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*Research paper*

# *Optimizing Setup Process in Manufacturing: A Novel SMED-Based Framework*

*Gul Imamoglu*[a], *Yildiz Kose*[a,*], *Emre Cevikcan*[b]

[a]Karadeniz Technical University, Faculty of Engineering, Department of Industrial Engineering, Trabzon, Türkiye.
[b]Istanbul Technical University, Faculty of Management, Department of Industrial Engineering, Istanbul, Türkiye.
[*]**Corresponding author:** yildizkose@ktu.edu.tr

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## ABSTRACT

Manufacturing companies strive to economically produce small batches to meet diverse customer demands. However, small batch production often leads to higher setup times and increased unit costs. A common solution to this issue is reducing setup times using the Single-Minute Exchange of Dies (SMED) technique. This study introduces a new roadmap for the SMED methodology, incorporating parallel worker utilization. The roadmap consists of two phases: a detailed SMED implementation and a scheduling model integrating parallel workers. This study contributes to the literature by integrating parallel worker scheduling with SMED for the first time and proposing an efficient mathematical model for setup processes. Another key innovation is the model's ability to account for precedence relationships between setup tasks. The proposed SMED-based roadmap was applied to the setup process of a push-button switch product family in an electrical-electronics company. The setup time was reduced from 67 minutes to 48 minutes through SMED implementation. While SMED reduces non-value-added times, optimizing the makespan requires assigning parallel workers to maximize machine utilization. The developed scheduling model reduced the maximum makespan by about 48%. The application led to reduced setup times and improved work procedures, demonstrating the effectiveness of the new approach.

***Keywords:*** *Setup Process, SMED, Scheduling, Parallel Workers*

## I. INTRODUCTION

Setup time is defined as the duration between producing the last acceptable part from the previous setup and the first acceptable part from the new setup in manufacturing systems. Setup tasks typically include tool and equipment cleaning, removing old tools and fixtures, and installing new ones, ensuring precise alignment and calibration of equipment, and testing the setup to ensure production quality. Reducing setup time boosts productivity, minimizes downtime, and enhances manufacturing flexibility, leading to more efficient and cost-effective operations. Moreover, shorter setup times make the system more adaptable to changes in demand, product variety, and market fluctuations, enabling quicker responses to customer needs and adjustments in production scheduling.

One of the most organized and successful strategies for cutting setup times is SMED developed by Shingo (Shingo, 1985). The aim is to carry out setup tasks within a maximum time period of ten minutes. The first stage in SMED is to separate setup activities into internal and external setup tasks. The former can only be carried out when the machine is stopped, whereas the external setup can be performed without interrupting production. The second stage of SMED involves converting internal setup activities into



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external ones. The final stage focuses on minimizing or eliminating both internal and external setup activities wherever possible. SMED not only reduces setup times but also assists in locating areas for process enhancement, improving the production line's overall performance. Because it increases flexibility, this strategy is especially beneficial for companies with a wide range of products but low production numbers. Additionally, SMED promotes a continuous improvement culture and is a key component of Lean Manufacturing principles.

Some papers present case studies on setup reduction using the SMED methodology in various manufacturing environments such as pharmaceutical (Gilmore & Smith, 1996), automotive industry (Rosa et al., 2017), textile (Moxham & Greatbanks, 2001), and white goods supplier industry (Kose et al., 2022). The scope of recent studies conducted in the SMED literature has been examined through a critical analysis. Mohammad et al. (2024) applied the SMED method integrated with responsible, accountable, consulted, informed matrices in the garment industry. Braglia et al. (2023) propose a four-step changeover design to reduce setup time during the design phase, focusing on machinery identification, machine design for efficient setup, technical interventions, and construction solutions to minimize setup duration. Junior et al. (2022) establish a SMED framework tailored for an oil and gas company by applying strategies such as elimination, combination, reduction, simplification, and standardization of work. Studies that address the effects of Industry 4.0 technologies on reducing changeover times are generally studies that focus on the lean manufacturing philosophy (Narula et al., 2023; Rosin et al., 2020; Saad et al., 2023). Khakpour et al. (2024) have directly enriched the SMED literature by introducing a method called SMED 4.0 that includes Industry 4.0 technologies. Studies that have addressed the application of SMED in some assembly operations have shown improvements in preparation time, the extreme attenuation of the risk level of musculoskeletal disorders, delivery times, reduction of movement waste (Juárez-Vite et al., 2023; Sahin & Kologlu, 2022; Villacís & Burneo, 2020). Studies integrating SMED and the human factor are generally at the forefront for situations where the installation involves activities with a high human content and where it is difficult to transform them into external operations to be carried out during the machine's activity time (Fonda & Meneghetti, 2022; Kose et al., 2022). Afonso et al. (2022) examined the setup operations of a molding machine from an ergonomic perspective, employing various ergonomic methods for each critical task due to the differing inputs and outputs. Yazici et al. (2021) applied a SMED-fuzzy FMEA model in plastic injection molding to address issues that prolong setup time for internal activities that cannot be converted to external ones.

