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Quick changeover design: a new Lean methodology to support the design of machines in terms of rapid changeover capability

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Abstract

Purpose – This paper presents Quick Changeover Design (QCD), which is a structured methodological approach for Original Equipment Manufacturers to drive and support the design of machines in terms of rapid changeover capability.

Design/methodology/approach – To improve the performance in terms of set up time, QCD addresses machine design from a single-minute digit exchange of die (SMED). Although conceived to aid the design of completely new machines, QCD can be adapted to support for simple design upgrades on pre-existing machines. The QCD is structured in three consecutive steps, each supported by specific tools and analysis forms to facilitate and better structure the designers' activities.

Findings – QCD helps equipment manufacturers to understand the current and future needs of the manufacturers' customers to: (1) anticipate the requirements for new and different set-up process; (2) prioritize the possible technical solutions; (3) build machines and equipment that are easy and fast to set-up under variable contexts. When applied to a production system consisting of machines subject to frequent or time-consuming set-up processes, QCD enhances both responsiveness to external market demands and internal control of factory operations.

Originality/value – The QCD approach is a support system for the development of completely new machines and is also particularly effective in upgrading existing ones. QCD's practical application is demonstrated using a case study concerning a vertical spindle machine.

Keywords Lean manufacturing, SMED, Set-up optimization, Machine design, Engineer-to-order

Paper type Article

1. Introduction

Single-minute digit exchange of die (SMED) is a well-known Lean method for reducing the time needed to complete an equipment change, often to less than 10 min (Shingo, 1985). Some companies have even achieved setup times of less than one minute, thus effectively implementing the One-Touch Exchange of Die (OTED) evolution of SMED. Pushing this concept to the extreme, the Non-Touch Exchange of Die (NOTED) approach can be adopted (Dhankhar and Kumar, 2016).

Compared to traditional methods where setup times are assumed to be fixed, SMED is the first real strategy for the analysis and the reduction of set-up times. This assumption entails reducing the variety of products and combining production batches to reduce the number of set-up activities. This strategy, which clearly goes against the Lean philosophy, requires huge spaces for stocks of materials and finished products and leads to difficult and inaccurate demand forecasting, as well as the risk of product obsolescence. In contrast, the goal of SMED is no longer to reduce the number of changeovers, but to radically reduce their execution times, thereby increasing the overall performance of processes and meeting customer requirements.

Over the past 2 decades, the literature dealing on SMED has expanded significantly, reflecting the growing need to reduce product set-up times. As a result, SMED has become one of the most widely recognized tools of the Lean philosophy by companies worldwide (Benjamin *et al.*, 2013; Junior *et al.*, 2022). There are three key reasons why companies strive to reduce set-up times and adopt the SMED approach (Van Goubergen and Van Landeghem, 2002):

(1) Flexibility: given the significant increase in product variants that companies must provide to their customers along with the decrease in the quantities of each order, the ability to react quickly to product changes is crucial. This entails producing small batches, which inevitably necessitates shorter set-up times.

(2) Increase in the production capacity of the bottleneck machine: a machine is defined as a bottleneck when its production capacity is lower than that of the others, limiting the production capacity of the entire system. Often, high set-up times contribute to the low production capacity of the bottleneck.

(3) Minimization of costs: a decrease in set-up times also has a positive impact on the unit cost of the product, which in turn influences the profit earned.

The SMED methodology is widely supported in both the academic and industrial literature (Junior *et al.*, 2022). Today, implementing SMED is the natural evolution of the original formulation by Shingo (1985), thanks to the integration of Lean Manufacturing and the new possibilities introduced by Industry 4.0, also referred to as smart manufacturing (Buer *et al.*, 2018; Pagliosa *et al.*, 2021; Sanders *et al.*, 2016). SMED integrates method and mapping tools of Lean Manufacturing with Data Analysis and Ergonomics principles to address the increasing complexity reshaping the manufacturing scenario. The goal is to fully embrace Industry 4.0 technologies considering an Industry 5.0 perspective, which places the human factor at the center of the production. This approach is particularly suitable for those industries where craftsmanship still plays a key role and the workforce is a key resource (Vereycken *et al.*, 2021). SMED thus aims to increase the availability of resources and, consequently, the efficiency of a system.

Despite the increasing focus on SMED applications supported by the technology-driven progress typical of Industry 4.0, there are three major shortcomings. Firstly, SMED programmes may fail to sustain the gains made during the initial implementation (Culley *et al.*, 2003). Secondly, the SMED approach is often heavily focused the organizational-led improvements neglecting the potential benefits of focused technical improvements and modifications (Reik *et al.*, 2006). This results in missed opportunities, as technical improvements have proven more effective in reducing changeover time. Thirdly, the high expenditure and complexity involved means that preliminary action are needed at the design stage to allow companies to achieve lower set-up times without facing costly and time-consuming investments.

Many authors have consequently emphasized the need for Lean tools and methods that address the design phase (Mourtzis *et al.*, 2017). Mascitelli (2011) highlighted the importance of designing lean products to ensure the success of the implementation of lean projects. Pezzotta *et al.* (2018) developed a Lean method to support product and service integration at the design level, emphasizing the lack of Lean design rules aimed at detecting and removing waste throughout the entire life cycle. The changeover process is usually the reason for poor performance, and this aspect will likely worsen due to the growing pressure for greater variety and customization of production (Mourtzis, 2022).

This paper thus presents an innovative and structured methodological approach, named Quick Changeover Design (QCD), to support Original Equipment Manufacturers (OEMs) in reducing set-up times during the design phase. QCD can also be adapted to improve existing equipment as well. We believe that designing products in line with Lean principles can be highly effective in the SMED perspective.

Despite numerous studies dealing with SMED implementations and enhancements (Section 3), to the best of our knowledge, there are no methodological approaches that can be considered both as a support system for developing entirely new machines and upgrading existing ones.

The QCD approach and its tools can support equipment manufacturers in understanding the current and future needs of their customers. Through the use of QCD, manufacturers can:

(1) anticipate the requirements for new and different set-up processes

(2) prioritize possible technical solutions by analyzing at an early stage whether any interactions are likely to be beneficial or not

(3) build machines and equipment that are easy and fast to set-up under variable contexts

Overall, these benefits help overcome traditional changeover problems, such as the need for ample space for stocks of materials and finished products, difficult and inaccurate demand forecasts and the risk of product obsolescence which can result in high costs and implementation difficulties.

The remainder of this paper is structured as follows. Section 2 outlines our research objectives and methodology. Section 3 provides an overview of the literature, highlighting research gaps. After a brief summary of the original SMED methodology (Section 4), QCD is introduced and described in detail (Section 5), along with the procedures and some of the tools that can be used to implement it in real world applications. A case study is provided, to illustrate the methodology in action (Section 6). Section 7 discusses the proposed approach's strengths and limitations. The conclusions and future potential developments are reported in Section 8.

2. Research objectives and methodology

There are two key research questions: (1) "What are the most effective strategies in an industrial environment to reduce changeover times?"; and (2) "How can the QCD methodology be applied to successfully reduce set-up times in a real industrial application?"

These research questions are addressed by a thorough review of the literature highlighting the research gaps and through the analysis of a real industrial case concerning a vertical spindle machine. To this purpose, the "Applied Research" method (Brown and Hale, 2014) has been adopted by following the phases listed below (Figure 1):

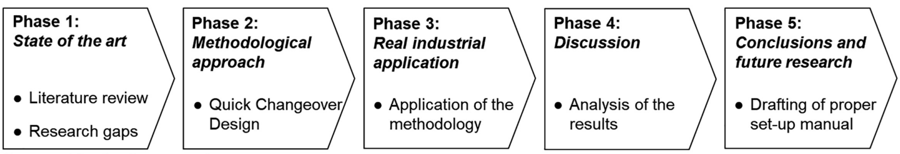

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Figure 1. Phases of the methodological research

(1) Phase 1: State of the art. A literature review was conducted to analyze how industries addressed changeover time reduction. The aim was to determine which improvements have been mostly adopted and where they have been implemented.

(2) Phase 2: Methodological approach. The proposed structured approach aims to improve the performance of a newly developed machine in terms of reducing set-up times. The method follows a step-by-step procedure that begins by defining the product that processes and its characteristics and leads to the realization of customized technical solutions to minimize set-up times.

(3) Phase 3: Real industrial application. To assess whether the method is actually able to understand how to technically act at the design level to accelerate set-up activities in a real industrial environment, the approach has been applied to a vertical spindle machine. The case study allowed us to thoroughly analyze some operational aspects and verify its practical applicability and effectiveness.

