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Improving Manufacturing Supply Chain by Integrating SMED and Production Scheduling

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Abstract: Globalization has led to a significant effect on today's manufacturing sector. Manufacturers need to find new and innovative ways to increase efficiency and reduce waste in the manufacturing supply chain. Lean/six sigma tools can help companies increase production efficiency and stay in competition. Manufacturing in smaller batches can keep the supply chain lean and customizable. This leads to frequent changeovers and downtime. A changeover is usually required when a single machine produces different products based on the requirement. A large-scale industry can either install multiple individual production lines to cater to the demand (usually expensive) or make frequent machinery changes. Single Minute Exchange Die (SMED) is a system designed for reducing the changeover time for machines. It reduces the time taken to complete the activities and eliminates non-essential activities throughout the changeover. Scheduling an operating procedure within SMED in such case is a challenge. Project scheduling model with workforce constraints can be used to create a set of heuristics to provide us with an optimized list of tasks. The paper proposes to design a scheduling heuristic model to allocate tasks to the operators to get the least amount of operator idle time and reduce changeover downtime costs. The paper further illustrates the benefit of the model in a case study and proposes its integration within the existing SMED methodology. This results in a benefit-to-cost ratio of 7.5% for production scheduling compared to that of stages 4 and 5 in SMED, which is 1.2%.

Keywords: changeover; single minute exchange die (smed); thermoforming; production scheduling

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1. Introduction

This century has seen a significant change of the manufacturing sector. Companies focus on reducing non-value-add activities, eliminating wastage, and decreasing the setup time to remain competitive. Industries have to compete with manufacturing from other countries with relatively cheap labor. A significant portion of the losses in manufacturing industries can be attributed to high changeover costs. The companies tend to be unaware of these costs or sometimes underestimate the potential for improvement [1]. There has been an increased interest in research on lean manufacturing and its effectiveness in the industry [2]. Its implementation and compatibility remain an active area for research.

In recent years there have been many studies on lean manufacturing and its applicability in manufacturing. Cherrafi and Elfezazi proposed a specific integrated model highlighting its importance to sustainable manufacturing [3]. Danese and Manfe conducted a literature review on lean six sigma implementation and its improvement areas. Furthermore, manufacturing in small batches helps the company keep supply chain logistics lean and customizable. However, small batches suffer from high changeover cost in between the production. Hence, small batches are only viable if the setup/change over time can be reduced. Working on machinery to reduce their changeover times can help companies reduce production costs. This can be done by installing new machinery or updating old machines to be more efficient and less time-consuming. These innovations help companies adapt to the increasing technological changes, thereby increasing their competitiveness [4].

Installing new machinery usually involves high costs; hence companies must evaluate the cost-to-benefit ratio before undertaking such projects. Improving the current machinery provides a cheaper alternative. This can also address the issue of non-value-added activities during the setup. Manufacturing industries use lean six sigma methodology to remove wastage and improve efficiency. In some cases, reviewing the current plans and schedule methodology and improving bottlenecks can improve the performance by 4.4% and reduce setup time by 47% [5]. By reducing or eliminating non-value-added activities, productivity can be improved. One of the leading techniques to minimize the setup time is single minute exchange die (SMED) [6]. This focuses on utilizing the full production capacity and hence increase productivity.

In addition to the six sigma methodology, job scheduling can decrease the setup time by reorienting labor and eliminating non-value-added tasks. Intelligent perception and continuous manufacturing data are utilized in cloud computing through IoT technologies, employing a large volume of information about the current resources. Setup time can be sequenced, focusing on more important and cost-effective steps, and redundant activities can be eliminated. There has been considerable research in lean production and new technologies like Manufacturing Execution System (MES), which can provide additional support and highlight improvement areas. Cottyn explored how different software tools utilize the data to quantifiable values, which can optimize operations [7].

To evaluate the right manufacturing time for each of the product, companies perform time study. Time studies include observing and video taping the time utilized to finish the tasks [8]. The activity is sub classified to each individual activity. This helps in standardizing average time taken by the worker to complete the tasks. In addition to time studies, recording and examining the ways the operator completes the tasks, easier and optimized working methods can be designed to reduce wastage and non-value added tasks [9].

Among the research done in applicability of SMED, there is a gap in designing the standard operating procedure used by the operators. This paper seeks to address how production scheduling heuristics can help to generate an optimized task list to reduce the idle time of the workers during the changeover. Moreover, the paper would attempt to integrate the proposed model within the existing stages of SMED methodology.