On the other hand, various types of scheduling problems are encountered in the scheduling literature (Pinedo, 2022). One of these types involves classifying scheduling problems based on setup times or costs (Allahverdi et al., 2008). In such studies, sequence-dependent setup times are included in the scheduling model, but the primary goal is not to reduce setup times. Pessan and Néron (2011) addressed the scheduling problem as an unrelated parallel machines problem and proposed solutions using hill-climbing and genetic algorithms. However, reducing setup times by improving setup operations was not the primary focus of their work. In flow shop scheduling problem with sequence-dependent setup time considerations has been widely studied (Tosun et al., 2020). In recent studies, some algorithms such as Particle Swarm Optimization (Ozsoydan, 2025), Genetic Algorithm (Zhang et al., 2025), Adaptive Large Neighborhood Search (Xie et al., 2025) are included in the parallel machine scheduling with sequence dependent setup times. There is no study in the literature that focuses on improving and reducing setup times from a lean perspective and worker centric on parallel machine scheduling problems. The worker scheduling variables may resemble those used to characterize machines, as both involve time allocation. However, unlike machine processing times, the task durations performed by workers will vary depending on their individual characteristics, resulting in a different correlation (Ruiz-Torres et al., 2015, 2017). Bacterial foraging algorithm is used for employee scheduling model (Dan & Tao, 2021). Another study aims to maximize the service level, defined as the probability of avoiding tardy jobs, by addressing a worker scheduling problem that considers predefined work shifts and the impact of workforce motivation (Liu et al., 2021). Ruiz-Torres et al. (2019) developed a worker scheduling model that considers workers' preferences for various task types in a parallel shop setting to highlight the connection between satisfaction levels and shop efficiency. Wang and Liu (2014) developed a mixed integer programming worker scheduling model for shift assignments, taking into account workers' preferences.

A notable limitation of the SMED methodology is the lack of integration with personnel scheduling. While this issue has been addressed in a few studies, it remains insufficiently explored, particularly in the context of developing optimization models.

In this study, a new roadmap focusing on SMED-based parallel worker utilization for reducing setup times has been designed. The roadmap begins with a detailed assessment of the current situation. The next phase involves the application of SMED. To thoroughly analyze the current situation, the setup process to be addressed must first be selected. The selected setup process is then broken down into a series of setup tasks. After determining the durations of these tasks, the availability of workers for the setup process is identified. The second main phase of the proposed roadmap, which is the application of SMED, consists of three sub-steps. These include separating internal and external setup tasks, converting internal tasks into external ones, and implementing improvements to reduce the time required for all setup tasks. In the improvement of setup tasks, organizational and technological improvement proposals have been developed. The key difference between the proposed roadmap and existing ones in the literature is the development of an optimization model that utilizes parallel workers for reducing setup times.

This study makes several key contributions to literature by integrating personnel scheduling with the SMED technique, accounting for worker-specific setup times, and providing a more comprehensive optimization approach. These contributions are summarized as follows:

- For the first time, parallel worker scheduling has been integrated with the SMED methodology, resulting in the proposal of an efficient mathematical model for setup time reduction in manufacturing processes.
- Model has ability to account for the precedence relationships between setup tasks, enabling more effective scheduling and optimization of the setup process.
- The newly proposed SMED-focused roadmap has been applied to the setup process of a push-button switch product family in a company operating in the electrical and electronics sector, demonstrating its practical applicability.

As a result of the implementation, the setup tasks were improved and their durations reduced, leading to the development of more efficient work procedures. Wastes such as walking, transportation, and displacement, which would typically be carried out by a single worker, were eliminated.

The rest of the paper is organized as follows. Section 2 presents a thorough depiction of the proposed parallel worker scheduling integrated SMED framework. Section 3 depicts the application of the methodology in a real-world case study about the plastic injection process of the push-button switch product line. Finally, Section 4 provides conclusions and prospective directions.

## II. THE PROPOSED METHODOLOGY

Organizations that fail to reduce lead times in the face of increasing product diversity lose their competitive advantage. Motivated by this, a new SMED-based roadmap has been developed in this study. The framework of the proposed roadmap is presented in Figure 1.

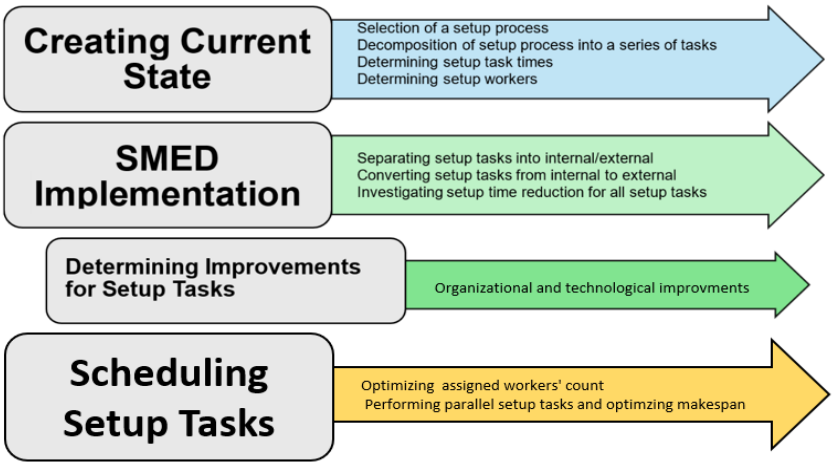



Figure 1. A new roadmap developed for the SMED methodology.

The details of the steps in the proposed roadmap are explained as follows. The first step is initiated with the classification of setup tasks. While many setup tasks can be performed without interrupting the machine, the common practice is to carry out these tasks while the machine is not running. To determine whether a setup task can be performed externally, it is first necessary to decide which of the following categories the task belongs to:

Internal Setup Tasks: those setup activities that can only be performed while the machine is stopped. These tasks are inherently tied to the machine's operation and cannot be performed externally without interrupting production.

External Setup Tasks: setup activities that can be performed while the machine is running. These tasks do not require the machine to be stopped and are conducted independently of the machine's operation, helping to minimize downtime.

