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Design and functional evaluation of a portable workstation for rapid changeover simulation

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ABSTRACT

The aim of this study was to develop and functionally evaluate a portable, reconfigurable workstation for controlled rapid-changeover simulation based on the single-minute exchange of die (SMED) approach. The device was designed to reproduce selected structural and organisational features of a machine changeover and to allow users to identify losses, introduce non-permanent modifications and measure their combined effect. The evaluation involved 30 four-person teams. Each team carried out two consecutive changeovers of the same workstation: the first in the baseline configuration and the second after implementing SMED-oriented improvements. Internal changeover time was used as the main performance measure, and the modifications introduced by the teams were grouped according to SMED principles. Mean internal changeover time decreased from 31 min 22 s to 7 min 32 s, corresponding to a mean saving of 23 min 50 s and a reduction of 75.32%. The difference was statistically significant, with a very large effect size, and internal changeover time decreased in all teams. Because the second changeover always followed the baseline trial, the observed reduction should be interpreted as the combined effect of the implemented modifications and repeated task performance, including increased familiarity with the workstation and task. After the improvements, 23 of the 30 teams achieved an internal changeover time below 10 min. The implemented modifications included external preparation of selected activities, simplified fastening and sheet attachment, standardisation of screws and tools, visual positioning aids and elimination of redundant nuts. The results show that the workstation provides controlled and standardised conditions for reproducing changeover losses, implementing alternative improvement paths and quantitatively evaluating the combined effect of SMED-oriented modifications.

Keywords: portable workstation, rapid changeover, changeover time, functional evaluation, single-minute exchange of die, lean management.

INTRODUCTION

The SMED rapid changeover concept

Single-minute exchange of die (SMED) is one of the key tools used in Lean Management, which aims to improve organisational processes through continuous improvement, cost reduction, and increased throughput and production efficiency [1]. SMED is an approach based on striving to reduce changeover time as much as possible – ideally to a single-digit number of minutes [2]. Changeover time is the time between the completion of production of the last item of the previous batch and the first good piece of the next batch [3]. In practice, machine changeovers are often unavoidable because dedicating separate machines to every product would increase equipment, maintenance, and floor-space costs. Machine changeovers, however, allow more than one type of product to be produced on the same machine [4].

Reducing changeover time increases production flexibility, enabling production that responds to diverse customer requirements [5, 6]. This stands in contrast to still-popular mass production in large batches, which generates a range of costs for companies [7] and is referred to in Lean Management as waste (Japanese: *muda*) [8].

The SMED concept is applied in almost every branch of manufacturing, as well as in services. This creates demand not only for equipping employees and future employees with knowledge and skills related to SMED, but also for controlled environments in which changeover losses can be reproduced, analysed and reduced without interfering with industrial production. Consequently, the importance of physical tools and scenarios enabling hands-on practice and the evaluation of SMED-oriented improvements under controlled and standardised conditions is increasing.

In this article, the workstation is treated as the primary engineering object, while changeover-time improvement is used as a functional response of the combined workstation-and-task system. The comparison of changeover times indicates whether the baseline configuration generates diagnosable losses and whether technically feasible, non-permanent modifications reduce internal changeover time as intended. It is not treated as a complete measure of learning outcomes.

The changeover process according to the SMED concept

A machine changeover may involve a range of activities needed to adapt the machine to a different product, depending on the machine and the operation performed [6, 9]. These may include, among others, workplace preparation, tool and material preparation, removal and installation of elements, cleaning, adjustment and programming [10].

The aim of SMED is to perform changeover activities so that machine downtime is minimised. The classic description of SMED proposed by S. Shingo takes the form of successive levels of improving the changeover process (from not distinguishing between internal and external operations to their full optimisation) [2]. In the literature, various adaptations of these levels into successive procedural stages can be found [11, 12]. SMED has also been combined with other setup-analysis tools [13]. Based on these approaches, the SMED procedure adopted in this study was organised into the following four stages:

- as accurate a representation of the initial changeover process as possible, followed by its analysis;
- optimisation of the performed activities, including:
  - eliminating unnecessary activities,
  - converting internal activities into external ones,
  - simplifying the performed activities,
  - introducing parallel operations;
- standardising activities and developing proficiency in carrying them out;
- further improvement of activities.

Regardless of the specific approach, a key element of SMED is the distinction between internal and external operations within all activities. Internal operations are those that can only be performed during machine downtime, i.e., when the machine is not running. External operations do not require stopping the machine and can be performed before or after internal operations [14].

Requirements for hands-on SMED training and workstation design

Despite its significant advantages, the SMED concept often encounters implementation problems, sometimes even leading to abandoning its implementation. It is considered demanding, especially when SMED is not sufficiently understood or when there is a lack of knowledge about how its individual stages are interrelated [15]. The main obstacle to implementing this method – highlighted by many researchers – is the lack of personnel training [16, 17]. Similar conclusions have been reported in other manufacturing contexts [18, 19].

As emphasised by E. B. Mahamad, T. Ito and D. Yuniawan [20], it is important that SMED training is not only theoretical but also combines theory with practice. They also point out that a lack of appropriate training in SMED (and more broadly: Lean Management) may lead to difficulties in choosing appropriate Lean tools. It is also noted that insufficient attention is paid to team performance during SMED programmes in the literature [21].

A meta-analysis of undergraduate science, technology, engineering and mathematics (STEM) courses showed that active learning improved examination performance and reduced failure rates compared with traditional lecturing [22]. For SMED, this relationship is

particularly important: applying it in professional work requires not only theoretical knowledge of the concept but also process optimisation skills, the ability to analyse individual activities in terms of converting them from internal to external, responsibility for the product and the machine, solution design and teamwork, and manual skills.