The rest of the paper is organized as follows: In Section 2, the literature review explains the current research done in the field. Section 3, the materials and methods, describes the production scheduling problem and proposes a model as a solution. Section 4 explains the case study on applying SMED in the manufacturing industry. Section 5 presents the result in terms of the amount of change over time, and physical work saved, and the last section covers the conclusion and scope for further research.

2. Literature Review

This section discusses the various related literature and provides a background on SMED and its usage. SMED is a method of lean six sigma used to reduce changeover time [10]. Lean six sigma principles focus on increasing efficiency and reducing wastage throughout the production line. In research studies, lean six sigma has been proven to reduce wastage and and increase company profits due to low product failure [11,12]. The system of SMED was evolved in Japan by Shiego Shingo in 1985 [13]. To maintain the high needs of the smaller lot sizes and meet the consumers' desires, he proposed a technique referred to as Single Minute Exchange of Die that required the changeover to take single-digit minutes or less than ten minutes. This method is effective in reducing the changeover time of a production machine. Better data processing techniques have resulted in better implementation of SMED in recent years [14,15].

SMED is a lean and six sigma system for setup reduction, and its essential goal is to reduce the time to a one-digit minute. It allows the company to decrease the extent of inventory and maintain the efficient utilization of the equipment [16]. As the product life cycle of the products decreases, the call for variable products increases, making SMED imperative in any organization [17,18].

Manufacturing industries use define, measure, analyze, improve, and control (DMAIC) to improve the production process. DMAIC is an integral part of six sigma but it can also be implemented alone. SMED is lean intervention part of six sigma which aims to decrease the manufacturing downtime.

The SMED analysis should begin with the detailing of the process and the time study. The internal activities which cannot be eliminated or converted should be replaced, combined, and simplified [19]. Here the primary job is to highlight the individual activities being done and then try to separate it. There are two types of activities that are undertaken in the changeover [20,21].

Internal Activities: These are the activities that can be done when the machine is not running. For example, removal of the fixture or the tool, etc.

External Activities: These are the activities that can only be done when the machine is still running. Examples of these activities include bringing the next mold or the fixture when the machine is still contributing to value-added activities. These activities add value to an item from the customer's perspective. These activities essentially change the raw materials into goods or services. So the goal of SMED is to minimize the non-value-added activities by converting all shutdown activities to external activities [17].

A significant amount of research has been done in scheduling problems in the last two decades [22–24]. This has resulted in much literature on different types of problems, solutions, and their applications [25]. Here, Moacir and Alyne discussed a project scheduling problem where employees and activity requirements are time-dependent. The employees had different skills and constraints, which were reflected in the problem statement. The problem was proposed as a linear program and solved using tabu search and heuristics. The validation of productivity on the changeover was also checked and in the case study showing a significant increase in productivity [26]. Aleksandar and Goran in their paper used a model for solving flexible job shop planning problem based on meta heuristic algorithms [27].

Another paper on multi-objective job-shop scheduling with lot-splitting production aimed to minimize the weighted stock machine idle time and carrying cost [28]. The study used LINGO and ant colony optimization (ACO) algorithms to obtain a solution.

Furthermore, a paper by Victor Cavalcante titled "A Resource-Constrained Project Scheduling Problem with Bounded Multitasking" discussed scheduling problems in scenarios' where the workers have different jobs with arrival time, due date, and penalty associated with delays [29,30].

3. Materials and Methods

This section describes the method proposed used to reduce the changeover time. Key terms and related research are defined, and general implementation stages used to gather data for the follow-up case study are discussed. The section further discusses a job proposed model that utilizes the jobs, limitations, and processing time to optimize the changeover and supplement the SMED methodology. Figure 1 describes the flow diagram.