Potential External Setup Tasks: tasks that are currently performed internally but can be performed externally. Tasks that require minor changes to be performed externally.

After classifying the setup tasks, the goal is to maximize the number of tasks that can be performed externally. Therefore, the second step of the proposed methodology is to convert internal setup tasks into external tasks. If there are setup tasks currently performed while the machine is stopped, despite being easily executable during machine operation without significant modifications, this constitutes a major waste of time. Such tasks as potential external setup tasks must be carried out while the machine is running. Additionally, for tool and fixture adjustments, it is preferable to perform these adjustments during external time whenever possible. Clearly, the machine should not be stopped solely to use the machine table. The third step involves proposing improvements for all setup tasks, considering various criteria such as technological advancements, organizational changes, and resource optimization. The improvement suggestions may include the introduction of new technologies, adjustments in processes, or the implementation of better practices in tool handling, all aimed at reducing the setup time. This step ensures that every task is evaluated for potential improvements, making the overall setup process more efficient. The fourth and final step focuses on reducing setup times by scheduling tasks in parallel, where possible, and utilizing the workforce effectively. This step aims to minimize workers' idle time by organizing the tasks so that multiple setup activities can be performed simultaneously by different workers. The use of parallel tasks not only shortens setup durations but also ensures that workers' time is utilized efficiently, enhancing overall productivity during the setup phase. For this purpose, a mixed integer linear programming (MILP) model has been developed for scheduling setup tasks among parallel workers. This model bears resemblance to parallel machine scheduling models but with distinct differences. In our model, instead of machines, workers are considered as the primary resources. The key feature of this model is its recognition of heterogeneous workers, meaning that each worker may have different processing times for the tasks they perform. The developed model takes into account the precedence relationships between tasks, allowing for the scheduling of tasks based on their dependencies. This enables the model to ensure that tasks are completed in the correct sequence, even if they require different workers or processing times. By scheduling tasks across parallel workers, the model optimizes the use of available resources, reduces setup times, and improves the overall efficiency of the process. The assumptions and details of the mathematical model are given as follows:

- There are *l* number of workers available at all times, and each worker can perform every task
- Processing times are task- and worker-dependent.
- The duration of each setup task is unaffected by the number of other setup tasks being carried out at the same time.
- Tasks are assigned sequentially: a worker must complete the current task before starting another.
- Precedence constraints apply only to specified task pairs.
- The objective is to minimize the makespan $C_{max}$.

Problem Notations:

Indices:
$I$: *the set of tasks indexed by i and j* (i = 1 … … . . m)
$K$: *the set of workers indexed by k* ($k$ = 1 … ….l)
$PR$: *Set of precedence relations, where* $(i, j) \in PR$ *implies task i must precede task j*
Parameters:

$P_{j,k}$: *the processing time of task j for worker k*
$M$: *A sufficiently large positive constant*

Decision variables:

$$x_{i,j,k} = \begin{cases} 1, & \text{if task } i \text{ scheduled before task } j \text{ for worker } k \\ 0, & \text{otherwise} \end{cases}$$

$$y_{j,k} = \begin{cases} 1, & \text{if task } j \text{ is assigned to worker } k \\ 0, & \text{otherwise} \end{cases}$$

$$w_k = \begin{cases} 1, & \text{if worker } k \text{ is commissioned to setup tasks} \\ 0, & \text{otherwise} \end{cases}$$

$c_j = completion\ time\ of\ task\ j$
$C_{max} = the\ makespan\ of\ the\ schedule$

$$Min\ Z = C_{max} \tag{1}$$

s.t.

$$\sum_{k=1}^{l} y_{i,k} = 1 \qquad \forall i \in I \tag{2}$$

$$\sum_{\substack{i=0 \\ i \neq j}}^{m} x_{i,j,k} = y_{j,k} \qquad \forall j \in I, \forall k \in K \tag{3}$$

$$\sum_{\substack{j=1 \\ j \neq i}}^{m} x_{i,j,k} \leq y_{i,k} \qquad \forall i \in I, \forall k \in K \tag{4}$$

$$\sum_{j=1}^{m} y_{j,k} \leq M * w_k \qquad \forall k \in K \tag{5}$$

$$\sum_{k=1}^{l} w_k \leq l \tag{6}$$

$$c_j - c_i + M\left(1 - x_{i,j,k}\right) \geq P_{j,k} \qquad \forall i \in I, \forall j \in I, \forall k \in K \tag{7}$$

$$c_j - c_i - M\left(1 - y_{j,k}\right) \geq P_{j,k} \qquad \forall k \in K,\ \forall (i,j) \in PR \tag{8}$$

$$C_{max} \geq c_j \qquad \forall j \in I \tag{9}$$

$$c_j, C_{max} \geq 0 \qquad \forall j \in I \tag{10}$$

$$x_{i,j,k}, y_{j,k}, w_k \in \{0,1\} \qquad \forall i \in I, \forall j \in I, \forall k \in K \tag{11}$$

Eq. 1 is the objective function of the proposed mathematical model. The objective is to minimize the tasks makespan, which is equal to $C_{max}$. Eq. (2) states that all task *i* should be assigned to exactly one worker. Eq. (3) ensure that each task *j* must have a predecessor job in the assigned worker. Here, task 0 is used as a dummy variable to be an antecedent of the jobs in the first rank. Eq. (4) indicates that each task *i* have at most one successor task for the worker to whom it is assigned. Eq. (5) ensures that a worker must be commissioned to setup tasks in order to be assigned to a task and Eq. (6) shows the total number of workers to commissioned on the setup tasks. Eq. (7) indicates that task j cannot be started before task *i* is completed that were assigned to same worker while Eq. (8) ensures that task j, which is the successor of task *i* due to

the precedence constraints, cannot start before task *i* finishes. Eq. (9) shows that makespan will greater or equal to completion time of all tasks. Finally, Eq. (10) and Eq. (11) represent sign restrictions of the variables.

