Setup time reduction: SMED-balancing integrated model for manufacturing systems with automated transfer

Maurizio Faccio

Department of Management and Engineering, University of Padua, Stradella San Nicola, 3 36100 Vicenza, Italy

Abstract—The importance of short setup times is increasing in every type of industry. It has been known how to address this problem for about 20 years. The SMED method, originally developed by the Japanese industrial engineer Shigeo Shingo for reducing the time to exchange dies, gives a really straightforward approach to improve existing setups. On the other hand, in the case of complex manufacturing systems the simple application of the SMED methodology is not enough. Manufacturing systems composed of different working machines with automated transfer facilities are a good example. Technological constraints, task precedence constraints, and synchronization between different setup tasks are just some of the influencing factors that make an improved SMED desirable.

The present paper, starting from an industrial case, aims to provide a heuristics methodology that integrates the traditional SMED with the workload balancing problem that is typical of assembly systems, in order to address the setup reduction problem in the case of complex manufacturing systems. An industrial case is reported to validate the proposed model and to demonstrate its practical implications.

Keyword-SMED, Balancing, Transfers, Manufacturing Systems

I. Introduction and Literature Review

As noticed in practice, especially in the mechanical sector, products that require the same job are grouped in batches that get moved to the next production stage when the whole batch has been completed. Jobs in the same batch are continuously processed after the setup. The setup time is defined as the time interval between the completion of the current job and the beginning of the next job. Setup involves all preliminary activities such as preparing a machine or workstation to perform the next operation, and may depend on the type of job, the type of machine or both [1]. There might be several reasons to adopt a batching system [2]:

- Tool capacity constraints for each machine, requiring parts to be divided into batches with tool changes in between.
- Wear and tear on tools during the machining operations, requiring that a tool replacement function to be integrated with the batch change-over procedure.
- Balancing the workload to maximize machine tool utilization on each machine also requires batching as well as relieving bottlenecks or avoiding potential ones, with the intent of maximizing system throughput.
- Batches could be mandated because internal pallet storage is insufficient to handle all parts at once.

In this sense, setup time is one of the vital parameters used in any manufacturing industry and is a form of necessary input to every machine or workstation [3].

The need for short setup times is not new; it has been around for quite a while. Indeed, the time between producing the last product of a series and producing the first product of a new series that meets all quality requirements has always been considered as waste or as ‘added cost’ [4].

But a high setup time is not only ‘added cost’. It can mean loss of market, or loss of customers. Today’s market demands contain more product variants in parallel to customization, with a related decrease of the batch sizes and an increase of the average setup number. Customers require short lead times and flexibility in response. As a result, operations managers are faced daily with the problem of reducing the setup time. In such a context, lean manufacturing systems have the ability to achieve responsive, small batch manufacture so that they can meet rapidly changing market demands. Rapid changeover is a fundamental technique for attaining just-in-time (JIT) production and for addressing the issues of flexibility and responsiveness, and is a substantial part of the lean philosophy. For this scope, Shingo [5] introduced his methodology called Single Minute Exchange of Dies (SMED). It can be defined as a set of structured techniques that make it possible to provide a setup time reduction (up to 90%) with moderate investments.

On the other hand, this methodology can be improved in some cases if integrated with other approaches.

For example, if we consider not a simple machine (i.e. a press or turning machine) but a set of different machines, connected by an automated system for moving, loading, unloading products, the simple application of the SMED methodology may not produce substantial results, or the achieved results could be improved. The reasons for this lie in the complexity of such manufacturing systems. They are composed of two main subsystems:

- the machines subsystem, that performs different tasks on the products
- the transfer subsystem, that moves load/unload products between and at the different machines.

The greater the flexibility of the transfer system (for example, permitting the machine bypass) and of the machines, the greater is the ability of the system to work on a wider mix of products. On the other hand, these kinds of manufacturing systems work as multi-model systems, not mixed-models systems. In other words, they are able to work different batches of products, but in any given batch there is only one model type.