(4) Phase 4: Discussion. Results from the real industrial application are discussed. Strengths and limitations are analyzed to express insights and implications for researchers, practitioners and policymakers.

(5) Phase 5: Conclusions and future research. Finally, the last step involves analyzing the results of the study and identifying possible future developments to further improve the methodology.

3. State of the art

Many industrial SMED implementations have been proposed, and our aim was to determine which have been the most common improvements and where they have been implemented. For this purpose, a literature was employed following the scheme adopted by Mourtzis (2019), Yadav *et al.* (2020) and Pansare *et al.* (2022). The review was carried out in three stages: (1) articles related to SMED implementations were searched for using Scopus and Web of Science using the following keywords: "SMED implementations", "SMED applications", "change time reduction", "set-up time reduction" and "changeover improvement"; (2) identification of relevant papers by abstract reading and (3) full-text reading and grouping into research topics.

Articles published from 2007 to 2022 have been considered. Only journal articles were included to ensure the quality of the articles, while all other types of articles such as conference articles, book chapters, short surveys, editorial notes, etc. were excluded. Using a snowball and backward approach duplicate papers have been eliminated and all relevant ones included. Our search resulted in a final sample of 30 changeover improvement implementations, which were selected for analysis in this research.

3.1 Changeover improvement implementations reported in the selected literature

SMED implementations form three main macro groups as shown in Table 1: (1) industrial cases where only organizational and/or procedural improvements have been implemented; (2) cases in which technical changes to the machinery have been implemented; and (3) cases where a combined improvement methodology has been adopted.

Organizational and procedural improvements aim to optimize the sequence of the operators actions, without making technical changes to the machinery or equipment, whereas technical ones have a direct impact on the machine or the equipment, by simplifying and speeding up the operators' actions during the tooling phases, as well as making them more reliable. Although organizational and procedural improvements are relatively inexpensive to

Table 1.
SMED implementations identified through the literature review

Improvements	Categories	References
Organisational and/or Procedural	Organization	Karwasz and Chabowski (2016), Ribeiro *et al.* (2011), Roriz *et al.* (2017), Sayem *et al.* (2014) and Sousa *et al.* (2018)
	Standardization	Méndez and Rodriguez (2016)
	Offline activities	Braglia *et al.* (2016) and Garg *et al.* (2016)
	Optimization	Ferradás and Salonitis (2013)
Technical	Simplification	Braglia *et al.* (2016), Dhake and Rajebhosale (2013), Kumaresan and Saman (2011), Ribeiro *et al.* (2011) and Singh and Khanduja (2011)
	Standardization	Bharath and Lokesh (2008), Cakmakci and Karasu (2007), Reik *et al.* (2006), Saravanan and Mothilal (2017)
	Quick fixing	Bevilacqua *et al.* (2015) and Braglia *et al.* (2017)
	Optimization of adjustment	Lozano *et al.* (2019), Saravanan and Mothilal (2017) and Singh and Khanduja (2012)
	Offline activities	Braglia *et al.* (2016), Garg *et al.* (2016) and Martins *et al.* (2018)
	Mechanization	Desai and Rawani (2017)
Combined		Gaikwad *et al.* (2015), Monteiro *et al.* (2019) and Vieira *et al.* (2019)

Source(s): Authors work

implement, their ability to reduce the overall downtime is generally lower. Technical improvements can be particularly expensive, but offer a higher reduction in set-up times, thus helping to achieve the main objective of SMED. By combining these two types of improvements and trying to limit their costs, significant results can be achieved with moderate investments (Ahmad and Soberi, 2018; Sayem *et al.*, 2014; Silva *et al.*, 2020). Finally, it is crucial to remember that preserving success is just as important as achieving it, otherwise all efforts to reduce the set-up time would be ineffective. In this regard, technical improvements are relatively more sustainable. In fact, once optimally designed and implemented, they will work as desired without alterations. Procedural improvements, on the other hand, are more challenging to maintain if not standardized and constantly monitored, causing a subsequent increase in set-up times.

The most popular solution for refining work organization and procedures during set-up activities, especially among medium-small businesses, is to use specific methods and strategies. This approach ensures relatively immediate, simple to implement and cost-effective results. We have classified strategies and the support tools for organizational-procedural solutions into four categories:

(1) Organization: the tools and methods in this category achieve a better organization of the work environment, facilitating and optimizing the operations and movements of the set-up worker. These strategies include using set-up trolleys shadow boards and visual storage (Ribeiro *et al.*, 2011; Sayem *et al.*, 2014; Sousa *et al.*, 2018). The most used tool in combination with SMED is the 5S technique (Roriz *et al.*, 2017), which provides the theoretical background to reorganize the work area and thus to optimize work procedures.

(2) Standardization: in addition to organizing the workstations, the work procedures need to be standardized as much as possible. For the standardization of external activities, checklists are often used so that everything required for the next set-up can be prepared in advance. These checklists set out the tools needed for the machine and the parts needed for the tooling phases, as well as any operations that must be performed before the machine stops (pre-assembly, functional checks, equipment

cleaning) and, possibly, the number and name of the operators who will have to take care of the set-up activities. For internal activities, Standard Operating Procedure (SOP) worksheets are sometimes provided on board or inside the set-up trolley, which describe in detail the sequence of operations that operators must perform (Méndez and Rodríguez, 2016).

(3) Offline activities: these involve the strategies for converting internal into external activities. The most well-known is the duplication strategy, which prepares pre-assemblies or presets for the next batch while the machine is still in operation (Braglia *et al.*, 2016).

(4) Optimization: entails several strategies used to optimize the set-up and reduce machine downtime. Planning parallel operations is the most common strategy and leads to significant reductions in time thanks by assigning a wild operator so that operators who are temporarily on standby can be re-assigned to help colleagues struggling with long and complicated set-up tasks. Another interesting strategy makes use of the visual approach, helping operators through simple visual systems, avoiding execution errors (Ferradás and Salonitis, 2013).

Technical enhancements come into play whenever the equipment is improved and set-up tasks are speeded up. This changes the way individual operations are carried out and is thus not a mere reorganization of the sequence of actions as in most organizational improvements. We have grouped the technical enhancements into six different categories:

(1) Simplification: involves simplifying and reducing the number of set-up operations, particularly during assembly and disassembly. Examples of this are the lightning of components and equipment to facilitate both transport and replacement (Singh and Khanduja, 2011); avoiding replacing parts by making them modifiable "at run time" (in shape or size) and designing them as "dynamic" systems. Typically, this involves dividing the same objects into elements that are able to move and reposition with respect to the others (Kumaresan and Saman, 2011). Modular assemblies are thus used to facilitate the removal and the assembly of small parts when the machine is stationary, or to remove the entire module thus enabling the whole module to be duplicated and prepared externally (Dhake and Rajebhosale, 2013). This approach is very effective when combined with rapid coupling systems (Braglia *et al.*, 2016). Simplification strategies can be complemented through modifications that facilitate the manual activities of the operators involved in the set-up, that improve the ergonomics of the work in general and that reduce the human error following the Poka-Yoke methodology (Ribeiro *et al.*, 2011; Singh and Khanduja, 2011).

(2) Standardization: this leads to lower variability in the elements an operator manages during set-up, to the reduction of errors during the picking phases and to fewer tools required (Cakmakci and Karasu, 2007). Standardizing the interface between groups or components of the machinery, such as between tools and tool holders, between intermediate masks and machine table, is particularly interesting. Often, this results in the adoption of universal tool holders (Reik *et al.*, 2006; Saravanan and Mothilal, 2017).

(3) Quick fixing: this involves using one-turn, one-motion or interlocking fixing devices. Manual locking systems provide good tightening, do not require specific tools and are relatively cost-effective. Clearly, in some cases operating conditions require more robust solutions (Bevilacqua *et al.*, 2015) and electromagnetic locking or hydraulic/pneumatic devices maybe be useful (Braglia *et al.*, 2017).

(4) Optimization of adjustments: this entails optimizing the positioning of parts and equipment and setting process parameters, i.e. two very delicate phases in internal tooling activities. Set-up times are always very high and reducing them involves setting and positioning activities before the machine stops, thus trying to completely eliminate any adjustment (Sousa *et al.*, 2018). Sensors, for example photoelectric cells, can help to optimally align the workpieces on the machine through fully automated systems managed by PLCs (Saravanan and Mothilal, 2017; Singh and Khanduja, 2012). Using graduated scales and/or counters can ensure correct placements and adjustments (Lozano *et al.*, 2019).