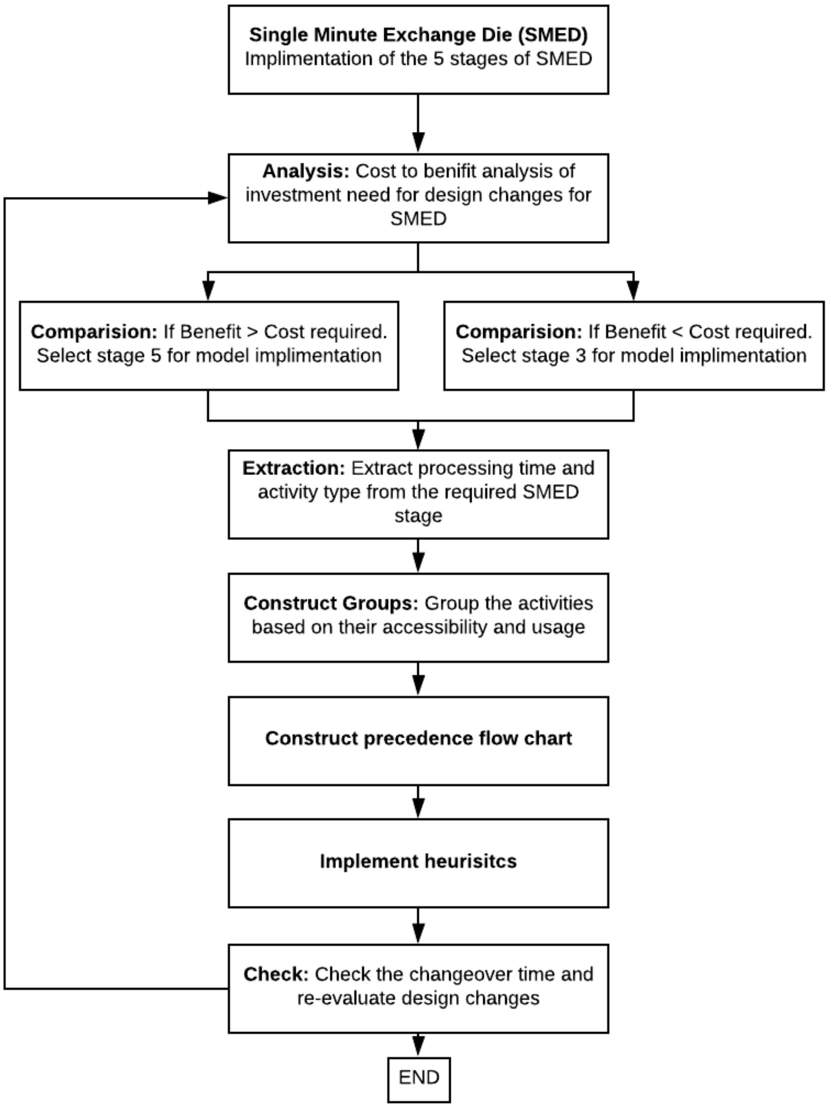

Figure 1. Research flow diagram.

3.1. SMED Implementation Stages

This section describes general SMED implementation and model formulation. This would be used in case study to discuss it implementation in a manufacturing industry. As a part of lean six sigma, SMED is implemented in the stages shown in Figure 2.

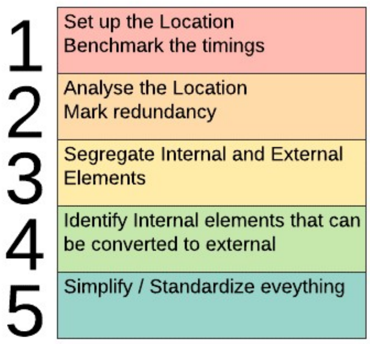

Figure 2. Stages for SMED.

Stage I: The first stage covers measuring how the changeover normally occurs. This included observing how long the changeover takes to complete typically. Time studies are done measuring every task and its sub-parts for further analysis.

Stage II: In this stage, tasks are analyzed and broken down into simpler steps where unnecessary delays occur in the changeover.

Stage III: Here, the external activities are isolated and moved to before or after the changeover, while machines are still running.

Stage IV: After removing all the possible external activities, targeted activities and sub-activities are identified where internal elements could, with some work, be converted to external ones.

Stage V: This final stage ensures that everything is better streamlined and standardized. In addition to that, design changes were considered based on the cost–benefit ratio.

3.2. Proposed Scheduling Model

The implementation of job shop scheduling has been limited to the employees working in the product assembly lines. However, the same principles can be modified to optimize the tasks in machine changeover. The activities and jobs can be analyzed to fit job scheduling with precedence constraints. The precedence constraints would mean that some jobs can only be commenced when its predecessor job/jobs are finished. The problem would also assume that the number of available operators would limit the number of jobs that can be processed. The objective here is to minimize the activity's makespan, which would reduce the changeover time.