## III. APPLICATION

The proposed SMED-based methodology was implemented in a company that manufactures electrical components for the white goods industry. The company is located in Tuzla, Istanbul, and the production facility covers an area of 8,500 $m^2$. The company produces rotary switches, push-button switches, toggle switches, and indicator lights. With an annual production of over 25 million components, the company strives to adapt to industry demands while aiming to gain a competitive advantage. Therefore, improvements in setup times have become crucial. The proposed methodology was applied to the plastic injection process of the push-button switch product family, as shown in Figure 2.



Figure 2. A product within the push-button switch product family.

### A. *Analysis of the Current State*

The proposed methodology for presenting the current situation, i.e., the analysis of setup tasks, has been carried out according to the flow shown in Figure 3.

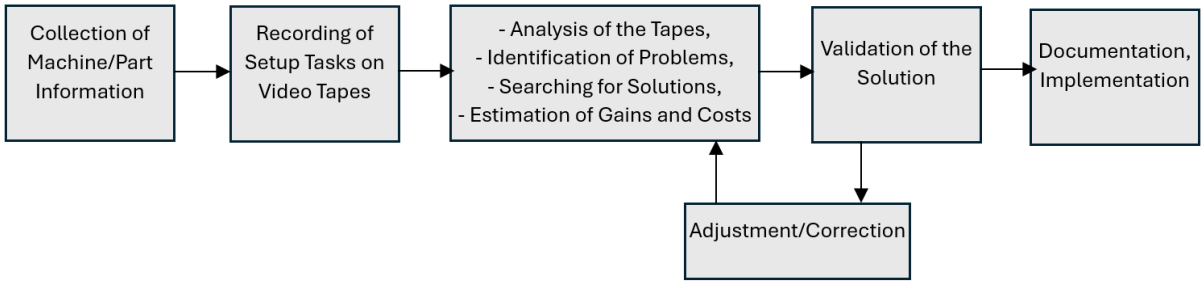



Figure 3. Stages of setup tasks analysis.

The setup process is divided into its components, and the setup tasks for each step are determined. After the setup tasks are defined, their durations and the setup materials used are identified. To accomplish this, video recordings of the setup tasks are made. After analyzing the recordings, identifying problems, searching for solutions, and estimating the gains and costs, the validity of the solutions is tested, and the documentation for all setup tasks is prepared. This documentation, which defines each setup task step by step and visually presents them, will facilitate the standardization and tracking of the tasks. The documentation prepared for the setup process of the push-button switch product family's body in the plastic injection machine is provided in Table 1.

Table 1. Preparation process for key switch body plastic injection machine.

| **Machine**: Injection Press- No. 4 | | **Previous task**: Cotherm Pin-Tile | | **Next task:** Single Switch Cover - N,66 (Natural) |
|---|---|---|---|---|
| **Task No** | **Setup Task** | **Performing time (min)** | **Setup Objects** | **Commentary** |
| 1 | Bringing a plastic bag to collect the previous material | 1.8 | Plastic bag | It is usually not done because there is no material left in the hopper. Injection continues to produce the previous batch. |
| 2 | Removal of material | 1.1 | Plastic bag | It is usually not done because there is no material left in the hopper. Injection continues to produce the previous batch. |

Table 1 (cont). Preparation process for key switch body plastic injection machine.

| | | | | |
|---|---|---|---|---|
| 3 | Removing the hopper from the injection press | 0.8 | Hopper | Space allocation is required for the hopper lid. It may needed in colour and material changes. |
| 4 | Cleaning the hopper with air | 1.2 | Hopper, air gun | |
| 5 | Inserting the hopper | 0.3 | Hopper | |
| 6 | Waiting for the previous batch's material to pass through the throat | 1.1 | | Waiting waste has been observed. |
| 7 | Rough cleaning of the mold Pouring new material into the hopper | 1.6 | Mold, cloth new material, hopper, stoup | Mold rough cleaning should be eliminated. Final cleaning should be employed in the molding room. |
| 8 | Taking the mold from the shelf, inserting it onto the mold cart and bringing it to the press. | 1.0 | Mold cart | A spare mold cart can be provided or appropriate space allocation for the mold cart is required. |
| 9 | Taking the mold and bringing it to the height of the press | 0.7 | Mold cart, mold | It can be eliminated or made external. |
| 10 | Removing the mold and lowering it to the ground | 2.6 | Mold cart, mold, hoist | The dismantled mold should be prevented from being lowered to the ground. Different mold cart designs can be considered for this purpose. It may be considered to bring the new mold in the previous batch. An electric hoist system will reduce the time. |
| 11 | Attaching eyebolts and bolts to the new mold, connecting the eyebolts and bolts with cloth Separating the hoist from the old mold and lifting the hoist up | 0.9 | Mold cart, mold, eyebolt, bolt, cloth, hoist | |
| 12 | Loading and positioning the new mold onto the machine with the hoist | 2.5 | Mold, hoist | An electric hoist system will reduce the time. |
| 13 | Connecting the mold and ejector pin | 3.6 | Mold, stud, 22 switches | Using a star or ratchet wrench can increase tightening torque and speed. |
| 14 | Connecting the cooling water to the mold Removing the old mold with a hoist and loading it onto the cart | 2.2 | | The duration can be shortened by providing plug&use type cooling adapters. |
| 15 | Throat cleaning and inserting new raw material to the group (at the same time made some adjustments from the control panel after waiting for some time.) | 4.8 | Throat cleaning material, raw material | The worker is waiting. It can also be done before connecting the mold. |
| 16 | Getting the first sample | 0.5 | Sample | Since some of the adjustment work was done during throat cleaning, the first sample was taken in a shorter time. |
| 17 | Operating the mold to remove dirt inside it | 4.5 | Test products | For time reduction, the new mold can come from the molding room in a well-maintained condition |
| 18 | Performing initial quality control of the sample | 24.0 | Caliper, sample, computer, Uyumsoft | The duration varies depending on the criteria and sample number. Currently, made externally. 20 out of 700-800 types of products, this process is not made externally. Average number of criteria=8, measurement time for each sample=approx. 1.5 min., mold for this model is 16 cavities |