(5) Offline activities: this is the most effective strategy for reducing internal set-up times as it means that many internal activities can be transformed into external activities, thus drastically reducing machine downtime. With this strategy operators must have access to parts or areas of the machinery while the machine is still operating but all within safety norms. It is thus difficult to develop this strategy on existing machinery and it is more feasible at the initial design stage. Using external buffers or duplicated elements on the machine is another way to reduce some of the set-up operations. Finally, exploiting equipment and simple tooling benches to carry out some set-up operations externally is strongly recommended (Braglia *et al.*, 2016).

(6) Mechanization: set-up mechanization (Desai and Rawani, 2017) should be considered only when all the five strategies above have already been applied. The other five reduce the set-up time from a few hours to a few minutes, whereas mechanization usually lead to reductions of just a few minutes, which may not be sufficient considering the cost of the intervention. Mechanization involves moving and transporting heavy, bulky or difficult to manage components by one individual operator who can make use of motorized trolleys, pantograph elevators, and devices equipped with idle and/or motorized rollers to avoid excessive efforts.

The recent literature shows that only a small percentage of manufacturers have used exclusively technical improvements (Bento da Silva and Godinho Filho, 2019), given that they are excessively expensive. Instead, companies tend to favor organizational improvements and low-cost compromises between organizational and technical improvements.

Companies that opt for procedural/organizational solutions are generally SMEs that do not want to make excessively high investments, or that did not have sufficient technical knowledge to be able to make changes at a technical level on the machinery from the SMED perspective. Interesting, there are very few cases in which the final goal of SMED has been achieved (less than 10 min set-up times). The only cases are those described by Roriz *et al.* (2017) for a company in the paper industry and Gargia-Gargia *et al.* (2022) in the food industries. In a few cases a 50% (or more) reduction in time has been achieved (Méndez and Rodríguez, 2016; Shinde *et al.*, 2014; Karwasz and Chabowski, 2016).

Technical improvements tend to be carried out by large companies with a higher financial budget or that have already implemented organizational improvements, but did not achieve the desired results. In most cases, changes to the machinery or equipment involved high costs both economically and in terms of time consumption. However, in the industrial cases analyzed, reductions in time have meant that the costs have been recouped quite quickly (Afonso *et al.*, 2022; Bharath and Lokesh, 2008; Braglia *et al.*, 2016, 2017). Reductions of over 55% in set-up times were achieved with a limited recovery period, which justified the high costs of implementation. Consequently, although technical improvements can be complicated and expensive, in most cases they become financially viable in the mid to long term.

The mixed strategy, which combines organizational-procedural improvements with moderate-cost technical measures, is particularly popular among medium-large companies.

This approach has been shown to provide excellent results in terms of the ratio between the reduction of time and the implementation costs (Gaikwad *et al.*, 2015; Malindzakova *et al.*, 2021; Monteiro *et al.*, 2019; Vieira *et al.*, 2019). In most cases the set-up times percentage reductions are on average 59%. In addition to costs, in the case of the mixed strategy and, especially, when adopting the technological improvement strategy, the implementation times are also generally high, as it is never easy to modify an existing machine.

Most companies that adopt procedural/organizational improvements are unwilling to make the high initial investment required by technical improvements thus leading to a set-up time reduction of less than 50%. However, technical and combined improvements do reduce changeover times, even though they require technical knowledge, time and high capital availability. It would be relatively easier and cheaper to think about these changes already in the design phase.

Consequently, making changes to the machinery in the SMED perspective in the design phase makes more sense (Singh and Khanduja, 2011) saving more time than through traditional organizational and procedural methods and strategies. Singh and Khanduja found that a very high fraction (84%) of the overall reduction in set-up time was due to various technical improvements. The researchers addressed the improvement of the changeover from the first SMED publication and even earlier. However, to the best of our knowledge, there is no methodological approach that focuses on reducing setup time at the time of design and is able to identify, prioritize and implement the best technical solutions without having to face the economic and temporal challenges entailed in technical changes to existing machines.

4. Single-minute exchange of die (SMED)

SMED consists of four stages that guide the transition from the current state to the desired state (Figure 2):

(1) Preliminary phase (or Stage 0). Organize, observe, record and tempify;

(2) Stage 1. Separate internal set-up operations from external ones;

(3) Stage 2. Convert as many internal operations as possible into external ones and

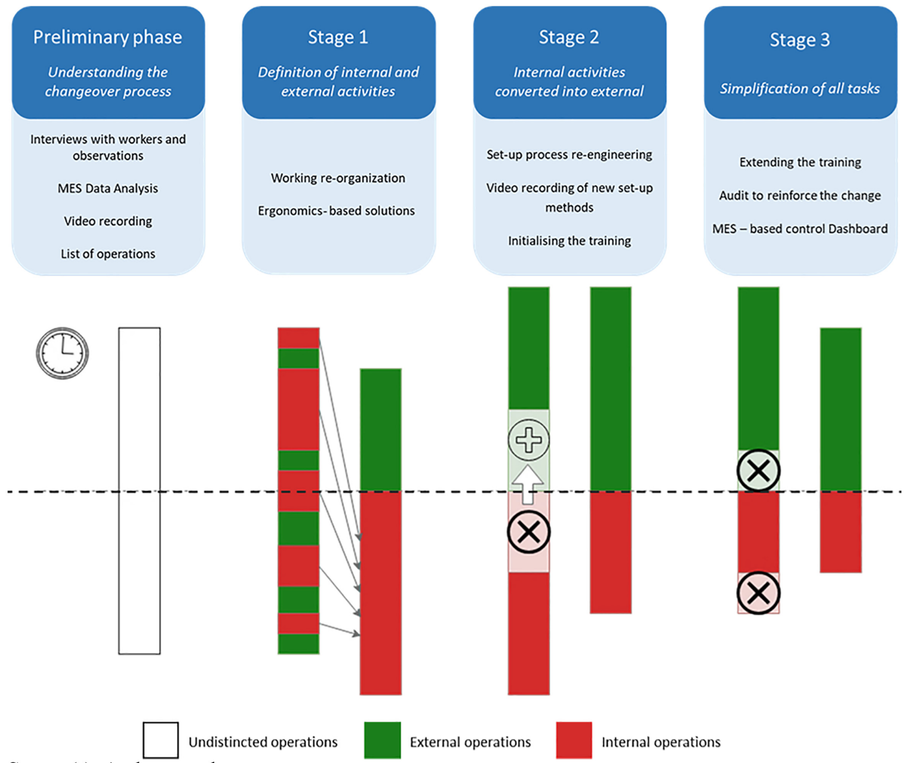
(4) Stage 3. Simplify and speed up all elementary operations, especially internal ones.

SMED can integrate Industry 4.0 technologies, Lean Manufacturing tools and methods and Ergonomics with a focus on the central role of workers.

During the preliminary phase, Industry 4.0 technologies can be used to analyze the vast amount of data from the shopfloor, which can be collected by the Manufacturing Enterprise System (MES) to identify the most significant cluster of changeovers on the performance of the system. Interviews, observation and analysis actions are carried out. First of all, after videoing the downtimes due to set-up activities, the machinery or the line is chosen and, finally, the desired/expected results in terms of reduction of set-up times are set. This step is time-consuming but is necessary for a thorough understanding of the set-up process.

The members of the SMED team are then selected, usually five to seven people – not only experienced technicians, department managers, supervisors and engineers, but also those who interact daily with the machinery.

Stage 1 of SMED involves differentiating between internal (with the machine still running) and external (the machine is not running) set-up operations. This entails (1) critically understanding the MES data analysis; (2) adopting a 5S mindset to introduce more order into the shopfloor; (3) exploiting ergonomic solutions to facilitate set-up. Although even a 30% reduction can be achieved this is not enough to achieve the goal of SMED, i.e. one-digit set-up times.



Source(s): Authors work

Figure 2.
The original SMED process

Stage 2 transfers the internal operations found in Stage 1 to the external set-up tasks. This entails (1) reviewing internal operations to determine whether some of them have been mistakenly considered as internal and (2) finding an intelligent way to carry out internal operations while the machine is running, that is, externally. In this stage, a re-engineered set-up process is defined and formalized. The workforce should be trained by using tools to map workers' movements, thus identifying and removing the avoidable ones.

Finally, Stage 3 aims to streamline all the set-up operations, in particular the internal ones, as these define the downtime of the machinery. This step requires a more detailed analysis of each elementary operation and by exploiting MES information other data-driven tools can support the management in the control of activities on the shopfloor. Data-driven tools, such as an MES-based control dashboard, can support shift supervisors to increase their daily awareness about the department's current performance. Virtual reality training can increase workers' professional development and motivation levels. This should all lead to increased efficiency, a reduction in downtime and potential cost savings.