From a design perspective, a physical workstation for SMED practice should enable safe experimentation, teamwork, feedback and repeated restoration of a defined baseline configuration. These requirements are consistent with experiential learning [23]. They are also reflected in Lean simulations and games [24, 25]. Similar emphasis on direct participation can be found in engineering education studies describing low-cost, easy-to-assemble laboratory test stands [26].

Gap in SMED training workstations

Lean education increasingly uses simulations [24]. Available literature indicates that the SMED concept appears in these simulations at most marginally [25, 27]. However, several training approaches have addressed SMED, or at least setup time reduction, either as one component of a broader Lean simulation or as the subject of a dedicated exercise. Examples of available training tools related to the SMED concept include the physical simulation game described by Vaz de Carvalho et al. [25], in which an extended stamp-change time provides a starting point for introducing SMED as one of several Lean tools; the Lean manufacturing learning laboratory developed by Helleno et al. [28], where one group of participants applied SMED to reduce the setup time of a drilling workstation within a broader Lean programme; the Lean manufacturing tools training system for SMED (LMTTS-SMED) proposed by Mohamad and Ito [29], which combines an e-learning module with computer-based simulation of SMED implementation on a modelled production line; and the three-round LEGO assembly-line simulation described by Haque et al. [30], in which the SMED component involved comparing two predefined die-mounting arrangements.

These tools are valuable, but address only part of the needs associated with practical SMED training. In the physical game described by Vaz de Carvalho et al. and the laboratory developed by Helleno et al., SMED is one of several Lean tools applied within a broader production-process simulation or an extensive laboratory programme, rather than the main subject of the training. The LMTTS-SMED system is computer-based and therefore does not involve the physical execution of changeover operations. The simulation described by Haque et al. allows participants to observe the effect of reduced changeover time on the production process; however, the exercise uses two previously prepared fastening arrangements. It is therefore not an open-ended task in which participants independently design an SMED solution and implement different alternative modifications to the changeover mechanism.

Against this background, a gap can be identified not only in simulation games but especially in dedicated, portable laboratory workstations that reproduce changeover losses and permit repeated implementation of alternative SMED-oriented modifications.

To document and evaluate these features, this paper: (1) describes the workstation design requirements, construction and operating rules; (2) shows how its baseline features create identifiable sources of changeover loss and allow multiple non-permanent modifications within defined constraints; and (3) presents a task-based functional evaluation based on changeover-time reduction and verification of the "single-digit minutes" criterion (Time II < 10:00) [2].

The novelty and main engineering contribution of this study lie in combining, within one portable and reusable workstation-and-task system:

1) hands-on SMED learning and training without the need to use industrial machinery or interrupt an actual production process;
2) a deliberately designed baseline configuration that contains identifiable sources of changeover loss and enables participants to recognise and analyse them;
3) practical application of the principal SMED logic, from analysing the baseline changeover and distinguishing internal and external activities to developing, implementing and evaluating improvements;
4) a reconfigurable design that allows participants to independently develop and physically implement different non-permanent technical and organisational solutions rather than reproduce a single predefined answer; and
5) objective assessment of the combined effect of the introduced improvements using measured internal changeover time and a clearly defined task-completion criterion.

The workstation can subsequently be restored to the same baseline configuration, enabling its repeated use under controlled and standardised conditions. This study evaluates the functional suitability of the portable training device and exercise scenario for hands-on SMED practice. The evaluation is based on comparing the time of the first changeover in the baseline workstation configuration (Time I) with the changeover time after implementing solutions characteristic of SMED (Time II) in a repeated-measures design.

The educational use remains an intended application, but the present analysis focuses on whether the physical prototype enables a complete and measurable SMED improvement cycle under safe and controlled conditions.

Research aim, questions and hypothesis

The aim of the study was to develop a portable and reconfigurable workstation that reproduces selected structural and organisational characteristics of a machine changeover and enables the implementation and quantitative evaluation of SMED-oriented improvements.

The following research questions were formulated:

1. RQ1: Does the workstation enable the implementation of SMED-oriented modifications that result in a measurable reduction in internal changeover time?
2. RQ2: Which modifications to the baseline workstation configuration are identified and implemented during the changeover improvement process?

The following hypothesis was formulated for the quantitative evaluation – the internal changeover time obtained after implementing SMED-oriented modifications to the workstation is significantly shorter than the changeover time obtained for its baseline configuration.

MATERIALS AND METHODS

The study used a repeated-measures functional evaluation in which the unit of analysis was the team performing two consecutive changeovers of the same device (baseline and after implementing improvements). This design allowed each team to serve as its own reference when comparing the baseline and improved workstation configurations, thereby limiting the influence of between-team differences in task execution. Quantitative data consisted of internal changeover times, and qualitative evidence consisted of observed workstation-related problems and optimisation actions reported by teams after the first changeover.

Design and construction of a device for teaching rapid changeover according to the SMED concept

Due to the identified gap in the availability of workstations enabling hands-on SMED practice, a portable laboratory workstation was developed to simulate the changeover of a simplified "printing machine" under controlled conditions. The workstation was designed to provide a clearly observable task-completion criterion and to enable changeover-time measurement, identification of waste, and implementation and evaluation of SMED-oriented modifications.

The schematic construction of the workstation is presented in Figure 1(a), while the physical prototype used in the functional evaluation is shown in Figure 1(b). The main structure consists of a base plate (1) supported by four legs (2) and two independent clamping assemblies. Each clamping assembly comprises a lower wooden clamping element (5) and an upper wooden clamping element (6), between which a wax crayon (7) is held. A slot (3) in the base plate allows the sheet carrier (4) to pass between the two oppositely positioned crayons.

