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Improving Manufacturing Supply Chains by Integrating Lean Six Sigma and Production Scheduling

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by

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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 competitive. 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. This paper proposes a model for production scheduling in a machine changeover and discusses its implementation in the stages of SMED. The paper further illustrates the viability and benefit of the proposed model. This results in a benefit-to-cost ratio of 7.5 for production scheduling compared to that of stage 5 in SMED, which is 1.2.

Keywords: Changeover, Single Minute Exchange Die (SMED), Thermoforming, PERT, Production scheduling.

1 Introduction

This century has seen a significant change in the manufacturing sector. Companies focus on reducing non-value-added activities, eliminating wastage, and decreasing the setup time to remain competitive. Industries have to compete with manufacturing from other countries with relatively cheap labor [1] [2]. A significant portion of the losses in manufacturing industries can be attributed to high changeover costs [3]. The companies tend to be unaware of these costs or sometimes underestimate the potential for improvement [4] [5]. There has been an increased interest in research on lean manufacturing and its effectiveness in the industry [6]. Its implementation and compatibility remain an active area for research [7].

In the literature, various approaches to lean manufacturing have been discussed. Cherrafi and Elfezazi discussed current literature in lean manufacturing and six sigma. They also proposed a specific integrated model highlighting its importance to sustainable manufacturing [8]. Danese and Manfe conducted a literature review on lean six sigma implementation and its improvement areas. The authors went in-depth about the relationship between lean sigma and environment/safety issues [9].

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 [10].

Machines produced in the last decade are designed to make the changeover quick and efficient. However, installing new machinery usually involves high costs; hence companies must evaluate the cost-to-benefit ratio before undertaking such projects. Improving the changeover of current machinery provides a cheaper alternative. This can also address the issue of non-value-added activities during the setup. 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% [11]. 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) [12]. This focuses on utilizing the full production capacity and hence increase productivity.

1.1 Background on SMED

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, a technique was proposed, referred to as Single Minute Exchange of Die that required the changeover to take single-digit minutes or less than ten minutes.

SMED is a lean and six sigma device 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. As consumer demand changes, the industries have to change their machines to produce different parts quickly. This makes SMED crucial in any manufacturing industry [14] [15].

The SMED analysis begins with the detailing of the process and the time study. The internal activities which cannot be eliminated or converted are replaced, combined, and simplified [16]. 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 [17] [18].

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

External Activities: These are the activities that are done when the machine is still running. Examples of these activities include bringing the next mold or the fixture when the machine is still running. Value-added activities are activities that 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 possible shutdown activities to external activities [14].

A significant amount of research has been done in scheduling problems in the last two decades [19] [20] [21]. This has resulted in much literature on different types of problems, solutions, and their applications [22]. 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 [23]. Another paper on Multi-objective job-shop scheduling with lot-splitting production aimed to minimize the weighted stock machine idle time and carrying cost [24]. The study used LINGO and ACO algorithms to obtain a solution. Also, 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 [25] [26].

1.2 SMED Implementation Stages

This section describes general SMED implementation and model formulation. As a part of lean six sigma, SMED is implemented in following 5 stages:

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

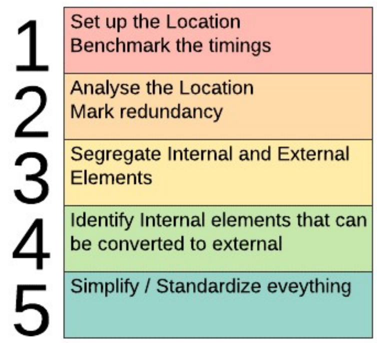

Figure 1: Stages for SMED

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 are considered based on the cost-benefit ratio.

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 [27].

Based on literature review, there is a gap in designing 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: Section 2, materials and methods, proposes a model heuristic to optimize the changeover activities. Section 3 explains the case study based on implementing SMED stages and implements the proposed model in the manufacturing industry. Section 4 compares the different stages of SMED and presents the result in terms of the amount of change over time and physical work saved. The last section covers the conclusion and scope for further research.

2 Materials and Methods

The section explains the terms and literature used for the follow-up SMED case study. The section further discusses a scheduling model that utilizes shifting bottle heuristics to optimize the changeover and supplement the SMED methodology.

2.1 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, we used the final list of activities and their time requirements from the last stage of the SMED. 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 are grouped under a single activity, i.e., removing the form. Categorizing these activities under a single activity, we get a list of few 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 [28].