There are different possibilities for automated moving/loading/unloading activities. A very diffuse equipment is composed of transfers, for straight layouts (transfer lines) and for circular layouts (rotating transfer tables).

In these cases, products are moved through special pallets that define the correct position and the correct accuracy during the production at the machines. These pallets need to be reconfigured every time the product changes.

Some examples of the considered manufacturing systems are shown in Fig. 1.

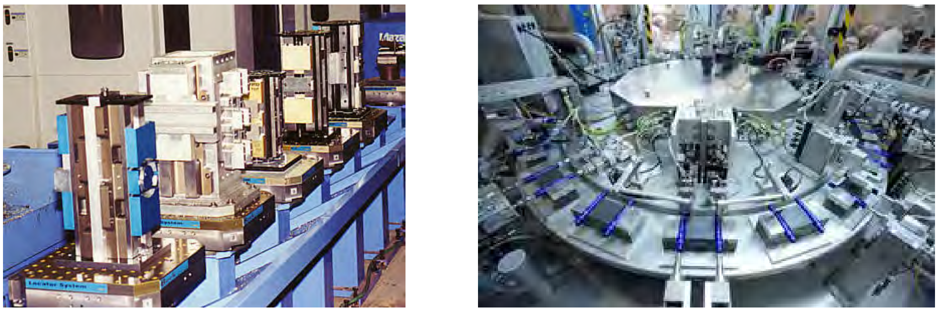


Fig. 1. Manufacturing systems with automated transfer lines (left) and automated rotating transfer tables (right)

As a consequence, setup activities can be divided into two subsets:

- setup activities at the machines (i.e. machine programming, change of tools, re-positioning, etc.)
- setup activities at the transfer system, (i.e. reconfiguration or changes of pallets, etc.)

There are typically strong constraints between and inside these two subsets of activities: task precedence, equipment utilization, task synchronization, necessary number of resources.

The synchronization between the setup activities at the machines and at the transfer represents a particular kind of constraint that is not included in the SMED procedure, but can have a great influence on the setup time reduction results. In fact, for safety reasons, manufacturing systems like those in Fig. 1 include barriers that close the machines and the transfer system, protecting operators outside. The products input/output zone is normally the only position where it is possible to perform the setup activities at the pallets, for changing or resetting tasks.

Fig. 2 shows a typical configuration for automated transfer lines (left) and automated rotating transfer tables (right), highlighting also the two subsets of setup activities (machines and pallets) and their possible/not possible parallelization.

As an effect of the space constraints and the safety devices for pallets setup, the number of operators possible is only one, without any possibility to parallelize these kinds of activities, whereas the setup at machines can be parallelized. It is clear that during the setup activities in a such manufacturing system the transfer will shift a number of times equal to the number of pallets, permitting the operator to perform the setup (i.e. change the pallet into the transfer).