During operation, the complete sheet carrier is moved through the slot between the crayons. Each crayon simultaneously produces a mark on the paper sheet located on its respective side of the carrier. The direction of carrier movement is not functionally constrained, provided that both crayons remain in contact with the corresponding paper sheets. The production of both required colour marks provides a clear criterion for determining whether the workstation has been assembled and adjusted correctly.

The main dimensions, mass, and construction materials of the workstation are summarised in Table 1. The workstation body height includes the protruding screws, whereas the overall height with the sheet carrier installed is reported separately.

The base plate, legs, and upper and lower clamping elements are made of wood. This material was selected because it is readily available,

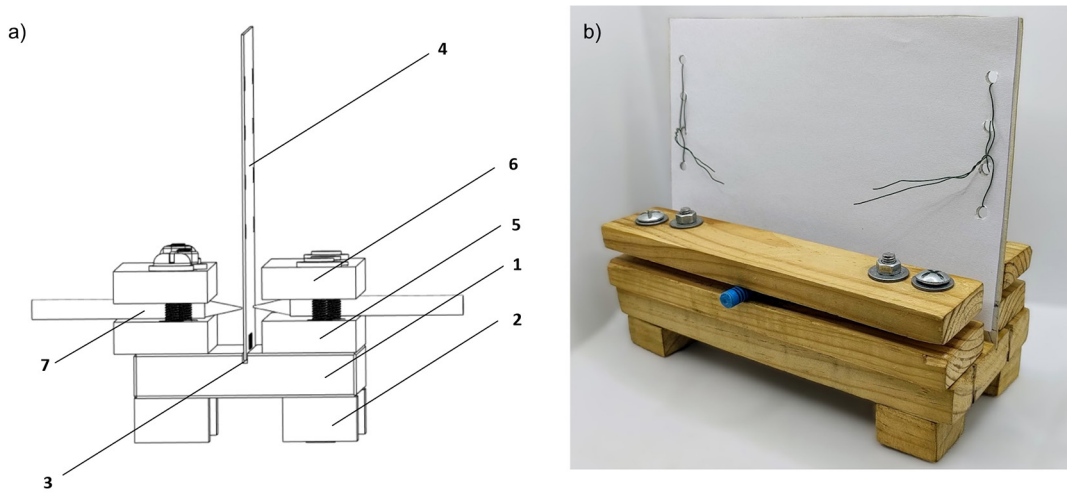


Figure 1. Construction and physical implementation of the portable workstation: (a) schematic side view with numbered components: 1 – base plate; 2 – leg; 3 – slot; 4 – sheet carrier; 5 – lower clamping element; 6 – upper clamping element; 7 – wax crayon; (b) prototype used for functional evaluation

Table 1. Main technical characteristics of the workstation

Parameter		Specification
Dimensions of the assembled workstation body, excluding the sheet carrier (L × W × H)		210 × 113 × 85 mm
Overall dimensions of the assembled workstation with the sheet carrier installed (L × W × H)		210 × 113 × 180 mm
Mass of the complete workstation		607 g
Materials	Main structural material	Wood
	Screws, nuts and threaded inserts	Metal
	Replaceable marking elements	Wax crayons
	Sheet-carrier materials	Stiffened cardboard and paper

easy to machine, and suitable for repeated disassembly, modification, and repair. Wax crayons are used as replaceable marking elements. Their brittleness introduces an additional material-handling constraint because incorrect positioning or excessive clamping force may damage them.

The workstation was intentionally simplified. Its purpose was not to reproduce the technological complexity or external appearance of an industrial machine, but to reproduce selected structural and organisational features of a changeover process in a portable, safe, and reconfigurable form.

The arrangement of the drilled holes and the disassembled workstation components is shown in Figure 2. The workstation contains twenty-four drilled holes. Each of the four wooden clamping elements contains four holes, giving sixteen holes in the upper and lower clamping elements. The holes marked 8 are through-holes used for the full-height connections formed by screws 13. They are aligned with the corresponding holes in the base plate (10) and the legs (11). The holes marked 9 are used to connect the upper and lower clamping elements by means of screws 12. In the upper clamping elements, holes 9 contain threaded inserts into which the screws are threaded from below.

Four additional holes marked 10 are located in the base plate, and one hole marked 11 is located in each of the four legs. The holes 10 and 11 contain threaded inserts and are arranged coaxially with holes 8 in the clamping elements. This arrangement enables each full-height screw 13 to pass through the upper and lower clamping elements and then engage successively with the threaded inserts in the base plate and the corresponding leg.

Twelve threaded inserts are permanently installed in the workstation: four in the base plate at locations 10, two in each of the two upper clamping elements at locations 9, and one in each of the four legs at locations 11.