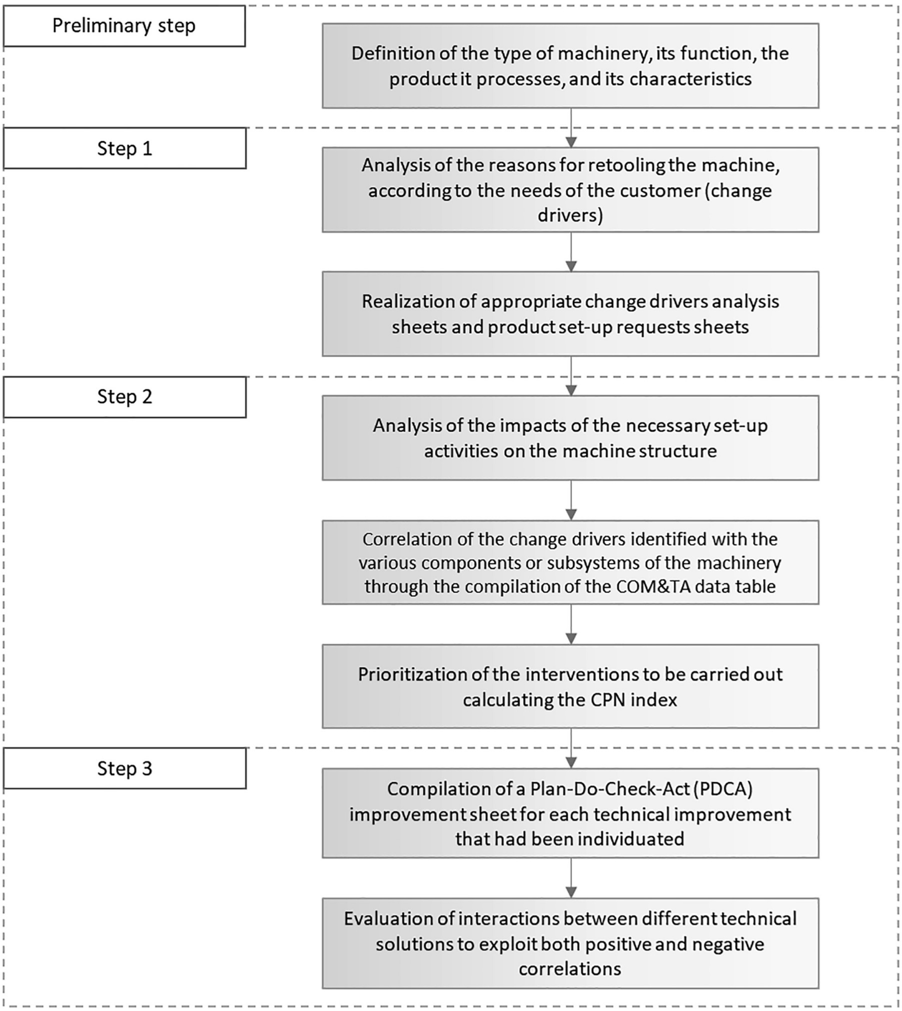
5. Quick Changeover Design (QCD)

QCD is a methodological scheme to design machines from a SMED perspective to reduce set-up times. Although conceived to support the design of completely new machines, it can also be adapted for simple design upgrades on machines that are already on the market.

A flowchart of the QCD approach, which follows the logical scheme presented in Yadav *et al.* (2018) is reported in Figure 3.

Following the Lean philosophy, the approach to help designers is based on a series of logical steps. After a preliminary step that allows having a starting picture of the machinery, its function and the product (or family of products) that it must process, there are three consecutive steps, each supported by specific tools and analysis forms, to facilitate and better structure the designers' activities:

(1) Step 1 analyzes the reasons for retooling the machine, according to the needs of the customer (known as change drivers). This preparatory work makes it possible to formulate the basic ideas for designing and building a machine that will guarantee low product set-up times and maximum ease of execution;



Source(s): Authors work

Figure 3.
The flowchart of the QCD approach

(2) Step 2 focuses on which of the areas of the machine identified in the first step, impact from a technical perspective, the structure and the components of the machine itself. This step allows for a translations of the customers' production variability needs into a more technical language typical of a designer. Various tools can be used at this step, ranging from the Barashi-board, for a clear initial visual approach, to a correlation matrix between change drivers and machine components and/or the priority evaluation table, which is inspired by technical analyses such as Failure Mode Effects Analysis (FMEA). The goal of all these tools is to understand where it is necessary to intervene technically from a SMED perspective. In addition, such tools can be used to prioritize all subsequent technical developments based on both customer needs and the technical issues of the set-up activities associated with each change driver;

(3) In Step 3, improvements are made and the project team must think about possible solutions, prevalently technical, by referring to specific design guidelines such as the Design-For-Changeover (DFC) rules proposed by Mileham *et al.* (1999) and Reik *et al.* (2006) – see Table 2. The aim is to minimize the time associated with the various set-up activities identified, making the set-up itself fast and easy. In addition to the technical feasibility of the improvement, the level of difficulty required for the implementation and, above all, the related economic aspects also need to be evaluated.

Technical improvement	Design guidelines
1. Simplification	• Lighten those parts that will be moved during set-up • Eliminate the need to disassemble elements that will not be replaced • Eliminate the need to replace elements by making them modifiable • Design modular assemblies/parts • Delete pipe connections, or use quick plug connections • Facilitate easy access to the machinery or to the parts subject to set-up operations • Simplify the actions of the employees by focusing on ergonomics • Design parts following the principles of Poka-Yoke
2. Standardization	• Standardize bolts • Standardize functional dimensions of parts of machinery and equipment • Design standard machine parts
3. Quick fixing	• Use few bolt types • Use quick locking devices (one-turn, one-motion, interlocking) • Use hydraulic, pneumatic or electromagnetic locking devices
4. Optimization of adjustments	• Avoid internal placements and adjustments • Avoid manual adjustments by using simple and quick adjustment systems • Equip the machinery with appropriate centering and positioning systems • Introduce integrated measuring and control devices • Equip the machinery with discreet positioning systems • Use centering templates • Use the Least Common Multiple principle
5. Externalization	• Grant safe access to the machinery while it is operating • Introduce external buffers or duplicate parts • Use masks or intermediate bases • Integrate equipment or workbenches for early preparation
6. Mechanization	• Integrate tools for moving heavy or bulky parts • Use special tools to speed up the internal tooling phases • Mechanize machine parts for quick, non-manual set-ups

Source(s): Authors' work

Table 2.
Effective design rules to reduce set-up times

Following the principles of the Lean philosophy, a well-defined and unambiguous scope is essential to initiate a QCD project. Therefore, it is crucial to form cross-functional team including designers, production experts and analysts and also employees and/or managers of the commercial department. Given that they interface directly with the customers, employees and managers can provide crucial information for the team during the initial stages of the project. During very preparatory phase, the team focus on answering a number of seemingly simple, but fundamental questions:

(1) What is the intended function of the machine?

(2) How should the product be processed by the machine?

(3) What are the existing prototypes of similar machines considering both a company's own machinery and that of its competitors?

(4) Is the new machine, or the improvement, a short-term or a long-term solution?

Answering the last question is particularly important for identifying the change drivers and for the subsequent cost-benefit analysis.

5.1 Step 1

Content. Analysis of the reasons for retooling the machine, according to customer needs.

Purpose. To understand how to design a successful machine or piece of equipment, that will ensure low product change times and ease of set-up.

The primary objective of Step 1 is to understand the underlying causes that necessitate retooling the machinery. This involves identifying those factors that require modifications, adjustments or changes to the machinery whenever there is a change in production. To achieve this, it is essential to get customer feedback and make sure that this acts as a driver for the development of the whole project. In essence, the first question to address in Step 1 is: "What are the future productions requirements that customers may need from the machine?". Answering this question correctly helps bridge the gap between the performance that a customer expects and what the company perceives from these requests, i.e. change drivers (Reik *et al.*, 2006). These drivers can be classified into two main categories (Table 3).

From an SMED perspective, the variability of the product to be processed by the machine has the most impact in this step. It is crucial to identify any product parameters that may vary during the different set-ups, including, for example size, shape and quality. For each parameter, the ranges of variation, the types of materials and any exceptions must be defined. Additionally, there may be some technological factors, linked to the process and its functional needs, which do not depend directly on any variations to the product. For example, in hot or injection forging, the molds must reach a given temperature before starting the process to ensure the final product meets minimum quality requirements. Key change drivers directly

Internal drivers		External drivers	
Company goals	Strategies, production goals	Society and politics	Rules, norms, laws
Products range	Strategies, products range	Technology	Known and available technologies and materials
Product	Design, functionalities, structure	Market	Prices, market shares

Source(s): Authors work

Table 3. Change drivers classification

linked to product variability include size, shape, configuration and quality, while those linked to the process variability are cleaning, consumables, machine or process status.

