

Integrating environmental sustainability into set-up efficiency: Eco-Efficient Quick Changeover

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Abstract

In an era of increasing environmental and competitive pressures, manufacturing firms are continually challenged to improve production efficiency while minimizing ecological impacts. This paper introduces a novel Lean methodology named Eco-Efficient Quick Changeover (EQC). It emerges as a strategic response to these dual imperatives, integrating the rapid set-up principles of Lean Manufacturing with comprehensive sustainability considerations. EQC employs a systematic four-phase approach that begins with assembling a multidisciplinary team, followed by quantifying both time and environmental losses through an innovative Losses Matrix, examining the interdependencies of these losses via a Cause and Effect Matrix, and ultimately prioritizing corrective actions through Ranking Matrix with a novel Green Set-up Index. A case study conducted in a plastic water bottle production facility revealed that this integrated strategy can reduce changeover time by 72%, lower energy consumption by 62%, and achieve substantial reductions in water usage, CO₂-equivalent emissions, and waste generation. These results underscore the potential of EQC to deliver significant operational improvements while advancing environmental performance, thereby offering a holistic framework that aligns with current sustainable development objectives.

Keywords

Set-up; SMED; Lean Manufacturing; Green Manufacturing; Environmental sustainability; Operational efficiency

Abbreviations	Meaning
AHP	Analytical Hierarchy Process
EIC	Environmental Impact Category
EQC	Eco-Efficient Quick Changeover
GHG	Greenhouse Gas
GLSS	Green-Lean Six Sigma
MCD	Manufacturing Cost Deployment
SDG	Sustainable Development Goal
SMED	Single Minute Exchange of Die
SSD	Set-up Saving Deployment
VSM	Value Stream Mapping
Symbols	Meaning
DEI [-]	Direct Environmental Impact
DST [s]	Direct Saving Time
EI [-]	Environmental Impact
ESUE [-]	Environmental impact Set-up Efficiency

GSI [s]	Green Set-up Index
IEI [-]	Indirect Environmental Impact
IST [s]	Indirect Saving Time
T [s]	Time saving
TEI [-]	Total Environmental Impact
TST [s]	Total Saving Time
TSUE [-]	Time Set-up Efficiency
ΔEI [-]	Environmental Impact difference
Δt [s]	Time difference
w [-]	Relative weight of the environmental impact

Table 1. Nomenclature of variables.

1. Introduction

In today's highly competitive global market, the success of manufacturing businesses hinges on their ability to create a leaner, more flexible, and highly responsive production environment. A crucial factor in achieving this agility is the ability to swiftly transition between different products. Shorter changeover times not only reduce batch size, they also help to lower inventory level, increase flexibility of the production system and improve responsiveness to the customer [1]. However, changeover processes remain one of the most time-intensive, non-value-adding activities in many manufacturing settings [2].

Among the various Lean Manufacturing tools, Single-Minute Exchange of Die (SMED) is a pivotal method for enhancing production flexibility [3]. As part of the Lean toolkit, SMED focuses on minimizing non-value-added activities in manufacturing by streamlining the changeover process. This methodology enables rapid changeovers, typically completed within nine minutes or less (single-digit minutes), and can be carried out directly by machine operators and set-up personnel [4]. By reducing set-up times, SMED facilitates smaller production lot sizes, making even one-piece flow feasible, thereby enhancing material flow and production efficiency. Studies have shown that implementing SMED and quick changeover strategies can lead to productivity improvements of up to 70%, making it a critical tool for optimizing manufacturing performance [5].

As environmental concerns continue to grow, there is increasing recognition that environmental and operational performance should be addressed as a bi-objective optimization problem rather than as separate, opposing goals [6]. From this perspective, lean manufacturing tools and methods offer a powerful means to enhance production performance while simultaneously reducing environmental impact [7]. However, traditional Lean tools, while optimizing time-based efficiencies, often overlook the environmental impact of these processes. Several studies have highlighted this limitation, emphasizing that Lean methodologies, including SMED, focus primarily on operational efficiency and often fail to account for resource consumption, emissions, and waste generation [8, 9]. Research

also suggests that Lean practices, when implemented without sustainability considerations, may unintentionally lead to increased environmental burdens, such as higher energy consumption during rapid changeovers and increased material waste [10, 11].