The objective here would be to minimize the processing time for the changeover while satisfying the constraints. The problem can be formulated as an integer program. It is 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 operators for job j needed from pool of operators l

H = Total processing time upper limit

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

The completion time for job j would be

$$\sum_{t=1}^{H} t x_{jt}$$

The complete makespan would be

$$\sum_{t=1}^{H} t x_{n+1,t}$$

The integer programming can be formulated as

$$Min \sum_{t=1}^{H} t x_{n+1,t}$$

Subject to

$$\sum_{t=1}^{H} tx_{j,t} + p_k - \sum_{t=1}^{H} tx_{k,t} \leq 0 \qquad for j \rightarrow k \in A$$

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

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

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, we use critical path method and shifting bottleneck method to create a heuristic [28].

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.

Thus, the steps are repeated.

3 Case Study

SMED implementation has been adopted in mold changeover and plastic manufacturing multiple times in literature [29] [30]. Generally, the research focuses on root cause analysis within SMED or suggests design changes to improve the overall changeover time. This case study illustrates a SMED applied to a thermoformer machine. Besides, 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 seconds. On average, the changeover occurs once per shift with three shifts in a day. The machine process is shown in Figure 2. 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 implementation was done in 5 stages described in section 2.2.

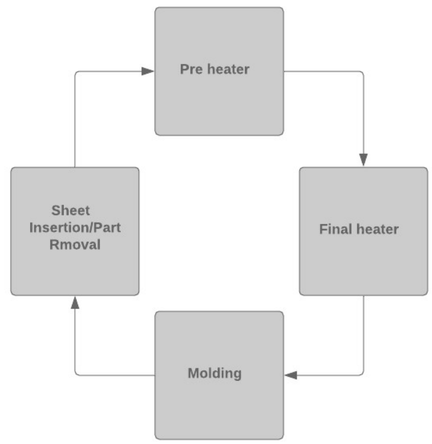

Figure 2: Thermoforming Process

3.1 SMED Implementation

Stage I: This included observing how long the changeover takes to complete typically. This set the baseline change over time to improve upon. This timeline was used to calculate the monetary loss during each changeover. A total of 5 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. Multiple changeovers were videotaped to obtain the data. This was used to gauge the approximate time taken by the operators, which helped 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.

Table 1: Stage I

	Warm-Up Time (minutes)	**Changeover (minutes)**
Stage I	20	55

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, like bringing safety equipment back to the site 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.

Table 2: 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. Creating and updating the standard operating procedure. Many activities like 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 minutes 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 a limited amount of tools on any piece of equipment in the shop makes the maintenance easier) and reorganizing things, so that little movement is necessary. The tasks of the changeover can be optimized and grouped to ensure minimum movement by the workers. Moreover, engineering changes to the machine 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.

Through the implementation of the SMED stages, we removed and simplified several internal activities. In addition to that, we made design changes to the machine to reduce the changeover time. This gave us a list of lean activities to allocate to the working operators. We use the final list of activities to create a precedence graph and apply the model discussed in section

2.

3.2 Model Implementation

As discussed in section 2.3, the final task list at the end of stage V is analyzed and combined to create the precedence graph shown in Figure 3.

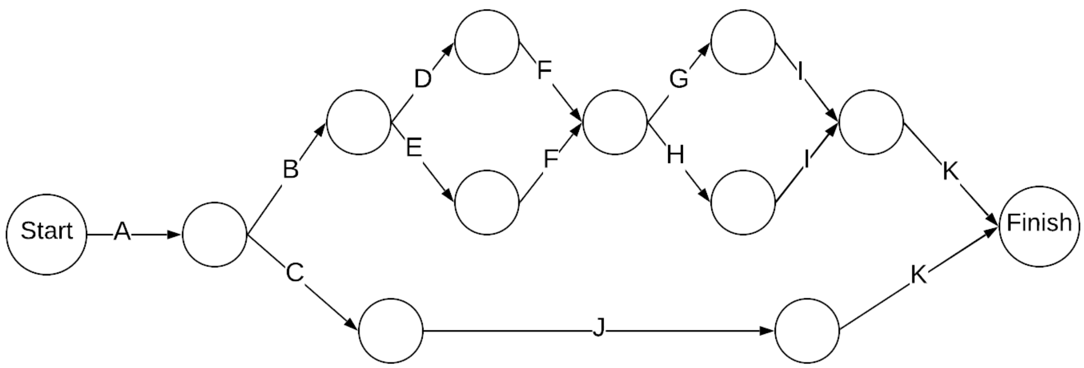

Figure 3: Precedence Graph

The Table 3 shows the jobs and their processing time.

Applying job scheduling heuristics to the list of activities described in the precedence graph, we get the critical path:

Finding 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 seconds.