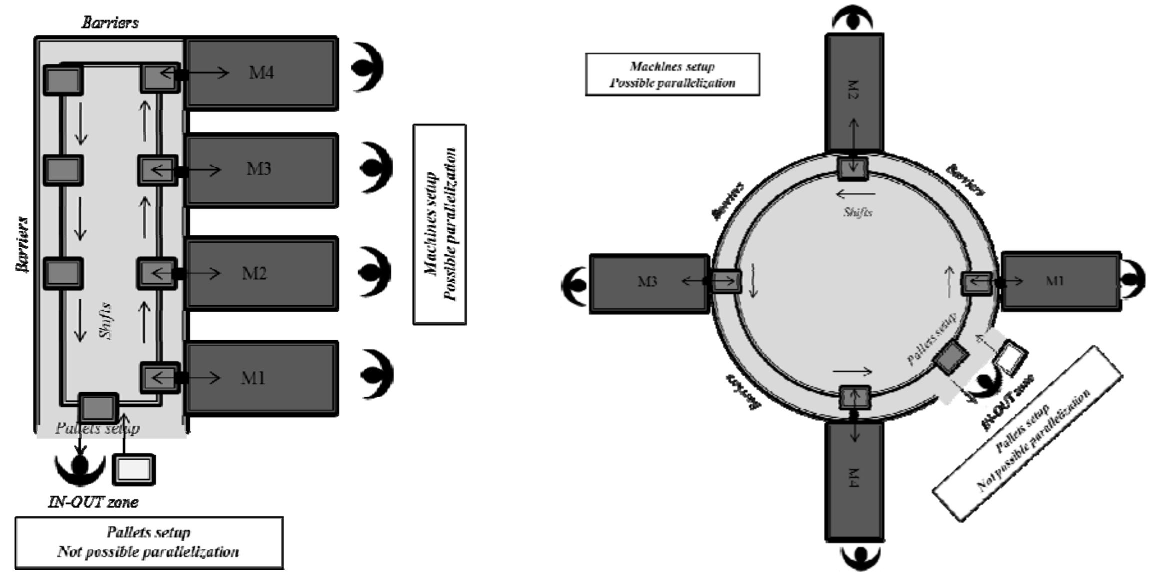


Fig. 2.Traditional configuration for the automated transfer lines (left) and for the automated rotating transfer tables (right).

In this kind of manufacturing system it is possible to find one of the two following scenarios:

- Scenario 1: if the setup at the machines is faster than the total setup at the transfer system, the bottleneck is the setup time at the transfer system (pallets). The lower bound in terms of setup time is the setup time at machines. It is therefore clear that simple application of the SMED technique without taking into account this aspect (especially in the case of parallelization) will give results that could be greatly improved.
- Scenario 2: if the total setup at the transfer system (i.e. reconfiguration or change of pallets, etc.) is faster than the total setup at the machines, the bottleneck is the machines setup. This is a typical configuration that can be found in many industrial systems, because the machines setup is longer and more complex than the pallets setup. Because the lower bound in terms of setup time is the transfer system setup time, and the setup activities at the machines can be parallelized, it is possible to optimally split the setup activities at the machines between different operators.

The high level of complexity is difficult to manage with an exact mathematical approach. For this reason, in many field of operations management in the last decades heuristics have been applied in different operations managements optimization contexts: production system design [1]; sequencing [6],[7]; routing [8]; inventory management [9]. Heuristics are experience-based techniques for problem solving, learning, and discovery. They can include some mathematical formulations in some parts, but the final solutions found are not guaranteed to be optimal.

The proposed study demonstrates how in such complex manufacturing systems, where the setup activity synchronization between the machines and transfer system and between the setup operators is a strong influencing factor, an optimized workload balancing procedure after the SMED application can greatly reduce the setup time. In consequence, the authors propose an integrated SMED-balancing heuristic model in order to achieve a further setup time reduction after the SMED application. Moreover, an industrial case is reported to validate the proposed model and to demonstrate the practical implications of the present study.

The workload balancing approach used has been derived from the assembly line balancing problem [10], [11]. From an assembly system point of view, the problem of optimally assigning operations to different operators (stations) with a certain objective is called Assembly Line Balancing. In the same way, it is possible to apply this methodology to the setup activities with an optimal distribution of the tasks between the operators and taking into account the different constraints that are typical of such complex manufacturing systems. The objective function will aim to optimally smooth the workload between the operators according to the definitions in scenario 1 and scenario 2.

The remainder of the paper is organized as follows. Section 2 provides a SMED overview, highlighting the need for an improved SMED, especially in the case of complex setups, as in the considered manufacturing systems with automated transfers. Section 3 describes the proposed SMED-balancing model for setup reduction in the case of manufacturing systems with automated transfer. Section 4 provides an industrial case with the model application, while conclusions are drawn in section 5.

II. SMED: BASIC METHODOLOGY AND THE NEED FOR IMPROVED SMED

The SMED methodology is a theory and set of techniques that make it possible to perform equipment setup and changeover operations in under 10 minutes. SMED improves the setup process and provides a setup time reduction of up to 90% with moderate investments.

Shingo [5] divides the setup operation into two parts:

- Internal setup: The setup operation that can be done only when the machine is shut down (attaching or removing the dies).
- External setup: The setup operation that can be done when the machine is still running. These operations can be performed either before or after the machine is shut down; for example, getting the equipment ready for the setup operation can be done before the machine is shut down.