If potential latent change drivers are identified, i.e. those that the customer does not openly request this can could greatly increase their level of satisfaction. All these requirements arise directly from the customers' production needs which are dictated by the market. This goes against one of the classic rules of new products development, which states that design can only begin when the requirements of the machinery have been fully defined. Today, the complexity of needs and the speed of change often make it impossible to separate the task of defining the requirements from the design stage. In fact, many companies begin designing before the requirements are complete.

Consequently, in order to obtain the most comprehensive list of requirements and potentially variable parameters, an analysis is required that is mainly based on subjective methods, derived from the personal opinion of market experts and traders or from market surveys. The Delphi method (Mauksch *et al.*, 2020) is a valuable tool for such purposes. The information gathered in this step should be recorded using change drivers analysis sheets and product set-up request sheets, as shown in Figures 4 and 5.

Figure 4 depicts all the change drivers identified, highlighting their variations with respect to the machine, the process and the product. This information can be presented using schemes, designs, pictures and any other helpful data for the analysis. For example, color codes can be incorporated for different change drivers it would be useful, as it will be highlighted in Step 2. Figure 5 shows the characteristics of the products and reports, in the four columns, the potential dimensional changes, the change in materials, process parameters and weight. All these must be constantly updated during all the subsequent redesign processes.

<table>
<tr><th colspan="6">CHANGE DRIVERS ANALYSIS SHEET</th></tr>
<tr><th colspan="2">Machine</th><th colspan="3">Process</th><th>Product</th></tr>
<tr><th>Category</th><th>Change drivers list</th><th>Variations</th><th>Notes</th><th>Color</th><td rowspan="11">Description and/or schemes and/or drawings</td></tr>
<tr><td rowspan="5">Product variability</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Process variability (Technical needs)</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Machine description and/or schemes and/or drawings</td></tr>
</table>

Source(s): Authors work

Figure 4.
Change drivers analysis sheet

5.2 Step 2

Content. Technical analysis of the impacts of the set-up activities on the structure of the machine.

Purpose. To understand how to intervene technically at the project level so that the machine can incorporate customer requirements and speed up individual set-up operations.

Once the various change drivers have been fully identified, it is necessary to understand the technical impacts on the machinery. To minimize the set-up times, predictable variations in settings must be analyzed, considering the potential future productions of the customer. Often customers express their needs in non-technical terms, particularly when the product is business-to-consumer (B2C). On the other hand, for business-to-business (B2B) there is less of a gap between the terminology used by customers and the manufacturers.

A good initial approach is to use visual tools, built from the original scheme of the machine. This involves having a board (in most cases a Barashi-board), where cards representing machine diagrams can be pinned. These diagrams can be CAD drawings or simplified diagrams of the machinery. The change-driver cards can also be pinned to the board and are structured to accommodate all the information needed (Figure 6). If color codes have been appropriately adopted in the change-drivers analysis sheet, each change driver card should be visually identified using this color.

Given that the number of cards may eventually cause the board to be rather chaotic, we propose a new methodological tool is proposed, that is formally derived from the well-known FMEA methodology. We have called this tool Changeover Occurrence, Mode and Time Analysis (COM&TA). It is a modified version of the Changeover Out of Machine Evaluation Technique (CoMET) proposed in Braglia *et al.* (2016). Our tool provides an objective evaluation of the individual set-up activities through an index which by analogy with the original methodology is called Changeover Priority Number (CPN).

The COM&TA uses a table (Figure 7) whose first two columns report the breakdown of the machinery. The next three columns describe the set-up activities to which the various components or subsystems of the machine are subjected. The remaining columns relate to the analysis of the set-up activities and the assessment of the priority of intervention.

The first column only allows for a fixed number of elements, which are the functional areas that may be directly interested by the changeover process. The second column includes, for each functional group, the components involved in the retooling activities. The third, fourth and fifth columns provide, respectively:

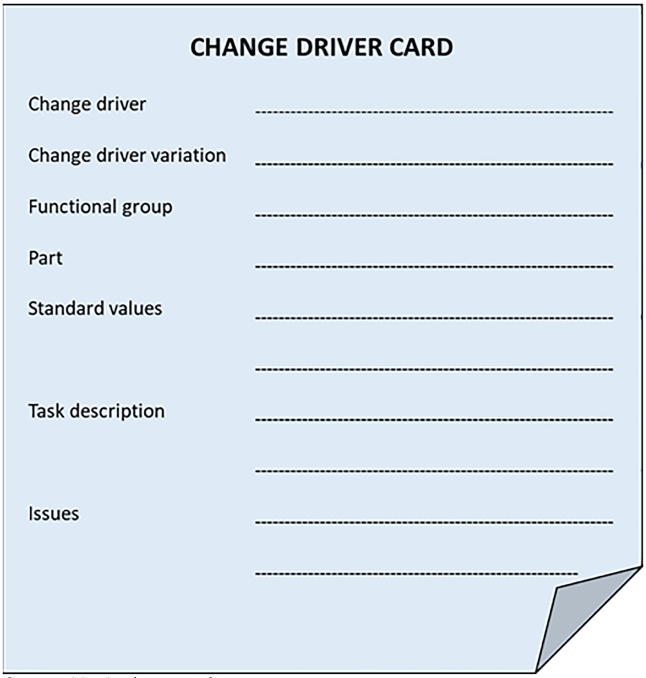
(1) The change drivers that impact the component.

(2) The type of set-up activity required for the subsystem or component, based on the change drivers that influence it. This may include assembly, disassembly, replacement, setting of process parameters, positioning or cleaning activities.

PRODUCT SET-UP REQUESTS SHEET			
Dimensions	**Material**	**Process parameters**	**Weight**
X = ...	Material 1	Pressure	...
Y = ...	Material 2	Temperature	
Z = ...	...	Velocity	
	...		

Source(s): Authors work

Figure 5. Product set-up requests sheet



Source(s): Authors work

Figure 6.
Change driver card to be applied on Barashi-board

(3) Description of the operations carried out by the operator in the current state of the machinery.

The value of the CPN is calculated based on the following factors:

(1) Time (T): the time required to perform the set-up at the current state of the machinery, which can be assessed or obtained from the user.

(2) Frequency (F): the frequency with which the set-up is currently performed or expected to be performed in the future.

(3) Difficulty (D): the difficulty and the level of ergonomics related to the set-up activity.

The numerical evaluation is carried out on a scale ranging from 1 to 10 based on conversion tables. Clearly, all the conversion tables can (and should) be modified and adapted to the actual operating context. The CPN is the product of three factors:

$$\mathrm{CPN} = T \times F \times D \tag{1}$$

The CPN serves as an evaluation index that enables the project team to prioritize improvement actions on the various components of the machinery. Similarly to the Risk Priority Number (RPN) of the FMEA analysis, the set-up activities with the highest CPNs are those that should be addressed first.

A potential drawback of this tool is represented by the length of the table itself, which makes the overall evaluation a bit complicated without the aid of dedicated information support. A correlation matrix can be used to overcome the problem. The rows of this matrix report the various change drivers identified. The columns list the various components or

FUNCTIONAL DECOMPOSITION		SET-UP ACTIVITY DESCRIPTION			CHANGEOVER ANALYSIS						
Functional Area	Component/ Subsystem	Change driver	Type of activity	Description	Current Set-up Time	Time [T]	Occurrence	Frequency [F]	Technical Issues	Difficulty [D]	CPN [T x F x D]
1. Fixture											
2. Machine/ Fixture Interface											
3. Machine body											
4. Tool											
5. Machine/ Tool Interface											
6. Handling systems											
7. Idraulic and electric systems											
8. Fittings											

Source(s): Authors work

Figure 7.
The COM&TA data table

subsystems of the machinery in functional groups. By inserting the associated CPN, calculated using the COM&TA method, into the intersection box between the change driver and the component a useful and readable compendium matrix can be obtained (Figure 8).

This matrix allows the project team to define, improvement priority ranges on the basis of the CPN. The ranges can be customized based on current needs and implementational ones. Additionally, each priority range can be associated with a specific color code to display the level of criticality of each individual set-up activity. In fact, one change driver can affect multiple components of the machine, belonging to different functional groups as well and the same component can be affected by multiple change drivers. This correlation matrix makes it possible to define the strategy for Step 3.