The Eco-Efficient Quick Changeover (EQC) methodology emerges as an innovative and operationally grounded solution to address this gap. Designed to be directly applicable in real industrial contexts, EQC combines the time-reduction logic of Set-up Saving Deployment (SSD) [12] with sustainability-focused objectives, aiming to optimize both operational efficiency and environmental performance during changeover activities. This approach not only reduces the duration of set-up times but also targets the minimization of resource consumption and environmental pollution, offering a holistic view of process optimization. This methodology follows a structured, four-step process that involves: (i) forming a multidisciplinary analysis team, (ii) quantifying both time and environmental savings, (iii) analyzing the correlation between efficiency and sustainability, and (iv) prioritizing improvement techniques based on an integrated performance metric, the Green Set-up Index (GSI). This makes EQC not only a conceptual advancement, but also a practical tool for structured and sustainable process optimization.

As a novel contribution to literature, the main objectives of this manuscript are:

- To introduce the EQC methodology as an advanced Lean tool that simultaneously reduces set-up times and minimizes environmental impact.
- To develop a structured decision-making framework for identifying and ranking changeover improvement techniques based on both efficiency and sustainability metrics.
- To investigate the challenge of improving a changeover process from both operational and environmental aspects in a real industrial application.

By integrating sustainability into traditional Lean thinking, EQC represents a paradigm shift in process optimization, aligning manufacturing practices with the broader global agenda of green industrial transformation. As environmental regulations become stricter and public awareness of environmental issues grows, methodologies like EQC will likely play a crucial role in helping industries meet both their operational and sustainability objectives. Indeed, EQC supports several United Nations Sustainable Development Goals (SDGs) [13] by promoting sustainable manufacturing practices. It aligns with SDG 6 (Clean Water and Sanitation) by reducing water waste during changeovers and SDG 7 (Affordable and Clean Energy) by optimizing energy use. EQC also contributes to SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production) by enhancing resource efficiency and minimizing waste. Lastly, by

lowering emissions and energy consumption, EQC supports SDG 13 (Climate Action), helping industries reduce their environmental footprint.

2. Literature review

The concept of reducing set-up times in manufacturing has been extensively explored, primarily through the development and application of SMED [14, 15]. SMED is a fundamental Lean Manufacturing tool that emphasizes reducing set-up times to less than ten minutes by separating internal from external set-up tasks and streamlining the process. Numerous studies have demonstrated the benefits of SMED in various manufacturing sectors, significantly improving production flexibility and reducing lead times [16].

However, the conventional Lean approach to changeover optimization has been criticized for its narrow focus on time efficiency, often neglecting the environmental consequences of rapid set-ups, such as energy-intensive machine restarts, increased material waste, and higher carbon emissions [17, 18]. This realization has led to the evolution of Green Lean Manufacturing, an approach that integrates Lean principles with environmental sustainability goals [8]. Green Lean methodologies recognize that while Lean eliminates operational inefficiencies, it does not inherently reduce environmental impact unless explicitly designed to do so. In this context, Lean and Green integration frameworks have emerged, such as the Green Lean Six Sigma (GLSS) methodology, which merges Six Sigma's defect-reduction approach with Lean waste elimination while embedding sustainability considerations [19]. GLSS has demonstrated success in various industries by achieving simultaneous cost savings, improved quality, and reductions in energy and resource consumption. Similarly, Pampanelli et al. [10] developed a structured Lean and Green approach that systematically identifies waste in the value stream with environmental impact considerations. Their research underscores the need for dedicated sustainability metrics to enhance the effectiveness of traditional Lean tools. Recognizing the growing importance of environmentally friendly products, Mourtzis et al [20] proposed a methodology for extracting lean rules to support the delivery of sustainable Product-Service System offerings, which they validated through a case study on power waste reduction. This Lean Green approach has been further enhanced through the integration of circular economy principles, demonstrating that the implementation of green solutions can optimize the production operations of manufacturing enterprises [21]. For instance, other relevant contributions integrating Lean and Green manufacturing are presented by [22, 23]. Serafim Silva et al. proposed a novel approach to efficiently integrate Value Stream Mapping (VSM) with sustainability considerations, based on the Five Sector Sustainability Model, resulting in the development of the VSM for Sustainability (VSM4S). Braglia et al., on the other hand, combined the Manufacturing Cost