As reported by Cakmakci [4], a SMED system includes three main steps, as follows:

- Phase 1: In separating internal and external setup in this step, an important question must be asked for each setup activity. “Do I have to shut the machine down to perform this activity?” The answer helps us to distinguish between internal and external setup. This step can reduce the setup time by 30% to 50%. The three techniques that SMED uses in this step are checklists, function checks and improved transport of dies and other parts.
- Phase 2: Converting internal setup to external setup. In order to achieve the single digit setup time objective, SMED introduces this step in which internal setup activities are converted to external activities. So the total time that the machine is kept down will be reduced. Advance preparation of operating conditions, function standardization and use of intermediary jigs are the techniques to support the second step [7].
- Phase 3: Streamlining all aspects of the setup operation. In this step, “specific principles” are applied to shorten the setup times. Implementing parallel operations, using functional clamps, eliminating adjustment and mechanization techniques are used to further reduce the setup time.

Table 1 shows the basic steps of the SMED technique.

TABLE I
SMED conceptual stages

Stage	*Activity*	*Time*
Before SMED	All changeover elements are performed while the equipment is stopped. These are referred to as internal elements (in black)	Changeover time
Step 1	Identify elements that can be performed while the equipment is running and make them external to changeover (in red)	Changeover time / External time
Step 2	Review remaining internal elements and ask what it would take to make them external and convert as many as possible to external.	Changeover time / External time
Step 3	Review all elements for streamlining and simplifications. This shortens both changeover time and external time	Changeover time / External time

Case studies about setup reduction in different manufacturing environments are described in various contributions [12], [13], [14]. As affirmed by different authors, a major lack of the SMED was the consideration and motivation of the human factor [15], [16]. On the setup methodology, also Mileham et al. [17] observed that operators develop their own way of working by trial and error, and when complex changeover operations are encountered this “inspiration of the moment” method must be replaced with a “standardized setup method” that is prepared by the machine designers [4]. From these considerations it is clear that in the analysis of such manufacturing systems where the complexity of the setup operations is high, the proposed methodology can improve the setup standardization. In fact, the proposed structured methodology, which merges the SMED with a rigorous balancing activity between the operators, defines and optimally assigns operations to different operators, without degrees of freedom. The outcomes are different: reduced setup time, increased operator efficiency, reduced idle times and standardized setup activities.

III. THE PROPOSED SMED-BALANCING MODEL FOR SETUP REDUCTION

This section provides the proposed SMED-balancing model for setup reduction in the case of manufacturing systems with automated transfer. As defined in the introduction, the proposed approach aims to reduce the setup time by using the SMED methodology and balancing the workload between the operators through a proper objective function.

The assumptions considered are as follows:

- The operators are totally involved in the setup activity without restriction.
- The setup activities can be divided into two subsets of activities: setup activities at the machines (i.e. machine programming, change of tools, re-positioning, etc.) and setup activities at the transfer system, (i.e. reconfiguration or changes of pallets, etc.)
- The setup activities at the transfer system can be performed by only one operator (no parallelization) as an effect of the space and safety constraints.
- The setup activities at the transfer system depend on the pallets to be set up. It is assumed that each pallet has the same setup time. This assumption can easily be changed considering the formulation of a different time as a function of the considered pallet.
- During the setup activities the transfer will shift when all the operators involved in the setup have completed their current tasks. In other words, tasks cannot be split. This aspect is typical of the considered manufacturing system where reference points need to be fixed during a setup task.