Table 1 (cont). Preparation process for key switch body plastic injection machine.

| | | | | |
|---|---|---|---|---|
| 19 | Opening the closed needle runner of the mold | 2.6 | Stapler, hammer, and mold | This process occurs in the mold control when the previous mold is removed and can be handled during that process, then the mold can be placed on the shelf. |
| 20 | Bringing the 6-7 switches and tightening the cooling water hose | 2.0 | 6-7 switches, hose, clamp | It took 40 seconds to search and retrieve 6-7 switches. The hoses must be avoided when removing the mold from the shelf. |
| 21 | Hose and column shaft cleaning | 0.1 | Cloth, Column shaft | Dripping occurred because the hoses were loose. If the clamps were tight, this job wouldn't be done. It's pointless to do it internally. |
| 22 | Bringing the tube and warming the nozzle | 4.5 | Tube, lighter, nozzle | It took 69 seconds to light the tube. (The lighter did not work, a match was used.) |
| 23 | Removal of raw material residues | 0.8 | Tube, lighter, nozzle | |
| 24 | Sampling after mold correction | 2 | Sample, crate | |

The setup process is divided into 24 work steps. For each work step, the materials used and the comments made regarding the improvement of the tasks are specified. The machine used for the setup process is the injection molding press machine. In the current situation a worker is responsible for the setup tasks, ranging from mold and material preparation to the finishing tasks after the switch body is removed from the mold. The precedence relationship between setup tasks is given in Figure 4.

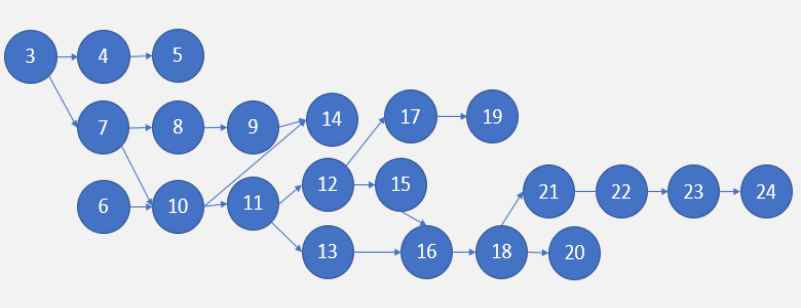



Figure 4. Precedence graph between setup tasks.

B. *Classifying the Setup Tasks*

When implementing the SMED steps, the first step involves the classification of setup tasks, separating them into internal and external tasks. Accordingly, 9 tasks can be categorized as external setup tasks, while 15 tasks fall under the category of internal setup tasks. Among the internal tasks, 2 tasks (H-9 and H-20) can potentially be performed as external tasks with some adjustments, and thus, they are classified as potential external setup tasks. Potential external setup tasks that require minor adjustments for external execution have been identified. Accordingly, the process of removing the mold and bringing it to the press level (H-9) can be performed externally with some modifications. The process of opening the closed pin channel of the mold (H-19) can be handled when the previous mold is removed, as mold inspection will also take place, and the mold can then be placed on the shelf. In other words, this task can be eliminated through an external inspection after the mold is removed. The task of bringing 6-7 switches and tightening the cooling water hose (H-20) took 40 seconds. These hoses need to be protected when the mold is taken from the shelf. This task can also be classified as a potential external setup activity.

C. *Converting Internal Setup Tasks into External Tasks*

Out of the 24 setup tasks, 2 tasks have been converted into external tasks with the implementation of certain suggestions. The potential external setup tasks, H-9, H-19, and H-20 have been classified as external tasks for future execution. Cleaning, lubrication, and tightening tasks currently need to be completed within 5.2 minutes. These types of setup tasks (H-7 and H-8) have been converted into external activities by transferring responsibility to the operator within the framework of Autonomous Maintenance. The implementation of Autonomous Maintenance has been consolidated with standardization, visual

management, planning, and layout operations to ensure that daily maintenance activities do not disrupt machine operation. As a result, the total time required to complete all internal setup tasks has been reduced by 5.2 minutes.