5.3 Step 3

Content. Minimization of the time associated with the set-up phases.

Purpose. To use specific techniques of robust design, so that the machine is set up rapidly.

The aim of Step 3 is to minimize the time required for each set-up activity identified in Step 2, paying particular attention to the costs associated with the solution itself. Clearly, zero set-up times are not possible. However new machines can be designed and existing ones updated on the basis of technical choices that make them easy to set-up. This step begins with the compilation of a Plan-Do-Check-Act (PDCA) improvement sheet, like the one shown in Figure 9.

Up to this point, the various technical interventions have been designed and implemented separately, without considering any interactions, positive or negative, among them. So, a table is needed to highlight any interactions. The first phase in creating this table is to bring together the various improvements and summarize the fundamental information concerning these improvements, such as:

(1) The identification code of the PDCA sheet;

(2) A brief description of the technical improvement;

(3) The design rules (namely, the technical strategies) on which the improvement was based and

(4) The type of organizational-procedural advice that has been proposed in the standardization of the sequence of operations.

The second phase is to highlight any interactions among the various construction solutions using a structure similar to the House of Quality used in the Quality Function Deployment (Berk and Berk, 2000) (Figure 10).

The positive interactions between the different construction solutions create opportunities for exploiting synergies to be exploited and addressing multiple needs simultaneously, resulting in significant cost savings for improvement actions. Conversely the case of negative interactions, it is essential to avoid designing solutions that could potentially damage or hinder each other.

6. Application to an industrial case study

To demonstrate the effectiveness of this methodology we applied it to an industrial case study involving a vertical spindle machine that expands heat exchanger tubes using ogive inserts to create the necessary interference with the fins, thus enabling efficient heat exchange between the primary fluid, which passes inside the pipes and the air to be heated or cooled, which passes outside the pipes (Figure 11).

Change Drivers	Vertical spindle machine													
	Fixture				Fixture/ Machine interface		Tool		Tool/Machine interface		Machine body		Electric/ Hydraulic system	
	Front plates	Rear plates	Lateral stoppers	Receivers	Mobile frame front plates	...	Ogive inserts	Rods	Rod guide plates	Rods stops	Limit switch	...	Hydraulic subsystem	Electric subsystem
Lenght [L]	512	576									120			
Width [A]			432											
Depth [B]			144		640									
True diameter							216							
Insertion scheme				810										
Tubes geometry									210	210				
Feed rate													56	

Low	0 ≤ CPN ≤ 250
Medium	251 ≤ CPN ≤ 500
High	501 ≤ CPN ≤ 750
Extreme	751 ≤ CPN ≤ 1000

Source(s): Authors work

Figure 8.
Change drivers vs components correlation matrix

PDCA IMPROVEMENT SHEET

Machine:	Functional group:		Subsystem:
Change driver:	Start date:	End date:	Performed by:

1. PLAN

DESCRIPTION

Describe all the issues that have been encountered during the set-up task

Add, whenever possible, schemes, drawings, pictures of the subsystem in the original state

POTENTIAL SOLUTIONS

Present the viable technical solutions, inserting schemes and drawings

2. DO

CHOICE

Indicate the technical solution that has been chosen, along with a brief but precise description of the motivation for the choice itself

Insert all available schemes and CAD drawings, indicating as well if there are variations with respect to the PLAN proposal

4. ACT

IMPLEMENTATION AND STANDARDIZATION

Share the final approved drawing representing the technical solution and the sequence of the operations involved in the set-up procedure

Indicate the appraised set-up times and the eventual additional information that are necessary/useful for the set-up

3. CHECK

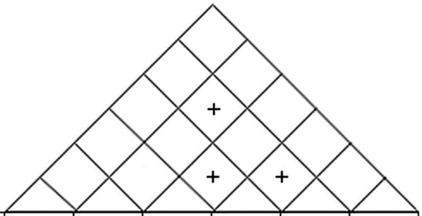
TEST AND VALIDATION

Test and validate the selected solution, with particular attention to the safety aspects of the set-up activities

Evaluate the costs of the proposed solutions, pinpointing the differencies with the original solutions, and execute a costs vs benefits analysis

Source(s): Authors work

Figure 9.
PDCA improvement sheet



	PDCA Sheet number	Technical improvement description	Technical strategies (design rules): Semplification	Standardization	Quick fixing	Optimization	Esternalization	Mechanization	Organizational-procedural advice: Organization	Standardization	Esternalization	Optimization
Fixture	PDCA-F1.1	Elimination of grooves on the side supports of the front plates	X		X							
Fixture	PDCA-F2.1	Inserting a graduated scale on the opposite side. Use of previously lightened square plates	X			X						
Fixture	PDCA-F3.1	Holes on the front plates to fix the side stoppers better and faster	X		X							
Fixture	PDCA-F4.1	Design of a new plate with a movable central part and a spring and cam rapid locking system			X				X			
M/F interface	PDCA-FMI 1.1	Rock and pinion system and dovetail guide for positioning the mobile frame						X				
...	...	...										

Source(s): Authors work

Figure 10. Improvements interaction analysis

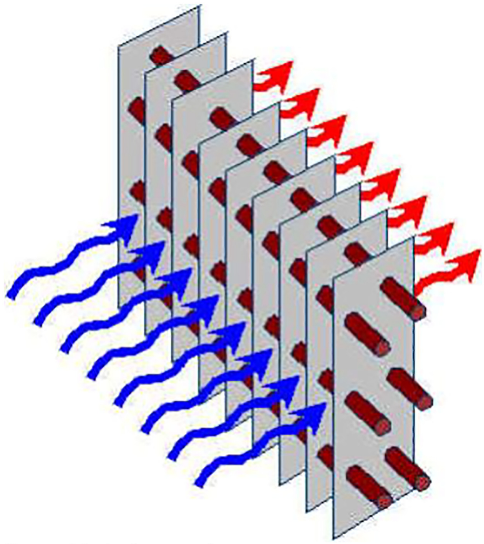


Figure 11. Finned pack heat exchanger

Source(s): Authors work

After collecting some information regarding the structure of the machinery and the product it processes, we analyzed how it performs on the exchanger tubes and the identified a list of change drivers (Step 1). To account for potential market demands and since we could not interact directly with the end customer, we included variations derived from surveys on catalogs and documents of companies producing finned pack heat exchangers. We then compiled the information gathered into some change drivers analysis sheets (Figure 12).

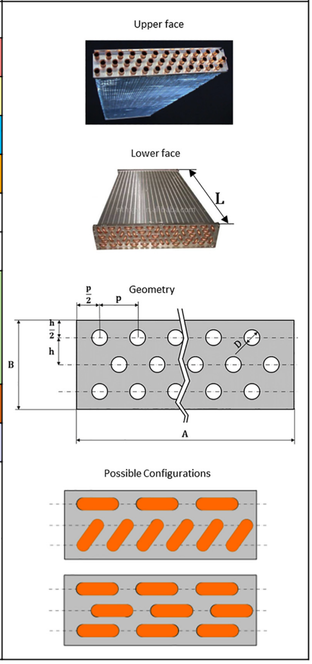
The analysis revealed that the size of the exchangers and the potential configurations of the tube bundle schemes had the greatest variability and, therefore, the most significant impact on the changes necessary to accelerate the set-up. We recorded all the variability ranges (Step 2) and used color codes to visually link the change driver cards, which were thin pinned on the Barashi-board (Figure 13).

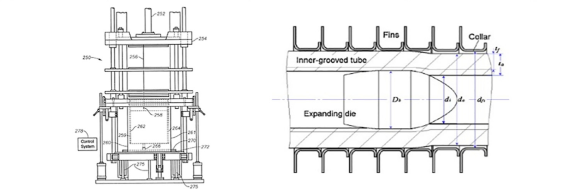
Most of the cards refer to areas of the machine on the product insertion side. The locking equipment (fixtures) and its interface with the machine assembly (fixed frame) appear to be the most critical from a set-up perspective. To have an objective prioritization of the interventions to be carried out, the COM&TA data table was compiled (Figure 14) and, after calculating the corresponding values of the CPN, the synthesis was carried out by filling in the change drivers vs components correlation matrix (Figure 15).

The CPN index is numerically presented on a scale of 1–10 on the basis of the conversion tables. Table 4 is built on the basis of the numerical value of the current execution time, the linguistic judgment on the frequency of occurrence of the set-up and the description of problems and difficulties in execution.