For this analysis, the team video recorded the changeover and analyzed each video to perform time and motion studies. Each task was individualized and required time and steps taken by the operator to do it were calculated. The distance travelled by the operator was measured in steps and three steps were approximated to one-meter distance travelled. The final list of activities and their time requirements from the last stage of the SMED were used. Job scheduling with these types of different jobs can be challenging. Moreover, these activities often include many grouped activities. For example, if an operator has to remove a form from the machine, he has to complete several tasks like unscrewing bolts from different locations, hoisting the support, and changing the ring. These tasks do not have to be done one after the other or in a proper sequence. These activities should be grouped under a single activity, i.e., removing the form. Categorizing these activities under a single activity to get fewer activities to complete the changeover and their time duration. We also have a maximum total project duration, which would be the sum of each activity. We would also like to know some parameters like critical path, the critical path's duration, maximum earliest completion, and the latest possible start time. The critical path would give us a critical set of activities that should be completed as a priority. Any delay in these activities would result in a delay in the total project. The non-critical activities are the one which can be started after a delay without effecting the earliest project completion date. The possible interval of the delay is known as the earliest start time and latest finish time. These parameters are vital to production planning as they would show where and how the jobs can be scheduled. This problem can be solved as a project scheduling problem with workforce constraints [31].

The objective here would be to minimize the processing time for the changeover which satisfies the constraints. To formulate the problem as an integer program, it was assumed that all processing times are fixed and an integer. A dummy job n+1 was introduced with zero processing time. This job would succeed in all other jobs, and all the final jobs would be the predecessor of job n+1. A binary variable was also introduced, which would assume the value of 1 if the job j is completed exactly at time t and 0 if not. The upper bound for the makespan was the total sum of all the activities' processing time.

The following notations have been adopted:

j = job number

p_j = processing time for job j

t = time interval
x_{jt} = A binary variable that assumes 1 if job is completed at time t
W_{lj} = number of operator for job j needed from pool of operators l
H = Total processing time upper limit

$$H = \sum_{j=1}^{n} p_j \tag{1}$$

The completion time for job j would be

$$\sum_{t=1}^{H} tx_{jt} \tag{2}$$

The complete makespan would be

$$\sum_{t=1}^{H} tx_{n+1,t} \tag{3}$$

The integer programming can be formulated as

$$Min \sum_{t=1}^{H} tx_{n+1,t} \tag{4}$$

Subject to

$$\sum_{t=1}^{H} tx_{j,t} + p_k - \sum_{t=1}^{H} tx_{k,t} \leq 0 \qquad forj \to k \in A \tag{5}$$

$$\sum_{j=1}^{n} (W_{lj} \sum_{u=t}^{t+p_j-1} x_{ju}) \leq W_l \qquad for: \ l = 1, ..., N_p : t = 1, 2...H \tag{6}$$

$$\sum_{t=1}^{H} x_{jt} = 1 \qquad for: \ j = 1, 2...n \tag{7}$$

The first set of constraints is to ensure that the precedence described in the flowchart is followed. For example, if job B follows job A, the completion of job B has to be greater than the completion time of job A and the processing time for job B. The second constraint makes sure that the total demand pool of operators does not exceed the availability of the total availability of the pool. The third constraint makes sure that each job is processed.

Solving this type of integer programming is computationally expensive when the number of jobs is large and the time duration is long. To solve this type of programming, shifting bottle heuristics are discussed by Pinedo in his book [31].

The precedence constraints are represented by a precedence flow chart. Calculating processing time and critical path from the precedence graph ensures that the first constraint is followed. To ensure that the second constraint is followed, we would need to evaluate the number of active operators in each iteration and ensure that the number is less than the total available operators. Calculating the critical path ensures all the jobs are processed by the time the jobs in the critical path are completed. The steps for the algorithm are as follows:

Finding Critical path
Step 1. Set time t = 0.
Set S_j = 0 and C_j = p_j for each job j that has no predecessors.
Step 2. Compute inductively for each job j

$$S'_j = max_{all\, k \to j} \, C'_k,$$

$$C'_j = S'_j + p_j$$

Step 3. The makespan is

$$C_{max} = max(C'_1 ..., C'_n).$$

STOP

This algorithm evaluates the optimal schedule, and the makespan of the schedule is the least possible time the task can be finished.

To evaluate the latest start time and completion time of the activities, we use the backward algorithm.

Step 1. Set time t = C_{max}

Set C''_j = C_{max} and S''_j= C_{max}-p for each job j that has no successors.

Step 2. Compute inductively for each job j

$$C''_j = min_{j \to all\,k}\, S''_k,$$

$$S''_j = C''_j - p_j$$

Step 3. Verify that min(S''_1.....S''_n) = 0

STOP

After evaluating the latest start time, we identify the activity with the highest amount of slack. Reducing this slack time on the critical path would reduce the overall process time. Hence these activities are chosen and transferred to another operator.