D. *Improvements for All Setup Tasks*

Reducing the durations of internal and external setup tasks can make the injection molding press setup process more efficient and cost-effective. The external setup tasks H-1 and H-2 often take longer because the material is usually not left inside the hopper. In some cases, the injection machine was observed to continue producing the previous batch. For the external task H-3, allocating a designated space for the hopper lid will significantly reduce the task's duration. For the external task H-8, a spare mold cart can be provided, or an appropriate space allocation can be made for the mold cart. The external task H-11 can be performed externally with the assistance of parallel workers by increasing the number of eye bolts, while technical equipment will be procured for connecting mold plates. For the internal task H-12, installing an electric hoist (a device used in industrial settings for lifting and transporting loads) will significantly reduce the time. In the internal task H-13, using a star wrench or ratchet wrench can improve the tightening torque and speed. The duration of the internal task H-14 can be shortened by obtaining plug-and-use cooling adapters. Using a magnetic ignition torch in the internal task H-22 will also reduce the time required. After all the improvements, the number of first quality control samples (H-18) has been reduced by half. Because now that production has been improved, the number of flawless products has increased. By the end of the SMED steps, the total setup time was reduced from 67 minutes to 48 minutes, achieving an improvement of approximately 28%.

E. *Scheduling Setup Tasks*

In today's increasingly competitive conditions, having product diversity in the market gives firms a competitive advantage. However, producing in small batches leads to non-value-added setup process times. Although these non-value-added times can be shortened using the above-mentioned SMED methodology, the makespan of these processes should be optimized through the assignment of parallel workers to maximize machine utilization time. In this context, the proposed model aims to minimize the makespan of tasks by scheduling parallel workers for setup tasks. For this purpose, the completion time of 24 preparation tasks with five different workers was measured. By solving the model varying the number of worker allocations from 1 to 5, worker allocation and scheduling decisions were determined. The model also considers precedence constraints. The model's capacity to adjust the number of workers assigned to setup tasks facilitates scheduling applications under different scenarios. Importantly, the model was executed under two different conditions: (1) without applying SMED, and (2) after applying SMED, which results in improved setup durations. This dual implementation enables a clear comparison of the performance improvements introduced by SMED under different worker allocation scenarios. Thus, the model not only facilitates dynamic scheduling of parallel workers but also provides insights into the effectiveness of SMED in reducing setup times across varying workforce configurations.

The code for the proposed mathematical model is implemented in Python 3.11 using the Pyomo interface. The model was solved multiple times with the Gurobi solver, considering different numbers assigned workers. Different makespans were obtained by using different numbers of workers in set up tasks and given in Table 2. As expected, the assignment of a large number of workers shortens the makespan of tasks.

Table 2. The results for changing the number of workers.

| Number of workers | SMED | Makespan of tasks ($C_{max}$) | Worker occupancy rate | | | | |
|---|---|---|---|---|---|---|---|
| | | | W1 | W2 | W3 | W4 | W5 |
| 1 | NO | 67.17 | - | - | 100 | - | - |
| | YES | 48.21 | - | - | 100 | - | - |
| 2 | NO | 43.18 | - | 64.71 | 91.79 | - | - |
| | YES | 25.09 | - | - | 95.89 | 92.19 | - |
| 3 | NO | 42.62 | - | 20.38 | 83.10 | 53.54 | - |
| | YES | 24.59 | 36.1 | - | 82.9 | 74.6 | - |
| 4 | NO | 42.21 | 32.48 | 20.55 | 60.75 | 39.73 | - |
| | YES | 24.45 | 48.43 | - | 66.83 | 36.40 | 32.07 |
| 5 | NO | 42.21 | 34.26 | 17.65 | 64.29 | 24.65 | 10.86 |
| | YES | 24.44 | 17.76 | 15.63 | 66.98 | 44.84 | 40.30 |

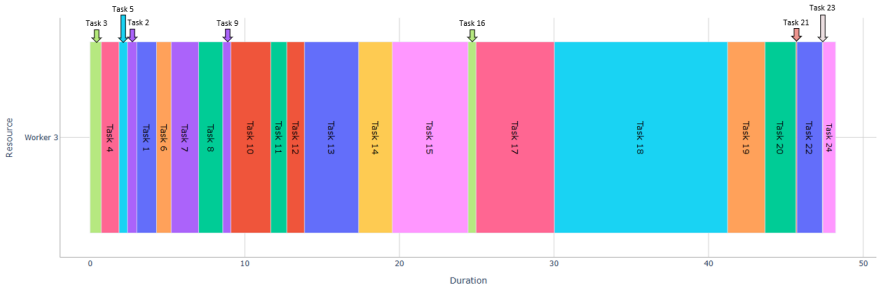
The results clearly demonstrate the substantial advantages of applying the SMED methodology in reducing makespan. Across all worker scenarios, SMED significantly lowers task completion times by reducing non-value-added setup durations. When one worker is assigned to setup tasks, SMED reduces the makespan from 67.17 to 48.2 minutes, representing an improvement of nearly 28%. Beyond the standalone impact of SMED, the results also show that combining SMED with parallel worker allocation further enhances system performance. When parallel workers are assigned, providing improvements of approximately 42% when 2, 3, 4, and 5 workers are assigned. This indicates that SMED enhances the effectiveness of worker allocation by minimizing setup durations, enabling workers to contribute more efficiently to task completion.

According to the results, initially, increasing the number of workers leads to a significant improvement in makespan values in both the SMED and non-SMED cases. Specifically, when SMED is implemented, the transition from 1 to 2 workers reduces the makespan from 48.21 to 25.09 minutes. Similarly, in the absence of SMED, the makespan drops from 67.17 to 43.18 minutes. These results indicate that increasing worker numbers yields substantial gains at early stages. However, as more workers are added, the benefit of increased parallelism gradually decreases in both SMED and non-SMED scenarios. This indicates that after a certain number of workers, additional workers provide diminishing returns, and the overall efficiency becomes limited. The limited impact of increasing the number of workers on makespan highlights the role of precedence constraints, which are based on the sequence and priorities of tasks. These constraints prevent additional workers from accelerating the workflow, thereby limiting the improvement in makespan.