The two fastening arrangements used in the baseline workstation configuration are shown in Figure 3. Screws 12 are slotted-head screws

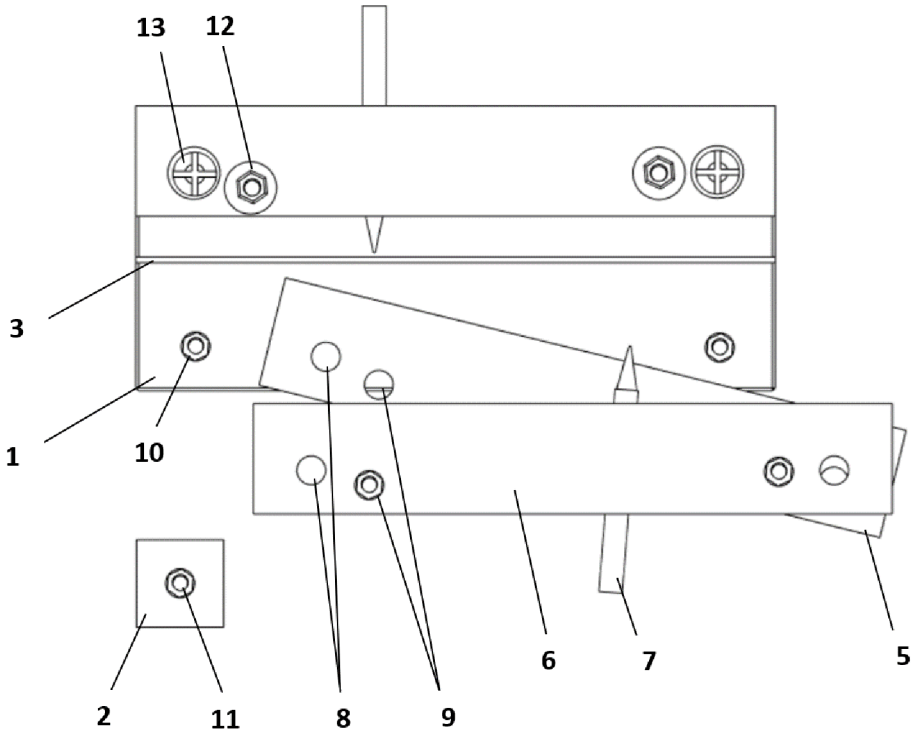


Figure 2. Top view of the workstation and its disassembled components: 1 – base plate; 2 – leg; 3 – slot; 5 – lower clamping element; 6 – upper clamping element; 7 – wax crayon; 8 – through-holes for the full-height screws; 9 – holes used to join the upper and lower clamping elements; 10 – threaded-insert holes in the base plate; 11 – threaded-insert holes in the legs; 12 – slotted-head screws joining the upper and lower clamping elements; 13 – full-height Phillips-head screws connecting the clamping assemblies, base plate, and legs

inserted from below through the lower clamping elements and threaded into inserts embedded in the corresponding upper clamping elements. A nut is additionally threaded onto the protruding upper end of each screw. However, the nut is functionally redundant because the screw is already retained by the threaded insert. The nuts were deliberately included in the baseline configuration as unnecessary components that could be identified and eliminated during the improvement stage.

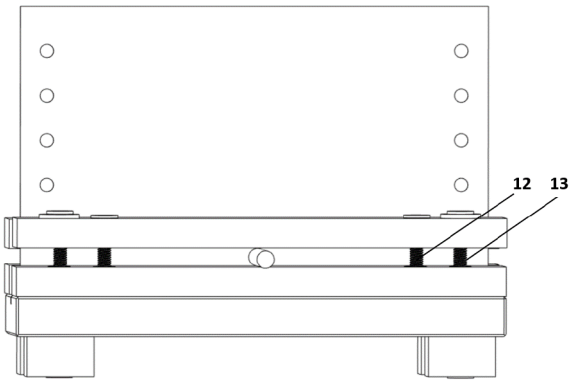


Figure 3. Front view of the workstation showing the slotted-head screws joining the upper and lower clamping elements (12) and the full-height Phillips-head screws connecting the clamping assemblies, base plate, and legs (13)

Screws 13 are long Phillips-head screws inserted from above through the upper and lower clamping elements. Each screw is then threaded successively into an insert embedded in the base plate and an insert installed in the corresponding leg. Consequently, a single full-height screw connects the clamping assembly, base plate, and leg. To separate these components, the screw must be completely unthreaded from both inserts. The use of slotted-head and Phillips-head screws in the baseline configuration additionally requires different tools during disassembly and assembly.

The construction of the sheet carrier is shown in Figure 4. The sheet carrier (4) consists of a stiffened cardboard insert placed between two replaceable paper sheets, one on each side. Four holes are punched on each lateral side of the cardboard insert and the paper sheets. In the baseline configuration, the three layers are joined using wire passed through these holes. The lower section of the cardboard insert is marked as an area

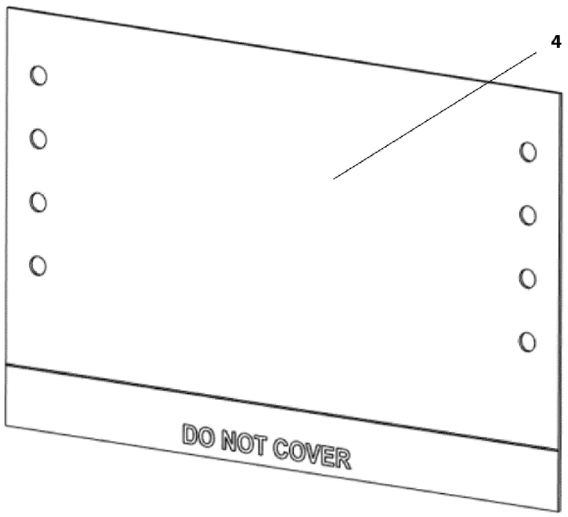


Figure 4. Sheet carrier (4) consisting of a stiffened cardboard insert and two replaceable paper sheets, with punched attachment holes and the marked area that must remain uncovered

that must remain uncovered. Covering this section with the paper sheets could cause them to rub against the edges of the slot and impede movement of the carrier through the workstation.