As the activities are a set of smaller activities, each activity can be worked on together by multiple operators. If operator 2 is idle, reduce the processing time of the current activity of operator 1 by a factor of 2. This would represent that both the operator is completing the specified activity together. After completion of the activity, repeat the heuristic to find the next activity with highest slack.

4. Case Study

SMED implementation has been adopted in mold changeover and plastic thermoforming [32,33]. Generally, the research focuses on root cause analysis within SMED's different stages to improve the overall changeover time. This case study illustrates a SMED applied to a thermoformer machine. It also proposes reorganizing tasks using job scheduling to obtain a model to improve the changeover.

For this project, a SMED study was conducted on a rotary thermoformer in a medium-scale production facility. The thermoformer creates plastic parts for the refrigerator and freezer. To produce different parts of plastic in the same machine, the form must be changed on average once every shift. This machine is capable of producing a part every 32 s. On average, the changeover occurs once per shift with three shifts in a day. The machine process is shown in Figure 3. It consists of two different sections of heating, one section for insertion and another for the mold. This machine runs 24/7 every day, as it is considered a production bottleneck for the specific parts. Hence the downtime losses for the changeover are high. A single operator was charged with the changeover during the initial implementation. The team video recorded the changeover and analyzed each video to perform time and motion studies. Each task was individualized and required time and steps taken by the operator to do it were calculated. The distance travelled by the operator was measured in steps and three steps were approximated to one-meter distance travelled. The implementation was done in 5 stages described as in Section 3.1.

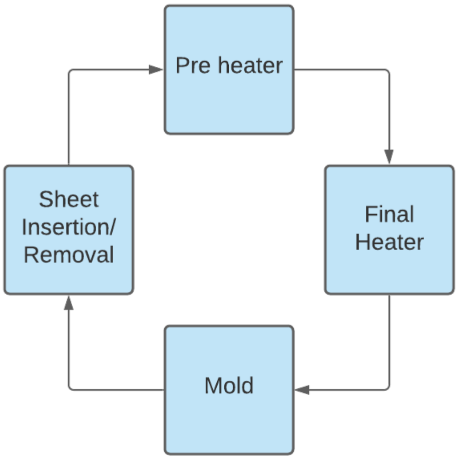

Figure 3. Thermoforming process.

4.1. SMED Implementation

Stage I: This included observing how long the changeover takes to complete typically. This set our baseline change over time to improve upon. This timeline was used to calculate how much the company was losing on each changeover. A total of five readings were taken to analyze the mean and variance of each activity. The first part involved recording the time taken for each operator′s action and the number of steps involved in the tasks. The changeover was videotaped multiple times over a week. Three readings were averaged out to calculate the mean keeping the variance low. This was used to gauge the approximate time taken by the operators, which helped us figure out which activities to focus on. The team listed down all the activities and then classified them as internal or external. The team then converted all possible internal activities to external activities, which could be done before or after the shutdown. As the task was previously optimized, there were not many external activities.

Stage II: This stage covered analyzing and breaking down steps where unnecessary delays took place in the changeover. These areas were noted as the target areas. In addition to that, some activities had a high degree of variance. This indicated that some work could be done in these activities to reduce the changeover time. Some workers grouped simple activities that saved time. Others clubbed different activities in parallel, which would reduce additional effort later on, like bringing safety equipment back to the sight while ensuring the machine's shutdown. These best practices were observed and shared among people in other shifts to reduce activity variance and overall time.

After listing out the changeover tasks, the external task like cleaning the new form and bringing the new form near the machine, were eliminated as shown in Table 1.

Table 1. Internal activities converted to external.

Internal Activities Converted to External	Time Saved (Seconds)
Documenting the production	37
Bringing the lockbox to the machine	30
Getting and placing the hard hat near control panel	14
Bringing new form near the machine	85
Cleaning the new form	145

Stage III: Separate external activities and move them before or after the changeover, while machines are still running. It was found that some activities done during the changeover were not limited to the no production time for the specific machine. These activities could be done before or after the changeover. Some examples of such activities included parts retrieval, inspection, and cleaning non-moving parts of the machinery. These activities were removed from the analysis as these were not necessary. The next task was creating and updating the standard operating procedure. Many activities like lock out tag out (LOTO) , chain hoisting, ring adjustment could be done more efficiently than the current random procedure. The team streamlined the tasks, which reduced the operator movement and time.