To complete Step 3 and to facilitate and justify the choice of the technical solution, the most critical CPN values were used to create a PDCA improvement sheet for each technical improvement (Figure 16). Finally, an excerpt of the improvements interaction analysis was carried out and the results were recorded (Figure 17).

CHANGE DRIVERS ANALYSIS SHEET				
Machine: Vertical spindle machine		**Process:** Heat exchanger tubes expansion		
Product: Finned pack heat exchanger				
Category	**Change drivers list**	**Variations**	**Notes**	**Color**
Product variability	Lenght-L [mm]	Min 500-Max 2500		
	Width-A [mm]	Min 100-Max 1400	Depends on Nt and p	
	Depth-B [mm]	Min 25-Max 200	Depends on Nt and p	
	Tube Diameter-D [mm]	7-7.94-9.52		
	Number of ranks-Nr	1 to 8	Strong impact on B	
	Tubes per rank-Nt	Max 55	Strong impact on A	
	Tubes geometry [h x p]	Offset Equilateral: 25 x 21.65 Non-Equilateral: 25 x 19, 25 x 12.5, 21 x 12.5 Online: 25 x 25		
	Insertion scheme	No predefined schemes Extremely variable		
Process variability (Technical needs)	Feed rate [m/min]	Min 0.7-Max 4.0		





Source(s): Authors work

Figure 12. Change drivers analysis applied to the vertical spindle machine

7. Discussion and outlook

The industrial application of the QCD methodology highlighted that significant reductions in set-up times can be achieved by addressing the problem in the design phase. This corroborates previous experiments showing that technical improvements lead to shorter set-up times. QCD reduced changeover times from 51.2 to 13.4 min, an overall reduction of about 74%. The most significant improvement was achieved through the reduction in the plate and support disassembly time (21% of total time saved) resulting from the implementation of a quick locking system and alignment pins that allow the plates to be quickly positioned and locked.

When compared to the changeover improvement cases presented in Section 2, the application of QCD ranked high. It exceeded the threshold value of 50% achieved by organizational improvements and surpassed the 70% upper limit for most technical solutions, mainly due to the high implementation costs. Notably, the improvements implemented would have required a greater economic effort if applied to an existing machine. The QCD methodology proved to be a valuable approach to tackling the changeover challenge, which is one of the main contributors to the machine's poor performance.

The implementation of this methodology offers significant advantages when applied to a production system consisting of several machines subject to frequent or lengthy set-up processes. Rapid and quality changeover greatly increases competitiveness, enabling

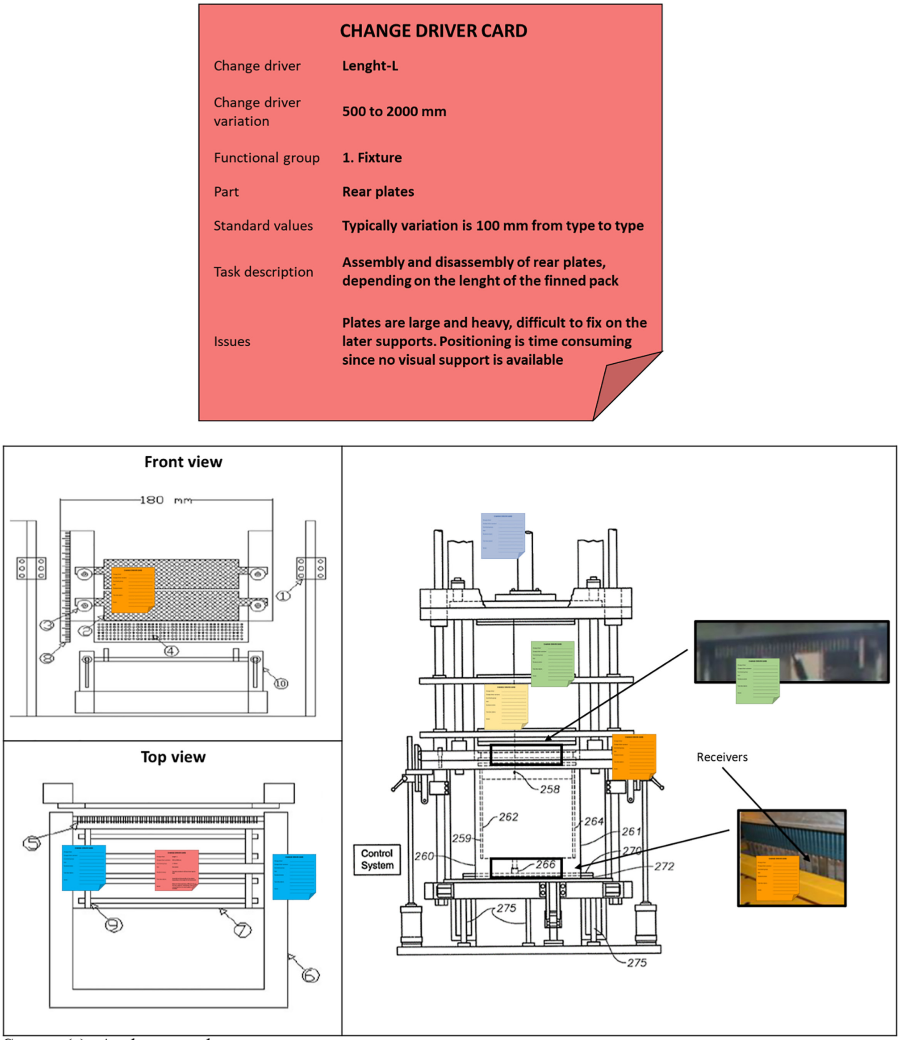


Figure 13.
Example of compiled change driver card and of the Barashi-board

Source(s): Authors work

responsiveness to external market demands and internal control of factory operations. Acting in the design phase leads to significant savings in both time and cost as well as improved ergonomics.

We are aware that may have some limitations. The most significant limitation of our QCD is the integration with the current way of designing, which is mainly oriented towards assembly and production, rather than quick-changeover capability. However, as more and more companies struggle with poor manufacturing performance, QCD can be applied progressively and thus better integrated with other design perspectives.

FUNCTIONAL DECOMPOSITION		SET-UP ACTIVITY DESCRIPTION			CHANGEOVER ANALYSIS							IMPROVEMENTS		
												PDCA Sheet Number	Outcomes	
Functional Area	Component/ Subsystem	Change driver	Type of activity	Description	Current Set-up Time [min]	Time [T]	Occurrence	Frequency [F]	Technical Issues	Difficulty [D]	CPN [T x F x D]		Final Set-up Time [min]	Time Gain [min]
1. Fixture	1. Front plates and lateral supports	1.1. Pack lenght	Disassembly Assembly	Operators must disassemble and mount the necessary plates on the moving frame and lock them by bolts on the side supports with grooves	10.5	8	Once per day	8	Heavy plates with slow bolt locking. Very complicated alignment	8	512	PDCA-F1.1	3.0	7.5
	2. Rear plates and supports	2.1. Pack lenght	Disassembly Assembly	Black plates are transported and arranged on the frame supports by two operators. Positioning, alignment and fixing are carried out in an approximate manner by means of a single graduated scale on one side of the machinery	11.2	8	Once per day	8	Heavy plates with slow bolt locking. Very complicated alignment. Many errors	9	576	PDCA-F2.1	3.0	8.2
	3. Lateral stoppers	3.1. Pack width	Positioning	Operators must place the stoppers by sliding them along the grooves on the plates. Tightening takes place at correct positioning. The operation impacts on that relating to the front plates	7.0	6	Once per day	9	Not easy adjustment, with alignment errors	8	432	PDCA-F3.1	3.0	6.0
		3.2. Pack depth	Disassembly Assembly	Thicknesses are modular and determine the positioning of the stoppers	2.0	3	Once per day	8	Not easy adjustment, with alignment errors	6	144			
	4. Receivers and receiver plate	4.1. Insertion scheme	Disassembly Assembly Positioning	Receivers must be disassembled and mounted each time according to the fork insertion scheme	9.5	9	Once per set-up	10	Insertion of the forks performed with hammer. Receivers and plates wear out quickly	9	810	PDCA-F4.1	3.0	6.5
2. Machine/ Fixture interface	1. Mobile frame	1.1. Pack depth	Disassembly Assembly Positioning	Frame is disconnected from the tipping system when it is an upright position and is manually translated according to the thickness of the pack. 6 bolts are used for fastening	11.0	8	Once per day	8	Dangerous manual positioning, with risk of overturning. Very long fastening with bolts	10	640	PDCA-FMI 1.1	2.45	5.55
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Source(s): Authors work