The combination of long threaded connections, different screw-head types, functionally redundant nuts, an asymmetric hole pattern, brittle marking elements, and a wire-connected sheet carrier creates a controlled baseline changeover containing several identifiable sources of unnecessary time, motion, adjustment, and material loss. At the same time, the workstation allows alternative fastening, preparation, marking, and assembly solutions to be introduced without permanently modifying its principal structural elements. This enables users to measure the baseline changeover time, implement SMED-oriented modifications, and quantitatively evaluate their effect.

Simulation assumptions

The task performed using the workstation consisted of replacing the paper sheets and crayons with new ones in the colours specified by the instructor. The dependent variable used in the functional evaluation was internal changeover time, measured for two consecutive trials: Time I for the baseline configuration and Time II after the implementation of SMED-oriented modifications. Before the first trial, participants were given time to inspect the workstation and received a short briefing covering:

1) the purpose and operating principle of the workstation;
2) the baseline changeover procedure;
3) the task-completion criterion;
4) the constraints governing the modifications that could be introduced.

The following constraints were applied:

- the workstation and the materials used in the task could not be damaged; for example, washers had to be placed beneath screw heads or nuts pressing directly against wooden surfaces;
- electronic devices could not be used;
- permanent modification of the workstation was not permitted, including additional drilling, cutting, or shortening of structural elements;
- a colour-identification label indicating the installed colour had to remain between the upper and lower clamping elements, representing the programme or settings of a real machine;
- the crayons had to be sharpened before each installation;
- the modifications had to be consistent with Lean Management principles and could not result in defective assembly or reduced structural integrity;
- the number of installed screws could not be reduced.

The workstation was provided in the baseline configuration described above. The full-height Phillips-head screws connected the clamping assemblies, base plate, and legs, whereas the slotted-head screws connected the upper and lower clamping elements. Redundant nuts were fitted above the upper clamping elements. Crayons were installed between the clamping elements, and an adhesive label identifying the installed colour was placed on the inner surface of the upper clamping element above each crayon. The paper sheets were attached to the stiffened cardboard insert using wire passed through the punched holes.

At the beginning of each changeover trial, the instructor issued an order specifying the two colours to be produced. To complete the changeover, participants had to:

- disassemble the relevant workstation components;
- remove the previously installed crayons;
- sharpen and install crayons in the required colours;
- prepare and attach the corresponding colour-identification labels;

- remove the used paper sheets from the sheet carrier and attach clean sheets to the stiffened cardboard insert;
- reassemble and adjust the workstation; and
- move the sheet carrier through the slot so that both crayons produced the required colour marks.

The changeover was considered complete when two correct colour marks had been produced, one on each side of the sheet carrier, and none of the stated constraints had been violated.

In addition to the workstation, participants initially received:

- wax crayons in various colours;
- a crayon sharpener;
- sheets of paper;
- scissors;
- adhesive label material;
- a pen;
- a hole punch;
- a Phillips screwdriver matched to the installed screws;
- a slotted screwdriver matched to the installed screws;
- a wrench matched to the installed nuts.

Additional materials and tools that could be used to introduce improvements were made available separately during the improvement stage, as described below.

Participants and study teams

To evaluate the functional response of the designed device and the task carried out with it, 30 four-person teams (n = 30; N = 120 participants) performed two changeovers of the same device (Time I and Time II). The unit of analysis was the team. Each team designated one leader, who remained the same in both rounds, while the remaining members supported process analysis and the selection of modifications. The resulting dataset comprised 60 internal changeover-time measurements: two paired measurements, Time I and Time II, for each of the 30 teams. Teams were identified in the dataset only by numerical codes from 1 to 30, which were used to pair the two measurements and the team-level records of implemented modifications. All teams completed both trials, and no teams, trials, or recorded measurements were excluded from the analysis. No participant-level identifiers were included in the dataset.

The evaluation was conducted under laboratory conditions between 2024 and 2026 with students enrolled in a quality-management course. All class participants were invited; inclusion criteria were attendance and consent to participate in the measurements. Participants had basic knowledge of Lean Management acquired during earlier classes, whereas their knowledge of SMED was exclusively theoretical; they declared no prior hands-on experience in measuring and reducing changeover time. Teams were formed randomly by the instructor based on drawing numbers.

Participation in the study was voluntary. Before the exercise, participants were informed about the study purpose, the scope of collected data and confidentiality rules, as well as the right to withdraw at any time without consequences; verbal informed consent was then obtained for participation and use of the data. Participants received no compensation; participation and consent had no impact on course completion and were not associated with institutional pressure. Collected data did not include information enabling identification of individuals, and results were analysed in aggregated form. No photos or audio/video recordings were made during the exercise. The Bioethics Committee of the University of Kalisz issued a positive opinion on the study protocol.

Functional evaluation procedure and statistical analysis

The exercise was conducted in two rounds. During the first changeover (Time I), the team leader performed the changeover in the baseline configuration, reproducing the way the device had been assembled by the instructor. In the next round (Time II), the team implemented selected improvements intended to reduce changeover time, in line with SMED principles and the constraints described above. To simulate organisational resource constraints, implementation also depended on the "resources possessed by the organisation". To enable participants to introduce changes, the instructor had a portable set of materials and tools (a "warehouse") from which – upon team request – elements needed for the proposed modifications were provided. The set was identical for all teams, and the access rules were the same throughout the study. To avoid suggesting ready-made solutions, participants were not given the resource list before the exercise began. The set

included screws of various lengths and head types, pieces of cut rubber, adhesive tape, wrenches and screwdrivers enabling the use of different screws, as well as paper clips and binder clips.

To standardise measurement, all manual activities in both rounds were performed by the designated team leader. Internal changeover time was measured by the instructor with a stopwatch from the start command to the moment a correct result was obtained (two lines in the required colours), provided that all task-completion criteria were met.