Stage IV: After removing all the possible external activities, targeted activities, and sub-activities were identified. Where internal elements can, with some work, be converted to external ones, these activities were selected based on the activities which took the most time. Design changes to the machine were identified, which would convert the internal activities to external. For example, adding safety equipment that allows all cleaning on a machine to be done while still running, or making equipment more modular so things can be changed out for different jobs much more quickly. In some cases, upgrading the machines' safety features could be cheaper if it ensures that the workers can safely execute more activities while the machine is running. It was realized that having an additional operator could reduce the time for specific activities like bolting a screw on the two ends simultaneously. The second operator would come in a total of 7 min to aid with bolting the screws to attach the new mold to the machine and bolting the clamps on the base of the mold. Using two operators was not allowed previously as the safety department believed having more than one operator would compromise safety. The team modified the safety lockouts such that the machines would not start unless both the operator removed the LOTO.

Stage V: This stage ensures that everything is better streamlined, like standardizing tools (using only limited amount of tools on any piece of equipment in the shop makes the maintenance easier) and reorganizing things such that little movement is necessary. The tasks of the changeover can be optimized and grouped to ensure minimum movement by the workers. In addition, engineering changes were considered. It is usually done after all other task reduction options are exhausted as it comes with large capital investments. In this case, engineering changes included eliminating the use of screws and tools to fix the molds. Instead, knobs were used, which could be screwed by hand. The number of screw turns was reduced to decrease the time further. Another major engineering change was redesigning the rings of the thermoformer. This helped in decreasing the ring adjustment time and physical labor.

4.2. Model Implementation

As discussed in Section 4.1, the final task list at the end of Stage V is analyzed and combined to create the precedence graph shown in Figure 4.

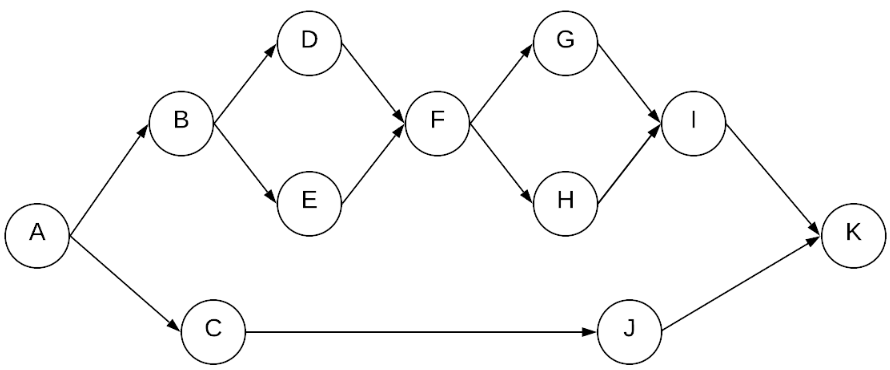

Figure 4. Precedence graph.

The Table 2 shows the jobs and their processing time.

Table 2. Jobs and processing time.

Jobs	Processing Time p_j (S)
A	38
B	109
C	35
D	33
E	44
F	40
G	14
H	12
I	103
J	92
K	41

Applying job scheduling heuristics to the list of activities described in the precedence graph, we get the critical path: Set time t = 0

$S'_A = 0$ and $C'_A = 38$ for job A

S'_B for job B = 38

Computing for each job, we get a makespan of 389 s.

The critical path is:

$$A \rightarrow B \rightarrow E \rightarrow F \rightarrow H \rightarrow I \rightarrow K$$

Evaluation of the latest start time and slack

$T = C_{max} = 389$

S''_K for job K = 389-41 = 348

Computing each job, we get the start time and finish time for each job shown in Tables 3 and 4.

It is observed that the A-C-J arc consists of less time-consuming activities. Hence, the slack is most significant in C and J. As the activities are a cumulation of sub-activities, it would be easier to add two operators on a single task to reduce the time taken by that activity. For this, we assume that the tasks within the job are independent. Adding another operator in the same activity would reduce the time by half. Continuing with the algorithm described in Section 3.2, we get the earliest start time and latest finish time shown in Tables 3 and 4. The final iteration of the algorithm reduces the duration of activity B from 109 s to 55 s. This brings down the changeover time to around 6 min, which is a significant reduction.

Table 3. Attributes of first iteration.

Jobs	Earliest Start Time (S)	Latest Finish Time (S)	Slack (S)
A	0	38	0
B	38	147	0
C	38	73	183
D	147	180	11
E	147	191	0
F	191	231	0
G	231	245	0
H	231	243	2
I	245	348	0
J	73	165	183
K	348	389	0

Table 4. Attributes of second iteration.