Deployment method (MCD) [24] with the environmental dimension of sustainability to specifically address greenhouse gas (GHG) emissions reduction in manufacturing plants.

Although the literature on the intersection of SMED and environmental sustainability is still emerging, recent studies have begun to explore ways to incorporate green metrics into changeover optimization. For instance, Leme et al. [9] propose a lean-green model based on the utilization of SMED in combination with carbon footprint to analyze the eco-efficiency of a machining center to reduce wastes such as idle time, resource consumption and environmental impacts due to GHG emissions. Ebrahimi et al. [25] propose an approach entitled sustainable set-up stream mapping (3SM), based on VSM and SMED approach. They provide a multi-level analysis of set-up operations and assess the impacts of SMED on energy consumption, inventory waste/consumption, operator waste/consumption, skilled operator, teamwork, set-up operational costs and set-up wasted costs. Queiroz et al. [26] investigated the application of Lean and Green in the automotive industry, showing that Lean interventions like SMED can be enhanced with environmental considerations. Their research demonstrated that reducing set-up times not only improves productivity but can also lead to reductions in energy consumption and waste generation, provided that environmental metrics are incorporated into the SMED analysis. Similarly, Verrier et al. [11] argue that aligning Lean practices with environmental goals can result in a synergistic effect that maximizes both operational and environmental performance. Finally, Khakpour et al. [27] developed a method entitled “SMED 4.0” as a development of conventional SMED to avoid defect occurrence during production and improve sustainability, besides reducing set-up time.

The literature reveals that, while several studies propose tools and methodologies to enhance SMED implementation, few have addressed the critical need to integrate sustainability considerations into changeover optimization. Despite the well-documented benefits of SMED in improving operational efficiency, there remains a significant gap in the development of comprehensive operational frameworks that simultaneously tackle both time and environmental performance. This lack of structured approaches highlights the urgency of methodologies that not only streamline changeovers but also minimize resource consumption and ecological impact, ensuring a truly sustainable and efficient manufacturing process.

This gap underscores the need for innovative methodologies, such as the EQC, which enables practitioners to identify inefficient set-up conditions while simultaneously addressing both time and environmental performance. By incorporating sustainability metrics into set-up activities, EQC provides a structured strategy for optimizing changeovers, reducing resource consumption, and minimizing environmental impact, ensuring a more holistic and eco-efficient manufacturing process.

The introduction of EQC into the Lean toolbox marks a significant evolution in process optimization strategies, aligning with the broader trend towards sustainable manufacturing.

3. Methodology

This section outlines the distinctive framework, design, and practical implementation of the EQC methodology, highlighting its innovative contribution to enhancing both operational efficiency and environmental sustainability. The first subsection briefly summarises the main aspects of SSD while the second subsection details the organizational structure and functioning of EQC.

3.1. Set-up Saving Deployment

In this paragraph a concise overview of SSD is presented to establish the foundational concepts upon which the EQC tool is developed by Braglia et al. [12].

The SSD is a Lean tool that efficiently integrates the SMED and the MCD. It aims to identify losses occurring during a set-up process to pinpoint areas where the implementation of SMED can lead to significant time savings. Like MCD, SSD employs a systematic step-by-step approach based on matrix compilation.