The measurement covered only the activities performed after the changeover start command, treated as internal operations in the SMED sense. Activities that could be completed before the start of measurement and that teams identified in Round II as external activities (e.g., preparing the worksheet and materials) could be carried out before the start command, and the time spent on these preparations was not included in the result.

Internal changeover time was selected as the primary metric because the main operational objective of SMED is to reduce the period during which a workstation is unavailable for production. The same start and end rules were applied in both rounds, allowing a direct within-team comparison. Requiring two correct colour marks and compliance with all stated constraints ensured that a shorter time was accepted only when the changeover had been completed correctly.

After Round I, a structured process analysis and debriefing session was conducted. Observations, improvement proposals, and implemented modifications were systematically recorded by the instructor in a spreadsheet and assigned to categories consistent with SMED logic (conversion of internal activities into external ones, optimisation, and elimination). These records formed the basis for the qualitative results presented in the Results section and were used to determine the number of teams for which each modification was documented. Each modification was counted once per team.

Changeover times were recorded in the min:s format and then converted to seconds for calculations. For each team, the time difference between the first changeover (Time I) and the second changeover (Time II) was calculated (Δ = Time I - Time II), as well as the percentage reduction relative to the baseline value ($\Delta\%$ = (Time I - Time II) / Time I × 100%). Descriptive statistics were computed for Time I, Time II, Δ and $\Delta\%$ and included the mean, standard deviation (SD), median, first and third quartiles, minimum, and maximum. The normality of the distribution of differences Δ was assessed using the Shapiro–Wilk test.

Because measurements concerned the same teams (repeated-measures design), a paired-samples t-test was used to compare Time I and Time II. Additionally, to confirm the robustness of the inference, the non-parametric Wilcoxon signed-rank test for paired samples was performed (two-sided). These tests were used to evaluate the research hypothesis that the internal changeover time after implementing SMED-oriented modifications would be significantly shorter than the changeover time obtained for the baseline configuration. Effect size was estimated using Cohen's d_z coefficient (mean difference/standard deviation of differences). A 95% confidence interval (CI) was determined for the mean time saving. The significance level was set at $\alpha = 0.05$. For the proportion of teams meeting the descriptive criterion Time II < 10:00, a 95% confidence interval was calculated using the Wilson method. Time II < 10:00 was treated as a descriptive benchmark reflecting the conventional SMED objective of achieving a single-digit changeover time, rather than as a separate research hypothesis. Most analyses were performed in Microsoft Excel (Microsoft 365) using spreadsheet functions. The Shapiro–Wilk test and the Wilcoxon signed-rank test were performed in Statistica 13, whereas the Wilson confidence interval was calculated in Excel.

RESULTS

Identified changeover problems and implemented SMED-oriented modifications

After Round I, teams reported observations regarding the most time-consuming elements of the changeover and quality-related problems. These were mainly related to the time needed to tighten and loosen the screws, sheet preparation, and crayon positioning. Crayons were often extended too far, which prevented the sheet carrier from moving, or too little, which meant that they did not mark the sheet. Changing the crayon position required reopening the device; attempting to adjust it by force without reopening it caused the crayon to break. Crayons also broke when the clamping elements were tightened too strongly. Damaged crayons had to be replaced and were recorded as material waste.

Between rounds, teams agreed on and implemented improvements, using available resources and the conclusions from the debriefing after Round I. Changes were grouped according to SMED logic into: (1) converting internal activities into external ones, (2) optimisation actions, and (3) elimination of selected activities. The most important changes introduced by teams are presented in Table 2. These modifications correspond directly to the workstation features described in the design and construction section and provide qualitative evidence that the baseline design elicited the intended SMED-relevant problems. The most frequently documented modifications were trimming the sheets before the timed changeover (25 teams), using binder clips instead of wire (23 teams), and replacing the original screws with hex-socket screws (23 teams). Replacing each full-height screw with two shorter screws and standardising screw types were each documented for 22 teams.

Quantitative results: changeover times and statistical analysis

Internal changeover time decreased for all 30 teams after the implementation of SMED-oriented modifications. The mean time decreased from 31:22 (SD 10:16) for the baseline workstation configuration to 07:32 (SD 03:26) after the modifications. This corresponds to a mean time saving of 23:50 (SD 08:44) and a mean reduction relative to the baseline time of 75.32% (SD 9.14 percentage points; range: 50.42%–88.00%). Detailed descriptive statistics are presented in Table 3. Figure 5 shows the paired team-level results, illustrating the reduction in changeover time for every team and the position of the Time II results relative to the 10-minute benchmark.

The distribution of paired differences did not deviate significantly from normality (Shapiro–Wilk $W = 0.957$; $p = 0.253$). The paired-samples t-test showed that internal changeover time after the implementation of SMED-oriented modifications was significantly shorter than for the baseline workstation configuration ($t(29) = 14.96$; $p < 0.001$). The 95% confidence interval for the mean time saving ranged from 20:35 to 27:06, and the effect size was very large (Cohen's $d_z = 2.73$). The Wilcoxon signed-rank test provided consistent evidence of a reduction in changeover time ($Z = 4.78$; $p < 0.001$). The research hypothesis was therefore supported.

After the implementation of the modifications, 23 of the 30 teams achieved an internal changeover time below 10 minutes (76.7%; 95% Wilson confidence interval: 59.1%–88.2%). The 10-minute threshold reflects the conventional SMED objective of reducing changeover time to a single-digit number of minutes; however, it was used here as a descriptive benchmark rather than as a separately tested hypothesis.