Jobs	Earliest Start Time (S)	Latest Finish Time (S)	Slack (S)
A	0	38	0
B	38	93	0
C	38	128	74
D	93	126	11
E	93	137	0
F	137	177	0
G	177	191	0
H	177	189	2
I	191	294	0
J	128	220	74
K	294	335	0

5. Results and Discussion

The improvements on SMED based on the job scheduling model are discussed, and the stages of SMED implementation are compared. Comparison is made in three aspects: Changeover time reduction, Monetary amount saved vs. investment, and distance traveled by the operator.

The reduction in changeover time of each stage of SMED is shown in Figure 5. We observe that there is not much improvement in the second stage and the fourth stage. In contrast, the application of stages three and five results in a more significant change in the time reduction. The results show that the time reduction is large when external processes are eliminated (represented by Stage III) or modifications to the machines are made (represented by Stage V).

Figure 6 plots the amount of money saved by reducing changeover time and the investment needed in each stage. The amount saved annually is calculated by multiplying the time saved in minutes by the changeover, parts produced by the machine in a minute and total profit gained by the product. It is observed that the initial stages of SMED provide us with time reduction without any capital investment. Still, the final stages require a higher amount of investment due to machinery modifications. The proposed model offers less benefit than SMED stages, but it does not require any additional design or equipment modifications that increase the monetary investment. This model can provide a better option where investing in design changes cannot be justified by the benefit of changeover reduction. Stage 5 requires an investment of USD 14,000 to provide savings of USD 16,000 annually. In comparison, the proposed model saves USD 3000 with around USD 400 spent on the modification for the revised procedure. This gives us a benefit to cost ratio of 7.5 of the proposed model when compared to benefit to cost ratio 1.2 of stage 5.

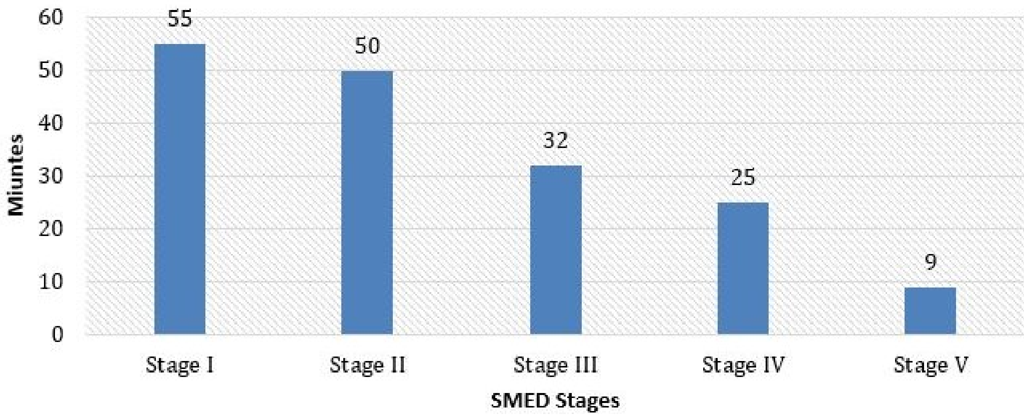

Figure 5. Changeover time.

Figure 7 shows how the distance traveled by the operator reduces after SMED implementation. It is observed that there is no significant drop after Stage II and III as most tasks are simplified and external tasks are eliminated.

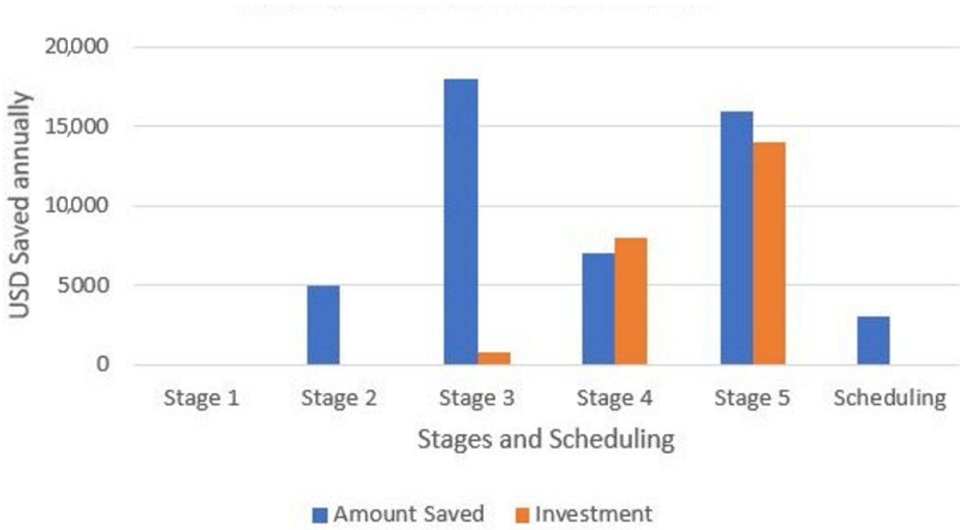

Figure 6. Amount saved vs. investment.