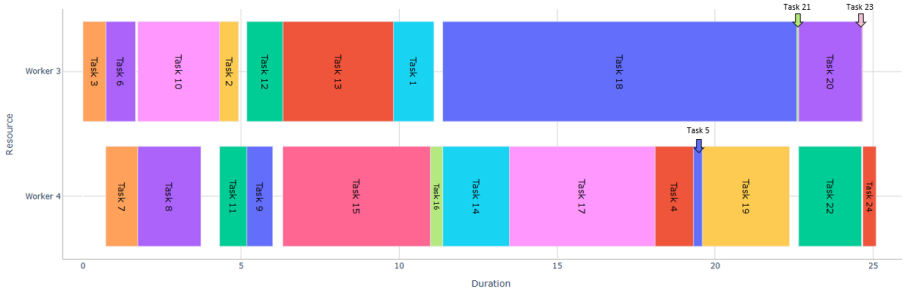
Increasing the number of workers affects the worker occupancy rates. Initially, for the scenarios 1 and 2 workers assigned, the occupancy rates are high; however, these rates gradually decline as the number of workers increases, falling below 20% for some workers in the five-worker scenario. When two workers are assigned, both exhibit high occupancy rates under the SMED scenario (e.g., 95.89% and 92.19%), indicating efficient utilization. In contrast, without SMED, the workload becomes less balanced, with one of the workers significantly underutilized. A similar trend is observed for scenarios with 3 and 4 workers. Although precedence constraints limit scheduling flexibility, the reduced task durations achieved through SMED enable more efficient allocation, allowing for a better-balanced distribution of workload across workers. In particular, the decline in worker occupancy rates with 4 and 5 workers, in both SMED and non-SMED scenarios, indicates that these worker numbers are not optimized in terms of workforce efficiency. Meanwhile, the makespan improvements from increasing the number of workers from 3 to 4 and from 4 to 5 are less than 1%. In this case, the improvement achieved by assigning new workers is insufficient when the costs are considered. Figure 5 depicts the Gant diagrams of setup tasks under different worker assignment scenarios within the SMED-applied context.

Overall, we observe fluctuations in the occupancy rates as the number of workers increases, and additional worker assignments do not always have the same effect on reducing the setup time. Especially after 3 workers, the lower occupancy rates suggest that adding more workers does not significantly improve system efficiency and may be approaching its maximum potential. In addition, some variation in individual worker load can also be observed across different scenarios. Worker 3 consistently takes on a greater workload across all scenarios. This outcome is a direct result of the worker heterogeneity incorporated into

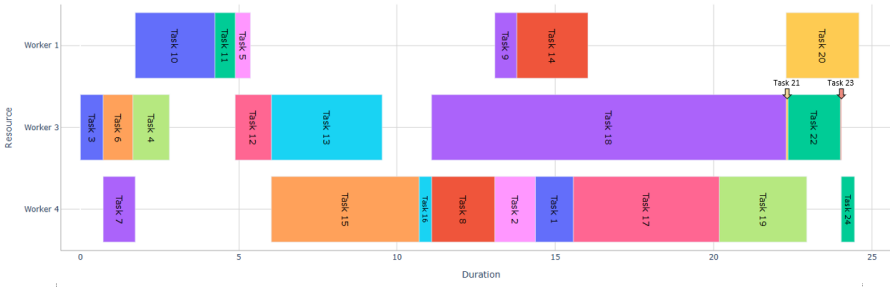
the model, where each worker has different task processing capabilities. From a purely mathematical optimization perspective, the model aims to minimize the overall makespan and hence favors assigning more tasks to faster or more efficient workers. However, in practice, such imbalanced workload distribution could raise concerns regarding fairness and workforce well-being. Therefore, future work may incorporate equity-based constraints, such as limiting the difference between the total workload assigned to each worker or introducing upper bounds on individual worker utilization, to ensure a more balanced distribution of workload among workers.



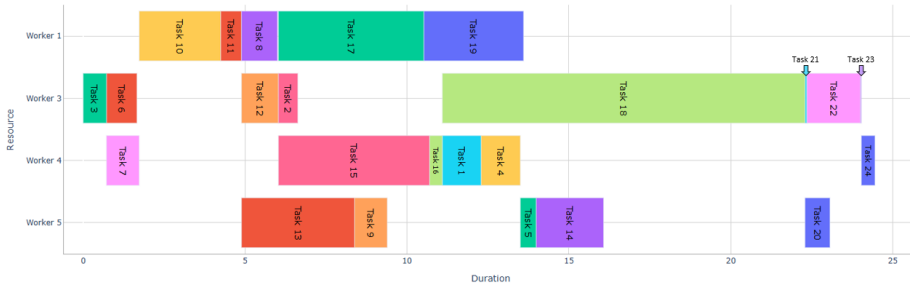

(a) One worker



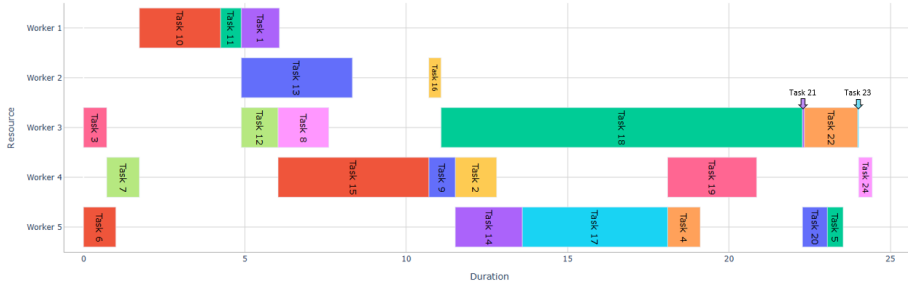

(b) Two workers




(c) Three workers




(d) Four workers




(e) Five workers

Figure 5. The Gant diagrams of setup tasks.