Table 2. Main SMED-oriented modifications implemented during the second changeover and their documented frequency among 30 teams

Type of activity	Activities performed	Teams with documented implementation
Converting internal activities into external ones	Trimming the sheets	25
	Sharpening the crayons	16
	Preparing the colour-identification labels	15
Optimisation actions	Binder clips instead of the wire connecting the sheet carrier	23
	Replacing screws with hex-socket (Allen) screws	23
	Replacing each full-height screw with two shorter screws, one joining the leg to the base plate and the other joining the clamping assembly to the base plate	22
	Standardising screw types	22
	Installing the colour signal on the crayon so that it remains between the clamping elements during clamping	15
	Preparing the colour signal by drawing the colour on the card instead of writing its name	11
	Marking the optimal crayon extension position	8
Eliminated activities	Discontinuing the use of nuts on the upper clamping elements	15

Note: Individual teams could implement several modifications; therefore, the values in the final column do not sum to 30. The frequencies are descriptive and do not indicate the separate effect of individual modifications on changeover time.

Table 3. Descriptive statistics and inferential test results for internal changeover time in 30 teams (Time I: baseline configuration; Time II: after SMED-oriented modifications)

Descriptive statistics			
Measure	Time I [min:s]	Time II [min:s]	Saving (I–II) [min:s]
Mean	31:22	07:32	23:50
Standard deviation	10:16	03:26	08:44
Median	29:10	06:24	22:01
Q1–Q3	23:47–39:19	05:12–08:20	18:38–28:39
Min–Max	14:03–54:09	03:18–15:08	07:05–46:05
Statistical test results			
Test		Result	
Percentage reduction relative to Time I		Mean = 75.32%; SD = 9.14 percentage points; range = 50.42%–88.00%	
Shapiro–Wilk (differences I–II)		W = 0.957; p = 0.253	
Paired-samples t-test		t(29) = 14.96; p < 0.001	
Mean time saving		23:50; 95% CI: 20:35–27:06	
Effect size		Cohen's d_z = 2.73	
Wilcoxon signed-rank test (two-sided)		Z = 4.78; p < 0.001	
Time II < 10:00 (proportion)		23/30 (76.7%); 95% CI (Wilson): 59.1%–88.2%	

Note: Q1 and Q3 denote the first and third quartiles; CI denotes the confidence interval.

DISCUSSION

Functional performance and interpretation of results

The functional evaluation showed that the effects of the SMED-oriented modifications could be measured using the workstation. Internal changeover time decreased for every team, with a mean reduction of 75.32% and a very large paired effect size. The hypothesis was therefore supported. The reported reduction of 75.32% concerns the measured internal changeover time and therefore reflects a reduction in workstation downtime. It should not be interpreted as an equivalent reduction in total labour time, because some activities were converted into external operations and performed before the timed changeover began. Because Time II always followed Time I, part of the observed improvement may have resulted from greater familiarity with the workstation and task. Developing proficiency through repeated performance is also consistent with SMED practice, in which the standardisation of changeover operations, increased proficiency in their execution, and further process improvement play important roles. However, the present study design does not allow the effect of repeated task performance to be separated from that of the implemented modifications; the result should therefore be interpreted as their combined effect. In addition, 23 of the 30 teams reached the conventional SMED benchmark of a single-digit number of minutes, consistent with Shingo's "single-digit minutes" criterion [2]. Although all teams reduced their internal changeover time, the magnitude of the improvement was not uniform, as Time II ranged from 03:18 to 15:08 and seven teams remained above the 10-minute benchmark. Together, these results demonstrate that the workstation-and-task system enables users to perform a baseline changeover, implement improvements, and quantitatively verify their combined effect. The results are consistent with industrial studies in which changeover-time reductions were achieved by separating internal and external activities, simplifying operations, and introducing technical and organisational changes. Sabadka et al. [31] combined SMED analysis with the redesign of equipment used during the changeover of a honing machine; Oliveira and Lima [6] applied SMED together with other Lean and quality tools to reduce the setup time of welding robots; and Sousa et al. [17] presented structured SMED workshops involving cross-functional teams.

Other studies have extended the classical SMED approach with additional analytical and organisational tools. Braglia et al. [32] developed Set-up Saving Deployment, which supports the classification of changeover losses, estimation of potential time savings, and prioritisation of improvement actions based on their efficacy, cost,