The notations used are as follows:

i=1……I	Elementary tasks for the setup activities at the machines
j=1…...J	Machines in the considered manufacturing system
k=1…...K	Number of pallets to be set up in the transfer system. Normally this number is equal to the number of transfer shifts during the setup.
n=1…..N	Number of operators involved in the setup activities
Tck	Setup time for one pallet (considered equal for all the *K* pallets).
$T_{i,j}$	Time for the setup task *i* at the machine *j*.
$X_{i,j,n,k}$	Binary variable that assumes a value equal to 1 if the setup task *i* at the machine *j* is assigned to the operator *n* synchronized with the setup of the pallet *k*, 0 otherwise. N goes from 1 to *N-1*.
Δ	calculated as $\Delta = \sum_i \sum_j t_{i,j} - K \cdot Tck$ (1)

represents the difference between the total time for the setup activities at the machines and the total time for the setup activities at the transfer system (pallets). This parameter is able to define which scenario we are in. If Δ<0, this means that the setup at the machines is faster than the total setup at the transfer system and the scenario to consider is scenario1. If Δ>0, this means that the total setup at the transfer system is faster than the total setup at the machines and the scenario to consider is scenario 2. This parameter, better explained in the following section, is important to enable us to understand where to focus the SMED activity.

The workload balancing function is derived from the assembly system [10],[11] and minimizes total idle times of the operators who conduct the setup activities, taking into account the synchronization with the pallets setup. The objective function used in the model is as follows:

$$Minimize: F(N) = \sum_{k=1}^{K} \left| Tck - \sum_{n=1}^{N-1} \sum_{j=1}^{J} \sum_{i=1}^{I} (X_{i,j,n,k} \cdot t_{i,j}) \right| \quad (2)$$

where *N* is the number of setup operators where *N-1* are involved in the machines setup, while 1 is involved in the pallet setup. In this kind of objective function, it is considered that the tasks cannot be split, as explained in the assumptions. *F(N)* as output will give the optimal number of operators involved in the considered setup (*N**) and the optimal task assignation between the *N*-1* operators for the machines setup ($X^*_{i,j,n,k}$).

The constraints considered in the proposed linear optimization model are:

1. Precedence constraints between the *i* tasks at the machines. Using the notations derived by the assembly line balancing problem [10], [11]

P_i set of immediate predecessors of task *j*

F_i set of immediate successors of task *j*

S_n set of tasks assigned to operator *n*

$$E_i = \frac{t_i + \sum_{h \in P_i} t_h}{Tck} \quad \text{earliest operator to which task } i \text{ may be assigned} \quad (3)$$

$$L_i = N - \frac{t_i + \sum_{h \in F_i} t_h}{Tck}$$ latest operator to which task *i* may be assigned (4)

2. Operator numbers constraints. The model is applicable for parallelized tasks and so the minimum number of operators is 2. When 2 are assigned, one is located for the pallets setup and one for the machine setup. When t $N>2$, one is located for the pallets setup and the others for the machines setup. This is a typical situation in reality, where the machines setup is longer and more complex than the pallets setup.

$$N \geq 2 \quad (5)$$

3. Task assignation constraints. All the tasks need to be assigned to a certain operator. The setup tasks for the pallets are all assigned to the *N*-operator, and the other *i* tasks need to be assigned to the *N-1* operators during the

$$\sum_{n=1}^{N} \sum_{k=1}^{K} X_{i,j,n,k} = 1 \quad (6)$$

4. Synchronization constraints. The operators who perform the setup activities at the machines have a task time equal to *Tck.* The synchronization constraints of the task activity *i* at the machine *j* with the pallet *k*, are taken into account, considering the decision variable $X_{i,j,n,k}$, that defines when (after how many transfer shifts) a certain task has to be performed and by what operator. The transfer can shift when all the operators have completed their task assigned for the setup.

The proposed setup reduction procedure for manufacturing systems with automated transfer is made by the follow steps:

- Step 1: SMED technique application. The different SMED phases are shown in Table 1.
- Step 2: Workload balancing using (2). The output of this stage is the N* and $X^*_{i,j,n,k}$ values.
- Step 3: Standardize and optimize setup. As a function of the model outputs N* and $X^*_{i,j,n,k}$ the setup is optimized and standardized. A sequenced task list to perform, indicating how (SMED) and who-where (balancing) each task has to be done, is developed thanks the outputs of Step 1 and Step 2.
- Step 4: Results and improvement. After this stage it is possible to check the real setup time reduction as an effect of both the SMED and workload balancing procedure in the case of complex manufacturing systems with automated transfer. As highlighted in section 1, as a function of the task time for the pallets setup and machines setup, it is possible to have two different scenarios in which the system bottleneck is different. As SMED is part of a wider management philosophy based on continuous improvement, it is at this stage possible to re-apply the SMED technique focusing on the critical task activities (machines or pallets), with the possibility also of changing the bottleneck from a setup typology to the other.