In the first step, the Losses Matrix (L-Matrix) is constructed to identify various types of losses occurring during a changeover process. These losses are categorized into three main groups including deviations from standard set-up procedures or the absence of defined procedures, such as lack of advanced preparation of personnel or missing functional checks of equipment; Design Losses, resulting from suboptimal machine or set-up process design, such as lack of preparation of operating conditions, absence of equipment duplication, or missing reference systems; and Internal Activity Losses, caused by inefficient design of internal activities, such as the non-use of standard parts or the absence of functional fast clamping systems. The sum of all these losses quantifies the gap between the *actual* set-up time and the *ideal* set-up time that could be achieved if all losses were eliminated. The L-Matrix organizes losses along the rows and set-up phases along the columns.

The second step involves correlating the identified losses to explore potential time-saving relationships among them (T). Subsequently, the “*as is*” set-up efficiency, which is defined as the ratio between Ideal set-up time and Actual set-up time, is evaluated using tailored Lean indicators. Ignoring this interdependency may prevent the analysis team from properly assessing the set-up efficiency and thus selecting the right SMED project to implement first. This allows the analysis team to pinpoint changeover processes with poor performance, requiring immediate attention.

The final step entails prioritizing improvement techniques to reduce set-up time. This is achieved by assessing corrective actions based on ease of implementation, associated costs, and efficacy (ECE-

Matrix). Once improvements are selected, the team can calculate the expected changeover time performance (i.e., “*to be*” set-up efficiency).

3.2. Eco-Efficient Quick Changeover

The EQC stands out as a novel Lean methodology specifically conceived to address two critical objectives: minimizing the environmental footprint of changeover processes while concurrently streamlining set-up times through the implementation of SMED principles.

EQC follows a clear, phased progression and begins with an initial assessment of the current state, followed by the selection of appropriate countermeasures, and concludes with a reassessment to evaluate their impact. This methodology unfolds in four sequential steps (Fig. 1):

- Step 1. It involves assembling the analysis team. This team should be multidisciplinary, including members from various fields to ensure a thorough implementation of the tool and a comprehensive understanding of its impact.
- Step 2. It involves determination and quantification of time and environmental impact savings. This pivotal step entails the construction of the Losses Matrix (L-Matrix), laying the foundation for subsequent analysis.
- Step 3. It investigates the relationship between time and environmental impact savings through the compilation of the Cause and Effect Matrix (CE-Matrix). This relationship enables an insightful evaluation of the current state (i.e. “*as is*” set-up efficiency), leveraging purpose-built efficiency metrics.
- Step 4. It focuses on the identification and prioritization of improvement techniques, quantified through the Green Set-up Index (GSI). This final step encompasses the building of the Ranking Matrix (R-Matrix) to prioritize enhancement initiatives and the evaluation of the “*to be*” set-up efficiency.

Through this structured approach, the EQC empowers organizations to navigate the tough intersection between operational efficiency and environmental performance, paving the way towards sustainable manufacturing practices.

The following sections analyze in-depth each step to provide a clear understanding of the operating logic of the tool.