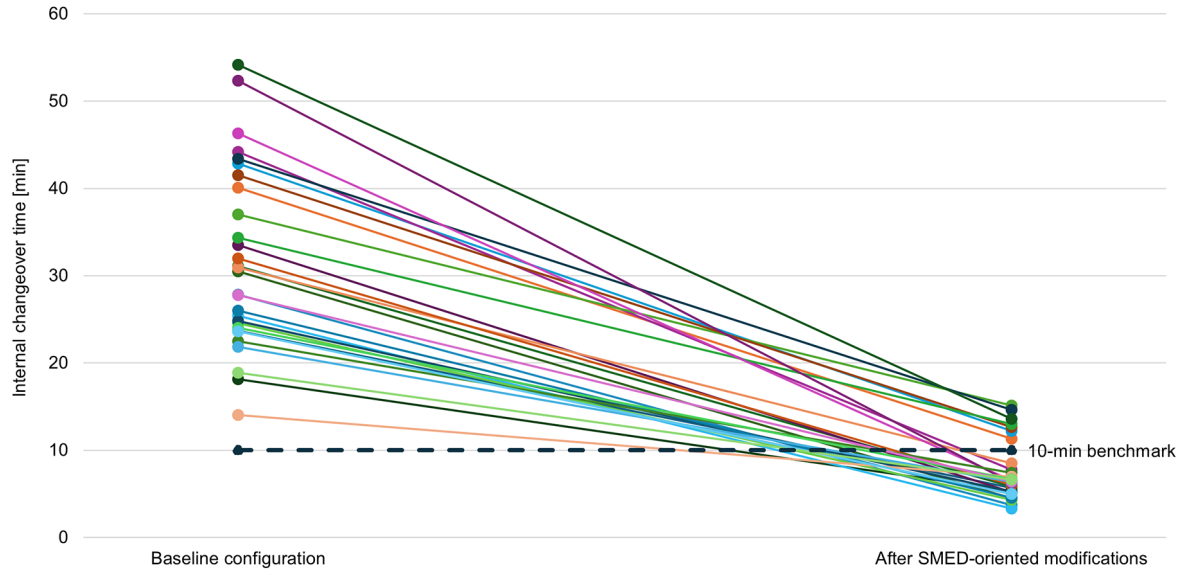


Figure 5. Paired internal changeover times for 30 teams. For each team, the line connects Time I in the baseline configuration with Time II after the implementation of SMED-oriented modifications. The dashed line indicates the 10-minute benchmark

and ease of implementation. The tool was applied in an industrial case study involving a resin-doming machine used to apply resin coatings to labels. Pacheco and Heidrich [33] systematised the conversion of internal activities into external ones by establishing a dedicated Presetting function responsible for the advance preparation of tools, parts, and changeover conditions. The approach was supplemented by operation standardisation, performance monitoring, employee training, and consolidation of the implemented changes. Tuncel et al. [34], in turn, adapted SMED principles to wind turbine blade manufacturing. They used them to distinguish internal and external operations and identify tasks that could be performed in parallel, and then integrated these findings with a scheduling model accounting for resource constraints.

Unlike these studies, which examined actual industrial processes, the present study evaluates a portable laboratory workstation designed to reproduce and enable the identification of selected changeover losses under controlled and standardised conditions. These studies and the present work share the core SMED logic but differ in scale, setting, and evaluation purpose.

The modifications in Table 2 show that the baseline design elicited the intended categories of changeover loss. Teams converted internal activities into external ones, simplified fastening and sheet attachment, standardised tools and screw types, introduced visual positioning aids and eliminated redundant nuts. The nature of the implemented changes is consistent with the SMED logic of separating internal and external operations and streamlining the remaining internal work [2, 9]. The findings also answer RQ2 by showing that the workstation permits alternative improvement paths rather than one predetermined solution. The workstation may also be applicable in different organisational settings in which practical SMED training is needed [16, 17].

Although manual activities were performed by one person – which facilitated exercise and measurement standardisation – the exercise was team-based: other members supported planning, identifying problems, generating improvements and assessing their feasibility. Such an arrangement supports development of teamwork competencies, an important pillar of Lean Management [35]. Observing the leader's work may additionally strengthen reflection on work organisation and team roles, especially when accompanied by a moderated debriefing after Round I.

The exercise should be interpreted within the broader Lean Management context rather than as an isolated effort to minimise changeover time. Shorter changeovers can support production flexibility, shorter lead times and waste reduction, but the resulting operational benefits depend on how the released production capacity is used. In industrial practice, the time saved through SMED-oriented changes may be used to produce more

products [5]. If this additional output exceeds actual demand, it may result in overproduction.

Opportunities for further development

The workstation can also support related topics such as 5S, standardisation, root-cause analysis and the relationship between changeover time, flow and planning. Additional rounds could be introduced to pursue successive improvements consistent with kaizen logic. The exercise may also be part of a broader process simulation in which participants observe how changeover time affects flow and planning (e.g., batch size, order sequence), thereby linking SMED with the elimination of various sources of muda [36].

Limitations and future research

Although the study demonstrated a statistically significant improvement between the two changeovers, the findings are limited by the laboratory setting and the use of a simplified prototype, which does not fully reflect the complexity of industrial changeovers. Further evaluation in industrial or industry-related settings would therefore be valuable.

Internal changeover time was used to assess how the workstation responded to the changes introduced by the teams. It should not be treated as a complete measure of learning outcomes. Because all teams performed Time II after Time I, some of the improvement may have resulted from becoming familiar with the workstation and task. However, internal changeover time decreased in every team, and the teams introduced specific modifications consistent with the SMED concept. The study therefore demonstrates the combined effect of repeated task performance and the implemented improvements, but does not determine the separate contribution of each modification. The study involved a limited sample of students from one course. All participants had theoretical knowledge of SMED but no previous hands-on experience in reducing changeover time. Although this gave the teams a similar level of initial experience, the results should be verified with other participant groups, including industrial employees. Future studies could include a control group that repeats the baseline changeover without introducing modifications, compare selected modification variants, and examine whether the improvements are maintained over time.

CONCLUSIONS

The study showed that the portable workstation enabled teams to identify changeover-related problems, introduce SMED-oriented modifications and evaluate their combined effect through changeover-time measurement. Internal changeover time decreased in all 30 teams, from a mean of 31:22 in the baseline configuration to 07:32 after the modifications. The mean reduction in internal changeover time was 75.32%, and the research hypothesis was supported. The modifications introduced by the teams included converting internal activities into external ones, simplifying and standardising fastening and preparation activities, and eliminating unnecessary components. This shows that the baseline workstation configuration generated identifiable changeover losses and allowed different non-permanent improvements to be implemented within the defined constraints. After the modifications, 23 of the 30 teams achieved an internal changeover time below 10 minutes, which is consistent with the conventional single-digit-minute objective of SMED. The workstation therefore provides a portable and controlled environment for hands-on SMED practice and task-based functional evaluation. It may be used in education and organisational training, although the present results concern changeover performance rather than broader learning outcomes.

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