Fig. 3 summarizes the flow chart of the proposed setup reduction procedure for manufacturing systems with automated transfer.

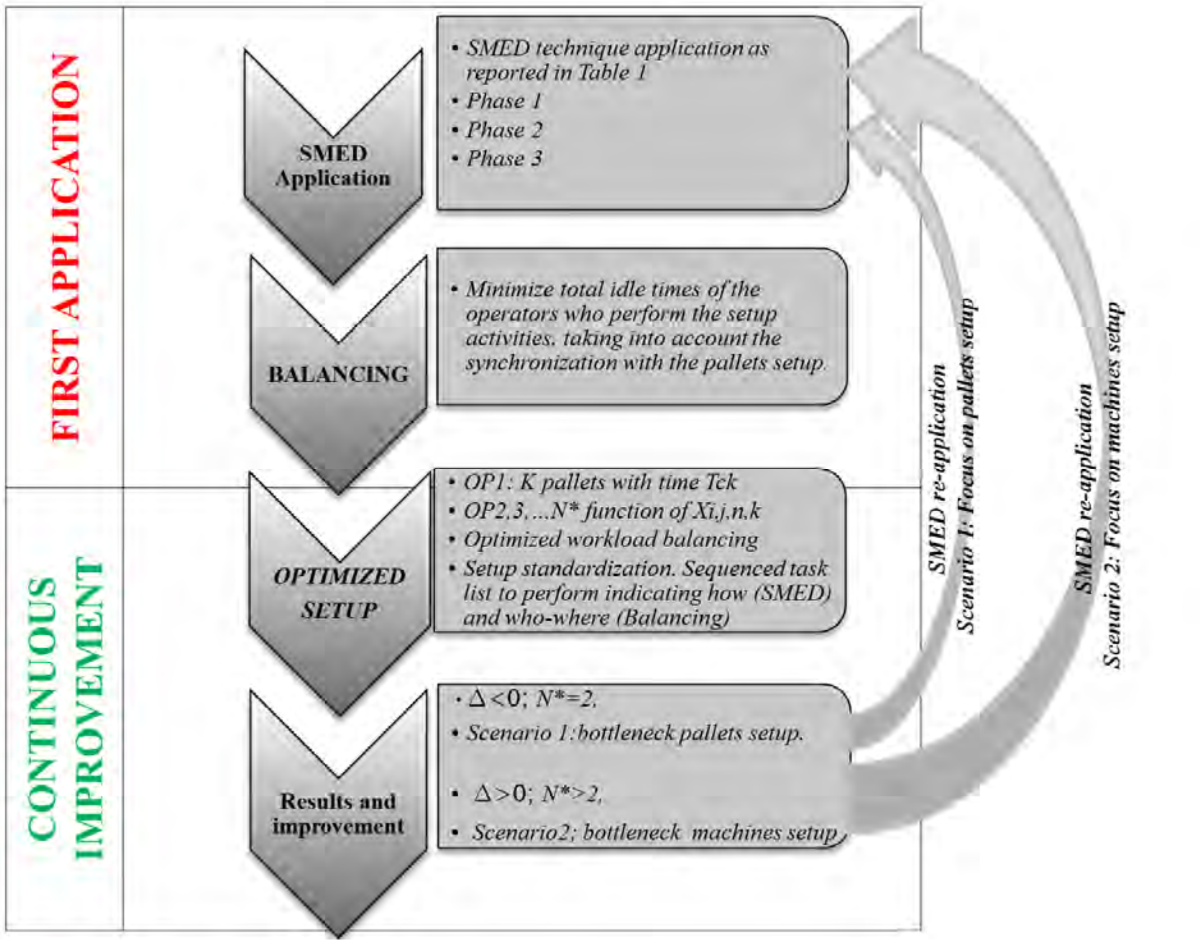


Fig. 3. Flow chart of the proposed setup reduction procedure for manufacturing systems with automated transfer