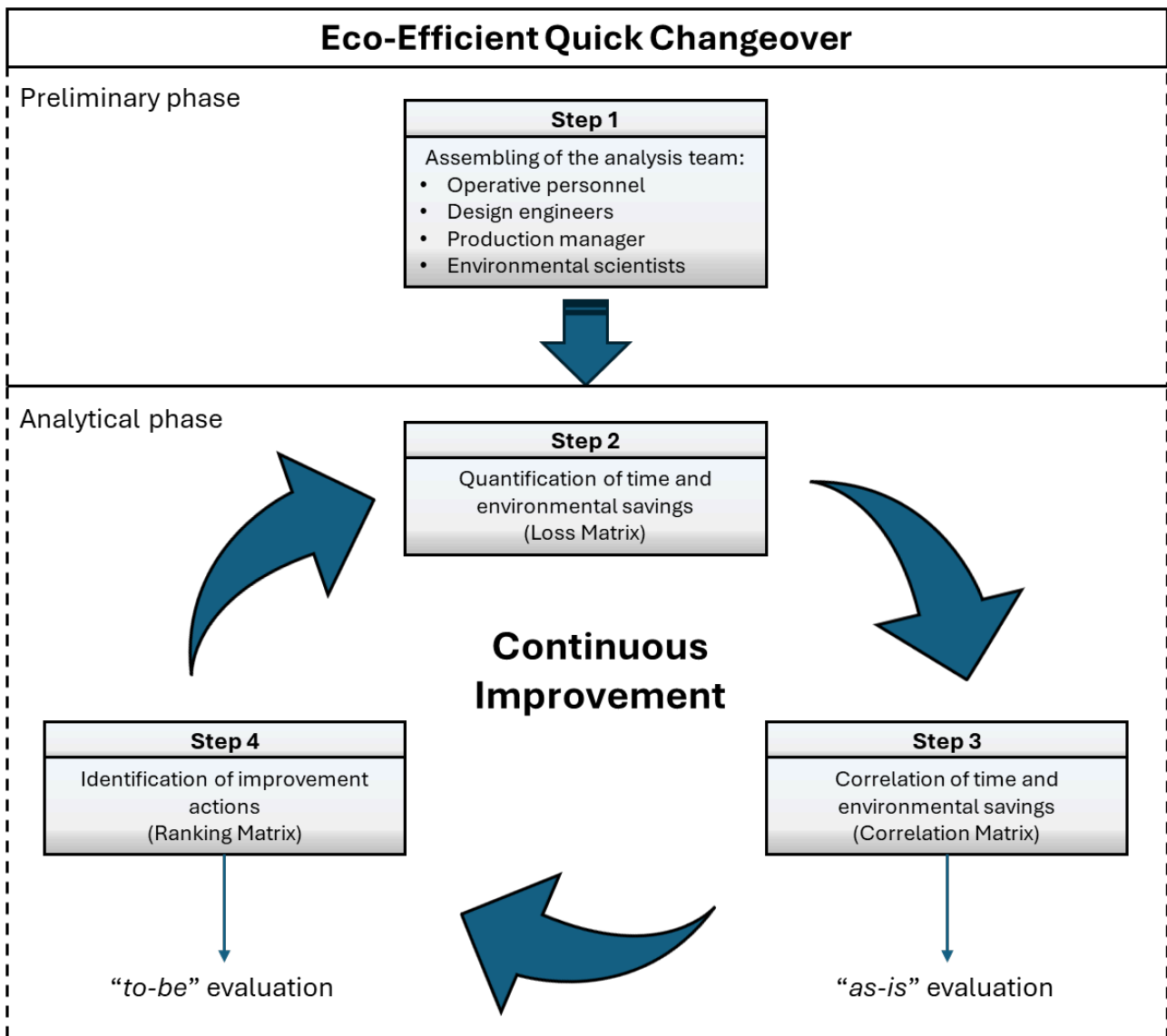


Fig. 1 Step-by-step procedure.

3.2.1. Step 1

The first step of the tool involves assembling the analysis team. This team should include individuals with diverse backgrounds, whose expertise ranges from environmental science to operational knowledge of the changeover process. This diversity ensures a comprehensive understanding of the various aspects involved in such a wide-ranging analysis. The team should ideally consist of:

- Environmental scientists: to provide expertise in environmental impact assessment and sustainability assessment.
- Design engineers: to offer technical insights into the design of the machine, extending beyond just the changeover process.
- Production manager: to contribute practical knowledge about the current process and operational constraints.

- Operative personnel: to offer technical insights into the changeover process and identify potential areas for improvement.
- Other relevant stakeholders: to represent the interests of various departments and ensure that the changes align with organizational standards, regulation and goals.

By including diverse perspectives, the team can better understand the various dimensions of the changeover process and the potential environmental and operational impacts of proposed improvements.

