	0.392	28	T-20	0.7	Internal	0.484	19
T-5	2	Internal	0.524	15	T-21	0.3	Internal	0.511	18
T-6	0.2	External	0.483	20	T-22	3	Internal	0.540	14
T-7	0.5	Internal	0.441	25	T-23	1	Internal	0.513	17
T-8	-	Internal	0.404	27	T-24	2.9	Internal	0.595	7
T-9	0.2	Internal	0.266	32	T-25	4	Internal	0.563	12
T-10	0.3	External	0.616	5	T-26	0.5	Internal	0.582	11
T-11	0.3	Internal	0.273	31	T-27	1	External	0.662	2
T-12	-	Internal	0.284	30	T-28	12	Internal	0.551	13
T-13	1	Internal	0.584	9	T-29	5	External	0.479	22
T-14	0.4	External	0.344	29	T-30	1	External	0.451	24
T-15	1.5	Internal	0.588	8	T-31	15	Internal	0.583	10
T-16	2	Internal	0.515	16	T-32	12	Internal	0.612	6
			Total risk score for the future state of setup process: *16.2*						

Setup task 19 ranked as the first with highest priority, followed by task 27; however, the last task with the lowest risk score was task 9. Since T-19 and T-18 have already been eliminated with corrective suggestions, the importance of T-19 and T-18 can be neglected.

4.5. Step 5-Scheduling of the Improved Setup Process

This step presents scheduling which decreases the total sequence-dependent setup time in parallel operators. The scheduling of the improved setup process is shown in Figure 7. A parallel operator was suggested for setup tasks T-3, T-4, T-6, T-7, T-10, T-14, T-15, T-19, T-20, T-21, T-23, T-27, and T-30 in Step 4. Precedence relationships of setup tasks are considered when scheduling is performed. One operator can deal with placing the back chock (T-7), while the second operator can deal with the wedges and cover (T-5). T-12 and T-15 can be initiated simultaneously. The improved flow of setup tasks T-3, T-4, and T-21 are equally shared between the operator and setup worker who assists an operator in the completion of a setup task. For instance, when one operator places one of the back chocks (T-4), the second operator handles the other chock.

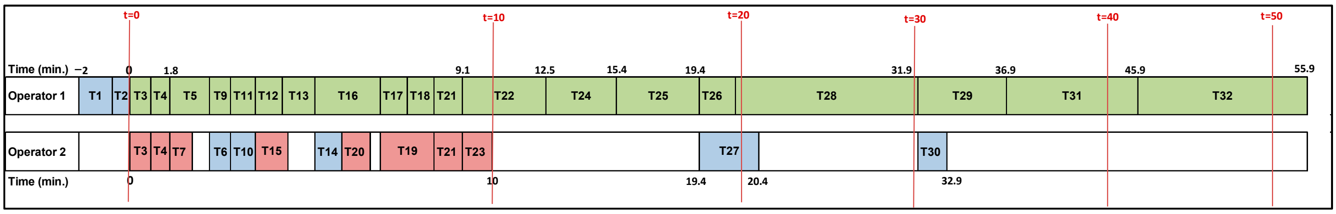


Figure 7. Scheduling of the improved setup tasks.

After scheduling, the total time required for the internal setup process of the gas safety valve product was 55.9 min and the external setup time was 2 min.

5. Results

SMED application based on human factors is presented for ergonomic risk assessment and setup time reduction. Most of the processing times of setup tasks have been reduced through the proposed model. A summary of the current and future state of the setup process is given in Table 16. In the current state, total duration to complete the changeover process was 137.2 min in Table 6. After implementing the proposed model, the required time was 57.9 min with a reduction of 58%. The setup time, when the machine is working, is increased by 81.3 min (137.2–55.9) for each setup task with the internal time reduction. Capacity utilization (*CU*) is formulized as follows:

$$CU = \frac{[(Total\ working\ time) - (Total\ required\ internal\ setup\ time)]}{(Processing\ time)}, \quad (21)$$

Table 16. The summary of the current and future state of the setup process.