The Gantt charts presented in Figure 5 illustrate the scheduling of setup tasks under varying worker allocations. As seen in subfigure (a), when only one worker is assigned, tasks are executed sequentially,

leading to the longest makespan. In contrast, subfigure (b) shows a significant reduction in total setup duration with the use of two parallel workers, as tasks are distributed across both workers with minimal idle time. With three and four workers (subfigures (c) and (d)), idle times increase and workload becomes less balanced, particularly in the case of four workers, where some workers are underutilized. With five workers (subfigures (e)) while the makespan remains nearly the same as in the four-worker case, a significant portion of the workers' time appears idle.

## IV. CONCLUSION

Reducing setup times remains a critical challenge in manufacturing systems as companies strive to adapt to increasing product variety and diverse customer demands. This study addresses this challenge by proposing a novel roadmap that integrates the SMED methodology with parallel worker utilization and personnel scheduling. By focusing on this integration, the study bridges an important gap in the existing literature, where the SMED methodology has seldom been combined with worker-specific scheduling optimization models. The proposed methodology was implemented in a company producing electrical components for the white goods industry, specifically targeting the setup process for the push-button switch product family using an injection molding press machine. The roadmap's application revealed several significant findings. First, the classification of setup tasks into internal and external categories allowed for systematic improvements. Nine tasks were identified as external, while 15 were internal, with three internal tasks classified as potential external tasks. The implementation of Autonomous Maintenance and other organizational and technological improvements successfully converted two internal tasks into external ones, reducing overall setup times. Operational enhancements such as material tracking systems, space allocation, and the acquisition of an electric hoist further streamlined the setup process. As a result of these efforts, setup times were reduced by approximately 28%, from 67 minutes to 48 minutes. This reduction only improved by applying classical SMED steps.

Although these non-value-added times can be shortened using the above-mentioned SMED, the makespan of these processes should be optimized through the assignment of parallel workers to maximize machine utilization time. In this context, the proposed model aims to minimize the makespan of tasks by scheduling parallel workers for setup tasks. The model considers precedence constraints. Additionally, in the model, the number of personnel commissioned to set up tasks can be varied, enabling scheduling applications under different scenarios. Solving the mathematical model demonstrated that utilizing two parallel workers reduced the maximum makespan by approximately 48%. However, improvements diminished when more than two workers were used. This reduction not only improved operational efficiency but also eliminated waste such as unnecessary walking, transportation, and displacement, typically carried out by a single worker. These improvements demonstrate the practical applicability of the proposed roadmap and its potential to enhance efficiency in similar manufacturing settings. The contributions of this study are significant. It is the first to integrate parallel worker scheduling with the SMED methodology, proposing a mathematical model that accounts for precedence relationships between setup tasks. This approach offers a comprehensive optimization framework for reducing setup times, enhancing its relevance for complex manufacturing environments.

Despite the valuable contributions of this study to the literature, it also has certain limitations. First, since the objective of the mathematical model is to minimize the makepsan, it may result in an imbalanced workload distribution among workers. To address this issue, the model could be extended into a multi-objective framework by incorporating workload balancing as an additional objective. Another limitation is the assumption that assigning multiple workers to setup tasks on the same machine simultaneously does not affect processing times. In practice, space constraints may lead to increased setup times due to interference between workers. In addition, the model was formulated under the assumption that every worker can perform every task, based on the dataset used in this study. However, in real-world scenarios, skill-based constraints may exist, where certain workers are not qualified to perform specific tasks due to differences in skills or competencies. All scenarios were solved using the Gurobi solver on a standard desktop computer equipped with an Intel Core i7 processor and 16 GB of RAM. The solution times consistently remained under 4 minutes, and memory usage stayed within acceptable limits across all instances. The model demonstrated efficient performance for small- to medium-sized problem instances. Nevertheless, it is recognized that the model's computational time and memory requirements may be increased as a result of the increased number of variables and constraints when its scaled to substantially larger instances. In large-scale manufacturing facilities, the proposed model can be expanded by considering more workforce groups and specialized tasks to optimize parallel workers. Additionally, Industry 4.0 technologies (such as IoT, AI-supported scheduling systems) can be integrated to enhance

workforce planning and scheduling processes with digital solutions. The core principles of SMED can be easily adapted to various manufacturing sectors such as automotive, food and beverage, pharmaceuticals, and textiles. Given the high product diversity and complex assembly processes, integrating workforce planning with SMED can increase flexibility on the production line.

Future studies could explore the adaptation of this roadmap to other industries or types of manufacturing equipment. Additionally, further research could expand on the integration of advanced technologies, such as IoT-based monitoring systems and predictive analytics, to further optimize setup processes. These advancements could pave the way for more robust and adaptive manufacturing systems, contributing to sustainable operational practices in the industry.

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**Availability of Data and Materials**: Data sharing is not applicable to this study.

**Use of AI Tools:** The author/authors declare that no Artificial Intelligence (AI) tools were used in the creation of this article.

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