Figure 14. Excerpt of the COM&TA data table for the industrial case under consideration

Change Drivers	Fixture: Front plates	Fixture: Rear plates	Fixture: Lateral stoppers	Fixture: Receivers	Fixture/Machine interface: Mobile frame front plates	Fixture/Machine interface: ...	Tool: Ogive inserts	Tool: Rods	Tool/Machine interface: Rod guide plates	Tool/Machine interface: Rods stops	Machine body: Limit switch	Machine body: ...	Electric/Hydraulic system: Hydraulic subsystem	Electric/Hydraulic system: Electric subsystem
Lenght [L]	512	576									120			
Width [A]			432											
Depth [B]			144		640									
True diameter							216							
Insertion scheme				810										
Tubes geometry									210	210				
Feed rate													56	

Vertical spindle machine

Low	0 ≤ CPN ≤ 250	Medium	251 ≤ CPN ≤ 500	High	501 ≤ CPN ≤ 750	Extreme	751 ≤ CPN ≤ 1000

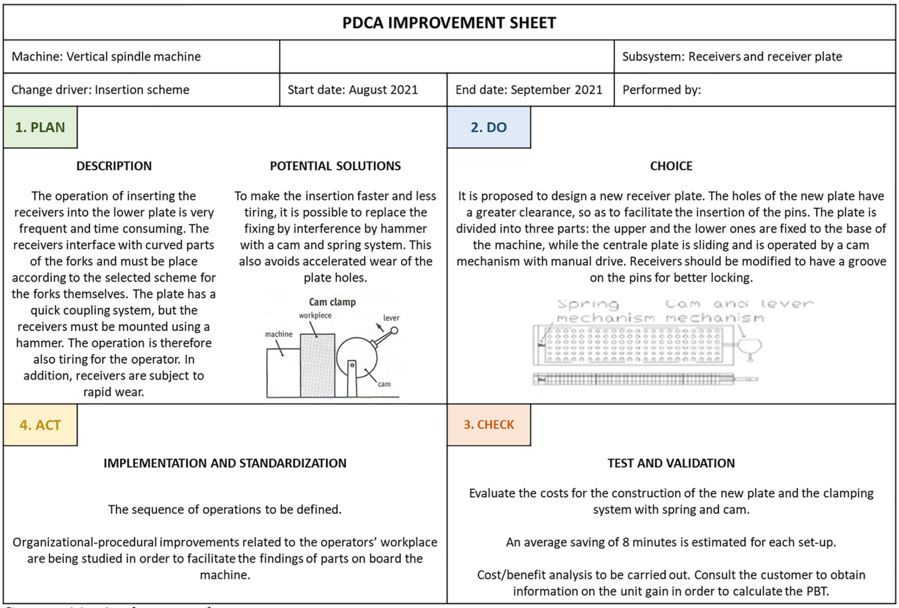
Source(s): Authors work

Figure 15.
Change drivers vs components correlation matrix for the studied case

CPN factor	Qualitative evaluation	Linguistic evaluation	Value
Time (T)	Very high	More than 20 min	9–10
	High	Up to 20 min	7–8
	Medium	Up to 10 min	5–6
	Low	Up to 5 min	2–4
	Very low	Less than one minute	1
Frequency (F)	Very high	Up to once per single shift	9–10
	High	Up to once per day	7–8
	Medium	More than once per week, but less than once per day	5–6
	Low	Up to once per week	2–4
	Very low	Once per month	1
Difficulty (D)	Very high	Unacceptable ergonomic conditions of execution (i.e. heavy parts, unsafe postures) and/or complicated operations that require the help of experienced technicians to be completed	9–10
	High	Uncomfortable ergonomic working conditions and complicated operations that require, for example, special training to be carried out correctly	7–8
	Medium	Acceptable ergonomic conditions and not particularly complex operations that require a certain test period in order to be carried out correctly	5–6
	Low	Good ergonomic conditions, easy operations to be performed with the help of tools	2–4
	Very low	Optimal ergonomic conditions and very easy operations	1

Source(s): Authors' work

Table 4. Time (T), frequency (F) and difficulty (D) evaluation table


PDCA IMPROVEMENT SHEET

Machine: Vertical spindle machine			Subsystem: Receivers and receiver plate
Change driver: Insertion scheme	Start date: August 2021	End date: September 2021	Performed by:

1. PLAN

DESCRIPTION

The operation of inserting the receivers into the lower plate is very frequent and time consuming. The receivers interface with curved parts of the forks and must be place according to the selected scheme for the forks themselves. The plate has a quick coupling system, but the receivers must be mounted using a hammer. The operation is therefore also tiring for the operator. In addition, receivers are subject to rapid wear.

POTENTIAL SOLUTIONS

To make the insertion faster and less tiring, it is possible to replace the fixing by interference by hammer with a cam and spring system. This also avoids accelerated wear of the plate holes.

2. DO

CHOICE

It is proposed to design a new receiver plate. The holes of the new plate have a greater clearance, so as to facilitate the insertion of the pins. The plate is divided into three parts: the upper and the lower ones are fixed to the base of the machine, while the centrale plate is sliding and is operated by a cam mechanism with manual drive. Receivers should be modified to have a groove on the pins for better locking.

4. ACT

IMPLEMENTATION AND STANDARDIZATION

The sequence of operations to be defined.

Organizational-procedural improvements related to the operators' workplace are being studied in order to facilitate the findings of parts on board the machine.

3. CHECK

TEST AND VALIDATION

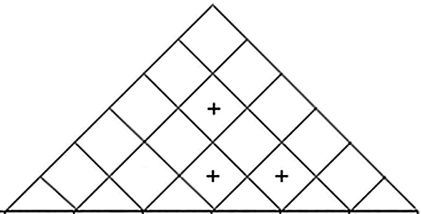
Evaluate the costs for the construction of the new plate and the clamping system with spring and cam.

An average saving of 8 minutes is estimated for each set-up.

Cost/benefit analysis to be carried out. Consult the customer to obtain information on the unit gain in order to calculate the PBT.

Source(s): Authors work

Figure 16. PDCA improvement sheet (PDCA F4.1) for the receiver plates' fixture



	PDCA Sheet number	Technical Improvement description	Technical strategies (design rules): Semplification	Standardization	Quick fixing	Optimization	Esternalization	Mechanization	Organizational-procedural strategies: Organization	Standardization	Esternalization	Optimization
Fixture	PDCA-F1.1	Elimination of grooves on the side supports of the front plates	X		X							
	PDCA-F2.1	Inserting a graduated scale on the opposite side. Use of previously lightened square plates	X			X						
	PDCA-F3.1	Holes on the front plates to fix the side stoppers better and faster	X		X							
	PDCA-F4.1	Design of a new plate with a movable central part and a spring and cam rapid locking system			X				X			
M/F interface	PDCA-FMI 1.1	Rock and pinion system and dovetail guide for positioning the mobile frame						X				
…	…	…										

Source(s): Authors work

Figure 17.
Excerpt of the improvements interaction analysis

8. Conclusions and future works

This paper proposes a methodological approach called QCD, to reduce the set-up times both newly designed machines and existing ones There is a preliminary step in which the type of machinery, its function, the product it processes and its characteristics are defined. Then Step 1 analyses how to design a successful machine/equipment that ensures low product change times and ease of execution of set-up operations. Step 2 focuses on technical interventions at the project level to incorporate the customers' requests and speed up and facilitate individual set-up operations. Finally, in Step 3 the designer must think about the best construction solutions that will minimize the time of a specific set-up activity. Finally, in Step 3 the designer must think about the best construction solutions that will minimize the time of a specific set-up activity.

Within each step, specific analysis tools are proposed in order to facilitate and better structure the designer's activities during the QCD project. Finally, the methodology was applied to in industrial case study of a vertical spindle machine.

The results obtained demonstrate that the QCD can support equipment manufacturers in capturing the current and future needs of their customers, in order to: (1) anticipate the requirements for new and different set-up process, (2) prioritize possible technical solutions (possibly considering at an early stage any beneficial or adverse interactions); and (3) to build machines and equipment that are easy and fast to set-up under variable contexts. By implementing the technical improvements outlined by the methodology, changeover time dropped from 51.2 to 13.4 min, an overall reduction of about 74%.

A future development would be to draft a set-up manual that includes all the information regarding the procedures, the standards, the timing for the execution of the various activities that make up the entire set-up cycle and, finally, any necessary tools and recommendations for better organizing the workstation. This would also be a valuable way of recording all the lessons learned for all subsequent activities. Such a manual would promote the training of new engineers, technicians and practitioners.

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