Setup Process	Total Setup Time (Minutes)	Total Internal Setup Time (Minutes)	Capacity Utilization (Unit/Year)
Current State	137.2	137.2	63,000
Future State	57.9	55.9	125,000

Total working time is equal to 6,750,000 s per year (250 day/year × 7.5 h/day × 3600 s/h) and Processing time for a product is 40.3 s. Total required internal setup time per year is calculated by multiplying the number of total setups per year (510 setups/year) with total internal setup time (137.2 × 60 s). Consequently, capacity utilization of current and future states is calculated approximately at 63,000 and 125,000 products per year, respectively. This means an additional production of 62,000 gas safety valve in a year owing to the proposed methodology.

The comparison of the processing time of setup tasks before and after implementation of the suggestions is presented in Figure 8. For instance, T-28, T-32, and T-27, which were found in the first three high-risk ranks in the first ergonomic assessment (Table 13), need to be completed within 72.2 min at the current state; however, they can be completed within 23 min after the proposed model implementation. Standardized work charts for T-28 and T-32 suggested in Step 3.2 reduce the required setup time by eliminating non-value-added activities. Since Autonomous Maintenance for T-27 suggested in Step 3.1 is consolidated with standardization, visual management, scheduling, and layout operations, the required time for setup is reduced. Therefore, the application of the proposed model is ensured the setup time reduction that leads to an increase in production efficiency. T-6, T-10, and T-27 were converted to external tasks and their times are reduced after the implementation of Step 3.1 by organizing and standardizing tasks in AM environment where daily regular maintenance tasks are performed by operators without any delay. Moreover, the accumulation of minor equipment issues or quality defects can be avoided without any interruption of the machines. Thus, the simultaneous working of machines and operators was ensured, and idle time was reduced.

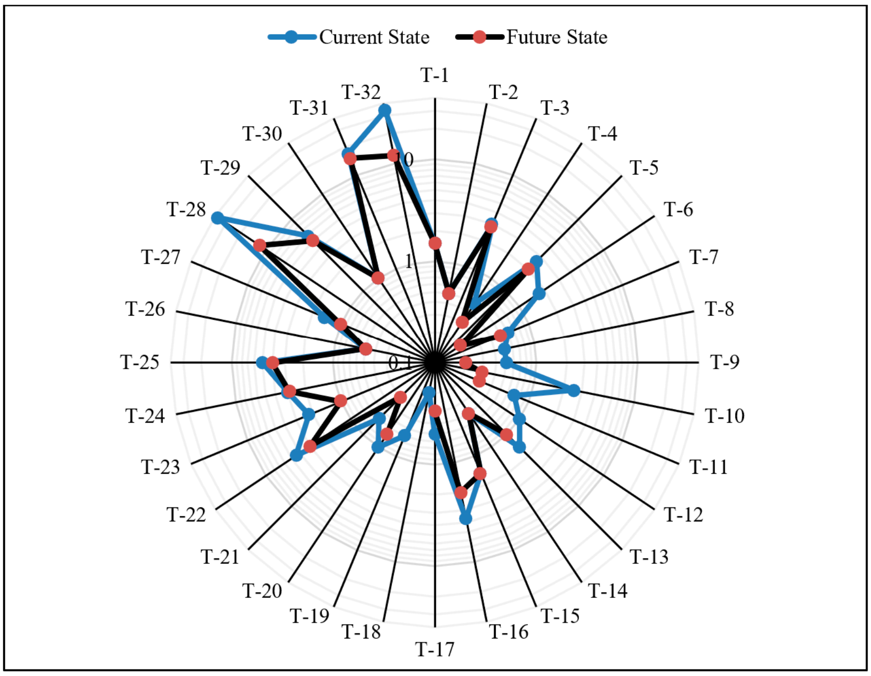


Figure 8. Processing time of setup tasks for before and after implementation of the proposed model.