IV. INDUSTRIAL CASE AND MODEL APPLICATION

The reported case study refers to a pump producer. The case company developed an automated rotating transfer table in which 7 machines and 10 pallets are present. These machines process the body pumps in an intermediate production phase. Fig. 4 shows a schematization of the automated rotating transfer table.

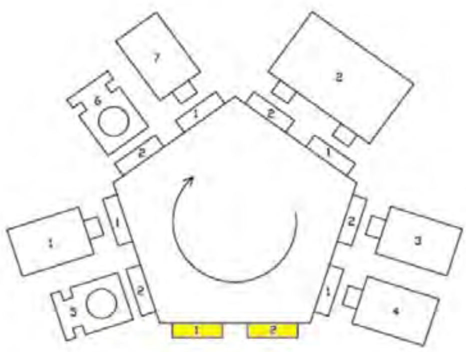


Fig. 4. Case study: automated rotating transfer tables

A particular aspect of this manufacturing system with automated transfer is that, as highlighted in the figure, there are two accessible pallets, not one. In this particular case the number of transfer shifts for the complete setup is not equal to the number of pallets (10) but is exactly half of this. As a consequence, the case study reports the following input data: $J=7$, $K=5$. The total number of setup tasks at machines is $I=170$.

- Step 1: SMED application. After the first setup analysis the total time was approximately 5 hours, performed by 1 operator, who managed on his own all the task activities for both pallet stations and machines, moving from one position to another continuously. As first indicated by SMED, the total external time was 52 minutes. First the transformation from internal activities to external activities was performed.

As a second phase, improvement of the external activities was developed using check lists and organized trolleys. Moreover, as concerns the internal activities, different indications about the improvement and/or simplification of tools and equipment were derived and implemented with a time reduction of about 2 more hours. At this stage, with the same configuration, the SMED application reduced the total setup time from 5 hours to about 2 hours, a reduction of more than 40%. In order to optimize the setup activities and to standardize them, defining by whom and where each activity has to be performed, the second balancing step of the procedure is applied.

- Step 2: Table 2 shows the total task time for the different operations at machines and pallets after the SMED implementation (Step 1). The pallets setup time is *Tck*, so 5 times ($K=5$) this time has to be considered for the total setup time.

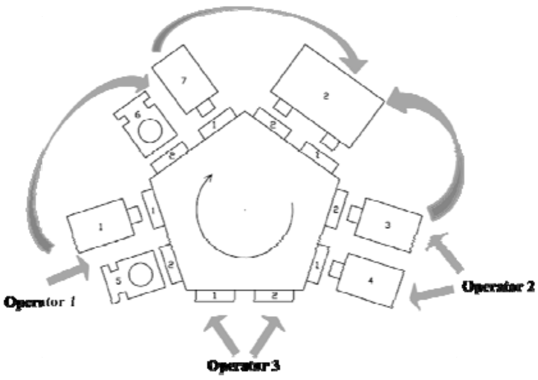
TABLE 2
Total tasks time after SMED application

Activity	***Minutes***
Total tasks time Machine 1	10
Total tasks time Machine 2	14
Total tasks time Machine 3	10
Total tasks time Machine 4	10
Total tasks time Machine 5	1.5
Total tasks time Machine 6	3.5
Total tasks time Machine 7	3.5
Total tasks time pallets (*Tck*)	5
First cycles, first pieces	45
Total Setup time before balancing	122.5

In this case Δ>0, so before balancing we are in scenario 2, where the total setup at the transfer system is faster than the total setup at the machines and parallelization inside the machines setup is possible to achieve a better result.

Application of the workload balancing function gives a result $N^*=3$ and an optimized $X^*_{i,j,n,k}$.