The critical path is:

Table 3: Jobs and Processing Time

Jobs	**Procesing time p_j (sec)**
A	38
B	109
C	35
D	33
E	44
F	40
G	14
H	12
I	103
J	92
K	41

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

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 4 and 5.

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 2 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.

The final iteration of the algorithm reduces the processing time of activity B from 109 sec to 55 sec as both operators are working on it. After its completion, the precedence constraint is followed, and the second operator can simultaneously work on the other activity. The iterations are repeated until the slack cannot be reduced or the operator limit is reached. This brings down the changeover time to around 6 minutes, which is a significant reduction.

In this case study, the model was implemented after stage V. Although the model can be used in any stage of SMED. The next step here would be to determine the stage in which the model can be incorporated. The next section compares the different SMED stages and discusses how the model compares in terms of reduction in changeover time.

Table 4: Attributes of First Iteration

Jobs	**Earliest Start time(sec)**	**Latest Finish time (sec)**	**Slack (sec)**
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 5: Attributes of Second Iteration

Jobs	Earliest Start time(sec)	Latest Finish time (sec)	Slack (sec)
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

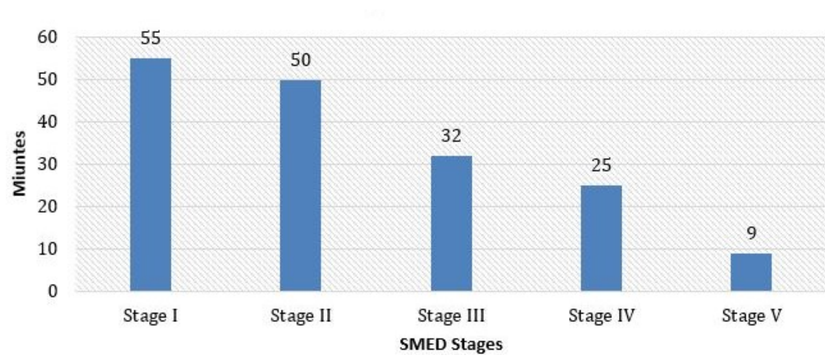

Figure 4: Changeover Time

4 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 4. 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 5 plots the amount of money saved by reducing changeover time and the investment needed in each stage. 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 $14000 to provide savings of $16000 annually. In comparison, the proposed model saves $3000 with around $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.

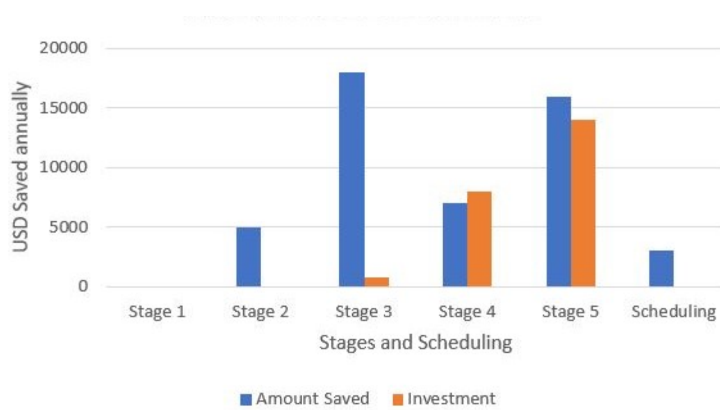

Figure 5: Amount Saved vs Investment

Figure 6 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.

The results can be summarized based on two types of improvements: The human element and the design changes. Initially, the human element

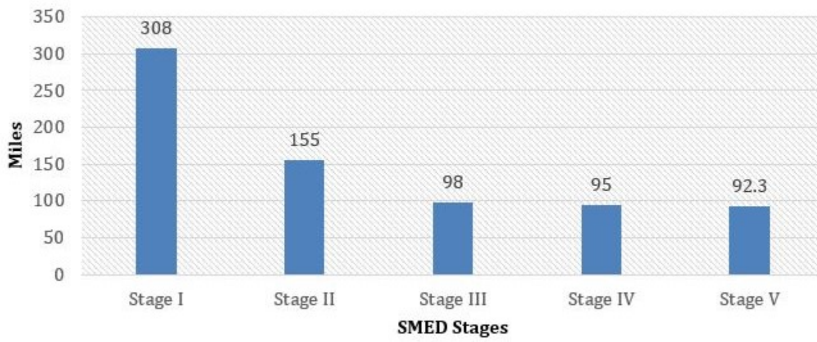

Figure 6: Distance Traveled by Operator

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%.

5 Conclusion

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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