As a result of multi-criteria decision analysis, the "posture" criterion, which is defined as the position of the body parts, emerged as the most important criterion in the decision process. This result can be confirmed by Ahmadi et al. [12]. They also concluded that the most important ergonomic factor is posture-related risk.

Two ergonomic assessments including current and future state of the setup process were realized in the proposed approach. In the future state, experts assessed setup tasks that were improved with the implementation of suggestions with respect to all risk factors. Using two parallel operators shortens the overall time required for the setup process due to parallel execution of setup tasks or dividing setup tasks among operators, thus reducing the ergonomic risk exposure of operators. Moreover, operators perform their tasks with a high level of communication and motivation in terms of cognitive ergonomic aspects. However, having more operators in the same area will increase the risks related to "space demand". Therefore, this suggestion for the T-3, T-4, and T-21 should be supported by layout planning. Manual disassembly was avoided by introducing a technical solution to the T-7. Although this suggestion reduces the risk levels related to the "posture", "task duration", and "exertion", it increases in the risk levels related to "complexity", "automatization", and "human-system interface". T-10 had a lower risk level related to visual workplace, equipment daily activities, and material handling risk factors thanks to AM application. It is not surprising that there are improvements in communication and top management, as this suggestion includes ensuring correct and uninterrupted communication between teams and top management. It was observed that the standardized work chart for T-28 creates improvements, especially in equipment complexity, level of automatization, and the human–system interface. T-28 also has a low level of risk related to task duration after the implementation of suggestion.

Afterwards, risk scores of all setup tasks were calculated for both before and after implementation of the suggestions by applying MCDM. At the current state total risk score of changeover process was 19.96 in Table 13. After implementing the proposed model, the total risk score was 16.2 with a reduction of 19.1%. The comparison of the risk score of the setup tasks for before and after implementation of the suggestions is presented in Figure 9. According to the Figure 9, considerable differences exist between two assessments. For instance, T-28 is ranked in the first position of the current state as the task with the highest risk score (0.80). Fortunately, the risk priority of this task was reduced to 0.55 as a result of the second assessment. The standardized work chart suggested for this setup task contributes to ergonomic improvement by eliminating non-value-added activities, optimizing walking path, and simplifying operations. That is, a 31% improvement was achieved in the content of ergonomic risk of the corresponding task implementing suggestion. Ergonomic improvement for T-27 is achieved, which was found in the third high-risk in the first ergonomic assessment, via integration of AM and visual management. Therefore, the workplace is transformed into a safe, clean, and organized environment. According to the interval between risk scores of before and after implementation, T-11 has the widest interval. The proposed model has the most positive effect on T-11 in terms of ergonomics. This task is followed by T-4, T-9 and T-28, respectively. Since some of the setup tasks are eliminated (T-18 and T-19) and some of them have insufficient suggestions (T-1, T-2, and T-15), the risk scores of the corresponding tasks do not change in the future state. Risk scores for the rest of the tasks evolve into reduced scores as justifying the proposed model. Especially, risks related to the "posture", which has the highest weight, was significantly reduced for all tasks. Hence, the positive impacts of the proposed model on the human factors are proven.