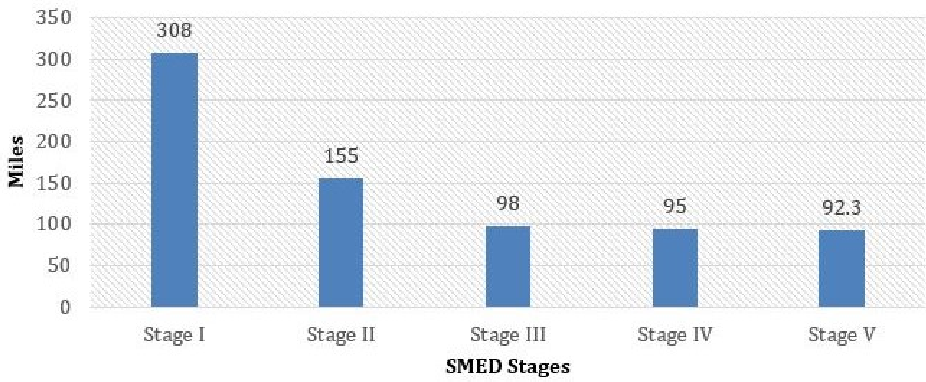

Figure 7. Distance traveled by operator.

The results can be summarized based on two types of improvements: the human element and the design changes. Initially, the human element is optimized to make it faster and leaner changeover, which accounts for 42% reduction in time. This is less expensive than investing in new design changes. The other elements, design changes, help in the later stages when all other options are exhausted and account for an additional 41% reduction in changeover time. The proposed model additionally increases the role of the human element in SMED changeover to decrease the changeover time by 5%. In comparison to other case study, like Jonathan David's SMED implementation on an interconnection axle manufacturing led to an Overall Equipment Effectiveness (OEE) increase from 77% to 85%. Although the OEE index cannot be compared with results in this paper but Davids paper helped reduce the changeover time by 22%.

6. Conclusions

Significant competition has forced the manufacturing sector to change towards lean manufacturing. To ensure their margin, have an efficient supply chain and remain competitive, companies invest massive capital to promotes lean six sigma practices in their day to day activities to reduce wastage and non-value-added tasks. Companies often use one machine to produce different parts to increase flexibility and maintain high volume production and, hence invest capital in reducing the machine changeover.

The paper introduced a novel approach to reduce the changeover time in SMED. In addition to eliminating external activities and converting the internal activities to external, our approach integrates job scheduling to provide the easiest and optimized job list to reduce the changeover time. The model formulation comprises grouping similar tasks together and reducing the time lag in each activity. The model utilizes the production planning and scheduling heuristics to identify and reorganize labor to reduce the changeover time. The model proposes re-purposing labor to reduce the lag between activities and comes up with an optimized operating procedure providing a higher benefit to cost ratio (7.5) than the 5th stages of SMED (1.2) in the case study.

To incorporate the model within the existing methodology of SMED, we compared the reduction time, investment need, and exertion by the operators in each stage. These comparisons help us determine where the model can be implemented within the stages. As Table 4 suggests, the model should be implemented with Stage III or Stage V. Stage III cuts down all possible external tasks and hence would only provide a crucial list of jobs and their processing times for the model. In cases where design change is a viable option, the model can provide an optimized list of workforce activities. In addition to that, we can also conclude that majority of the reduction in the distance traveled by the operator occurs in Stage II. This would mean that after Stage II, tasks are lean and simplified when used for our model. As the model does not factor in this attribute, its implementation in later stages would not impact the progress.

The study is subject to a few limitations which suggest future research directions. Firstly, it would be useful to test this model in various case studies to investigate its integration in general SMED programs. Secondly, there can be other influencing factors like safety procedures in a manufacturing setting, which might increase the changeover time. This case study does not factor in such influences. Lastly, the SMED investment depends upon production output and layout. If the machine is not a bottleneck in the production supply chain, reducing changeover might not be beneficial. Cost to benefit analysis can be done in such cases to check the viability of production scheduling. Further research can focus on such factors and their influence on SMED.

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