- Step 3: Using the outputs of Step 2 $N^*=3$ and an optimized $X^*_{i,j,n,k}$, it has been possible to define a sequenced task list to perform indicating how (SMED) and who-where (balancing) each task has to be performed. Fig. 5 shows a summary of this list.



Sequence	***Operator***	***Activity***	***Machine***
1	*Operator 1*	Robot setup. Remove hand effector	Machine1
2	*Operator 1*	Robot setup. Place new hand effector	Machine1
...	...	...	...
15	*Operator 1*	Machine setup Remove cutting tool	Machine 2
...	...	...	...

Fig. 5. Setup standardization after workload balancing

- Step 4: The results of the proposed SMED-balancing model applied to the case study are shown in Table 3.

TABLE 3
Case study results

Stage	***Minutes***	***Reduction***
Initial setup time	300	
After SMED application setup time	122.5	59%
After SMED-Balancing alancing application setup time	64.5	79%

The total setup time has changed from 300 minutes (5 hours) before the SMED application to 122 minutes after the SMED application, to 64.5 minutes after the SMED-balancing model application. Table 4 shows the total task times after the optimized assignation.

TABLE 4
Total task times after SMED and balancing application

Operator	*Minutes*
Operator 1	24.5
Operator 2	28
Operator 3	25
First cycles, first pieces	40
Total Setup time after SMED-Balancing	64.5

The optimized workload balancing, according to the task time defined by the pallets setup, has reduced the setup by about 1 hour. The task assignation between operator 1 and 2 depends on the single task times and on the related constraints. As a result, it is not possible to achieve a perfect balancing with operator 3 and with the transfer task time $Tck=5$. Moreover, the standardization of the setup activities obtained through the optimized $X^*_{i,j,n,k}$ permitted a reduction of the production tuning phase, decreasing the time for the first production cycles from 45 to 40 minutes, thanks to better operator organization. The results demonstrate how the benefits of the SMED application combined with an optimized workload balancing between the operators can bring substantial results in the case of a complex setup. Looking at the results, it is clear that the bottleneck in the system is operator 2 for the first phase of the setup. This means that we are again in the case of $\Delta>0$ (scenario 2). As SMED is part of a wider management philosophy based on continuous improvement, the result shows that the SMED re-application has to focus on the machines setup, and specifically on machines 2, 3, and 4. If the tasks assigned to operator 2 decrease after the SMED re-application, it is possible that the bottleneck of the system will change, and in this way the SMED re-application will focus on other activities. This concept is explained by the back arrows in the procedure workflow shown in Fig. 3.

V. Conclusion

SMED methodology, introduced by Shingo [5], is a powerful set of structured techniques that make it possible to provide a reduction of setup time with moderate investments. On the other hand, as observed by Mileham et al. [17], when complex changeover operations are encountered, operators develop their own way of working by trial and error, without a standardized method for the task sequence, the tasks assignation, etc. The proposed study demonstrates how, in complex manufacturing systems where machines are integrated with transfers, a setup reduction can be achieved by integrating the basic SMED methodology with a workload balancing between the operators through an integrated step by step procedure.

In fact, for typical setup activities in a manufacturing system with automated transfers, setup activity synchronization between the machines and the transfer system is a strong influencing factor in the setup time minimization. The authors propose a SMED-balancing integrated model, optimizing the parallelization of the setup activities through an objective function that aims to reduce the operators' idle times and synchronizing the activities with the task time of the fastest. As typically found in practice and also in the presented case study, the machines setup is longer and more complex than the pallets setup, which defines the task time for the task assignation. The results derived from the case study validate the methodology and show the strong practical application of the proposed procedure, reducing the setup time thanks to the workload balancing optimization after the SMED application, by about 50% more. After its application, the methodology moreover makes it possible, after its application with a continuous improvement approach, to understand where to focus the SMED re-application in order to understand system bottlenecks as a function of the optimized task assignation to operators. As further research, as highlighted in [16], application of this kind of methodology in different industrial systems would be desirable in order to understand possible improvements for its wider applicability.

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