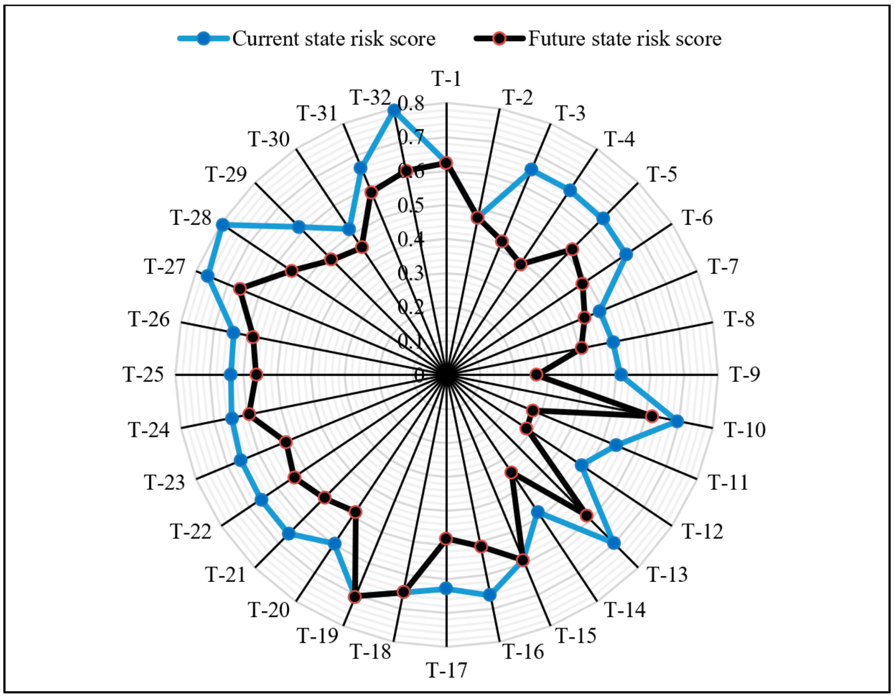


Figure 9. Risk scores of setup tasks for before and after implementation of the proposed model.

Suggestions for the T-1, T-2, T-6, T-10, T-14, T-27, T-29, and T-30 are presented within the third step of the proposed model. Even with Step 3.1 of the proposed model being applied to these tasks, it seems that ergonomic risks are reduced.

Furthermore, a comparative analysis was performed to show the robustness of the proposed MCDM model. The result of the first ergonomic assessment using the IVPF-TOPSIS methodology is compared with the CODAS (COmbinative Distance-based Assessment) method and WASPAS (Weighted Aggregated Sum Product ASsessment) method in terms of the evaluation of setup tasks. CODAS has been selected due to its consideration of the distances of alternatives from the negative ideal solution. Because of its optimal accuracy beyond combining the weighted sum and the weighted product methods, the WASPAS method is handled as another comparison method. PFSs are integrated into CODAS (see [71] for details) and IVPFSs are integrated into WASPAS (see [57] for details) for comparison. Additionally, the setup task evaluation scales given in Tables 5 and 17 are used in the implementation of the IVPF-WASPAS and the PF-CODAS, respectively. The criteria weights determined by the IVPF-AHP (Table 11) are used for two methods. The final rankings obtained from the methods can be seen in Figure 10. Although there are some changes in the results among the methods, the rankings obtained from the methods have the same trend. The results of the proposed method are more similar to the results of the WASPAS than the results of the CODAS. The potential reason for fluctuating among the rankings may be the number of setup tasks evaluated.

Table 17. Linguistic term used in the PF-CODAS method for setup task evaluation.

Linguistic Terms	PF Number	
	μ	v
Very Bad—VB	0.1	0.97
Bad—B	0.3	0.9
Medium Bad—MB	0.4	0.9
Fair—F	0.5	0.8
Medium Good—MG	0.6	0.7
Good—G	0.7	0.6
Very Good—VG	0.8	0.4

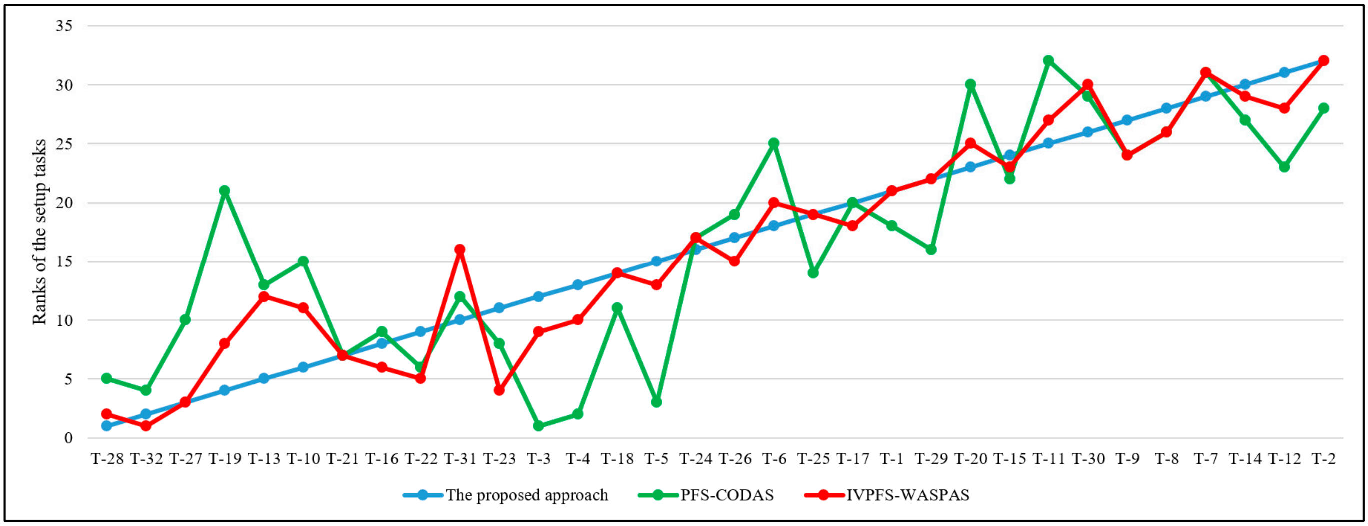


Figure 10. The ranking of the setup tasks in the different methods.

6. Conclusions

A setup process should be organized with the consideration of human well-being and capabilities. A poor ergonomic design of a setup task to be carried out can result in occupational accidents, injuries and diseases, quality defect, low capacity, and low profit. Thus, this study addresses the problem of setup time reduction and ergonomic improvement in the sense of SMED and multi-criteria decision making.

The proposed methodology is initiated by mapping the current state of the setup process. Then, risk factors affecting the level of ergonomic risk during performing of setup task are investigated and a detailed hierarchy of criteria is revealed with an extensive literature review. Opinions from an expert group that consists of academics and managers are used to weight criteria in AHP method. The same experts evaluate setup tasks with respect to the ergonomic criteria in TOPSIS. After the first ergonomic assessment of setup process, the remaining steps of conventional SMED, including the separation of external and internal setup tasks, converting internal setup tasks to external ones when possible, and streamlining the setup process, are employed. In these steps, lean manufacturing principles such as autonomous maintenance, 5S, and a standardized work chart are employed as corrective actions. The next step of the proposed model is an ergonomic reassessment of the setup process to show how corrective action effects the setup process in both ergonomics and organizational aspects. The last step is the scheduling including the sequence of setup tasks and their revised time requirements. The proposed model is validated through a real-life application in the white good supplier industry. The entire changeover process of gas safety valve production with 32 setup tasks improved based on different disciplines is considered.

The proposed methodology provides valuable insights and implications. First, the proposed human centric SMED model focused on ergonomic risk assessment of setup tasks with respect to seven main risk factors: posture, technical factors, working environment, worker characteristics, work elements, safety, and organizational factors. The consideration of factors from different ergonomic domains in the proposed framework reveals the superiority and inclusiveness of the proposed model over the conventional ergonomic risk assessment methods that handle only posture and work element attributes. Second, since the ergonomic risk factors determined as a result of a comprehensive literature review can be evaluated for different industries, the implications of the proposed model are not restricted to only a setup process. This study contributes to different research areas, such as assembly line worker assignment and task scheduling. Finally, the proposed model presents benefits, such as human health, manufacturing flexibility, and machine capacity development. Therefore, this study guides practitioners and researchers engaged in the working environment design and economic performance.

This study can be expanded by different multi-criteria decision-making methods or heuristics to compare the results. The proposed framework including setup time reduction and ergonomic consideration can be redesigned with human digital twin or big data analytics in human-centric manufacturing systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142113804/s1, Table S1: Consolidated second ergonomic task evaluation matrix.

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