3.2.2. Step 2

The initial phase of the analysis begins with the careful pre-selection of machine tools or production lines earmarked for analysis. The analyst team must consider all the aspects that affect the identification of which production units are suitable candidates for implementing a SMED project, such as the number of set-ups performed on the single production units and the criticality in terms of relevance within the production system of the units themselves (bottlenecks, special order realization, brand production, etc.). Ultimately, it is also important to integrate sustainability into the pre-selection to not only reduce downtime and resource usage, but also to enhance operational efficiency while aligning with eco-friendly practices.

Following this selection process, the construction of the L-Matrix ensues each designated unit. Losses are mapped along the rows, while set-up phases are delineated along the columns (Fig. 2). Cells within the matrix indicate the presence of a loss during a particular phase, with each cell containing two distinct values. The time value signifies the anticipated time savings achievable through removing the associated loss, whereas the environmental impact value denotes the cumulative environmental burden saving attributed to removing said loss.

		Set-up phases									
Loss category	Loss type	Preparation (P)		Extraction (E)		Mounting (M)		Control (C)		First Run	
		Time	Environmental Impact	Time	Environmental Impact	Time	Environmental Impact	Time	Environmental Impact	Time	Environmental Impact
Process Losses	Loss l										
	Loss l+1										
	...										
	Loss L										
Design Losses	Loss m										
	Loss m+1										
	...										
	Loss M										
Internal Activity Losses	Loss n										
	Loss n+1										
	...										
	Loss N										

Fig. 2 The L-Matrix.

To evaluate the total environmental impact saving of the loss i in the set-up phase s ($EI_{i,s}$), we propose the following formula:

$$EI_{i,s} = \sum_{j=1}^N w_j \times EIC_j \quad (1)$$

Where w_j is the relative weight of the normalized environmental impact category EIC_j . Normalization is necessary because the environmental impact categories vary in nature and units of measurement, making it impossible for the analysis team to directly sum them. By normalizing the values, it becomes feasible to compare and combine these diverse categories in a meaningful way. Normalization is achieved by calculating the ratio of the value of a specific environmental category to the overall value of that category for the entire set-up process. This provides a standardized measure that reflects the relative contribution of each category to the overall environmental impact. For example, the environmental impact of power consumption can be normalized by dividing the power consumption savings from a given improvement by the total power consumption recorded for the entire set-up process. This ensures that the analysis is both consistent and comparable across all impact categories, enabling the team to make informed decisions based on a unified scale.

The selection of the relevant environmental impact categories is dependent on the case at hand. In a broad context, reference can be made to the categories outlined in the standards of Life Cycle Assessment ISO 14040 [28] and ISO 14044 [29]. A valid option is the adoption of the eight Green “Muda” (a Japanese term meaning “waste”, referring to any activity or process that consumes resources without adding value from the customer’s perspective) proposed by Verrier et al. [11] including: GHG, Eutrophication, Excessive resource usage, Excessive power usage, Excessive water usage, Pollution, Rubbish, Poor health and safety. This choice is well justified for several reasons. To begin with, the 8 Green “Muda” aligns well with established environmental impact categories used in LCA and other environmental management frameworks. Each of these “Muda” can be directly linked to specific environmental impacts such as resource depletion, pollution, and ecosystem damage. Moreover, the focus of Lean Manufacturing on eliminating waste naturally extends to environmental waste, making the adoption of the 8 Green “Muda” a logical extension for organizations already practicing Lean. Additionally, each category of the 8 Green “Muda” is quantifiable, making it easier to measure and manage environmental impacts. This is a significant advantage in scientific and industrial settings where data-driven decisions are critical. Notably, Poor health and safety is not strictly related to the environment and hence could be easily neglected. A company seeking to introduce the methodology can choose its environmental impact category bearing

in mind that for a true comprehensive analysis of the environmental burden none of the aspects should be overlooked.

To establish the relative weight for each category, various methods can be employed. One of the most widely adopted techniques is the Analytical Hierarchy Process (AHP) [30]. Its attractiveness lies in its straightforward application compared to other Multi-Criteria Decision Methods [31]. The pairwise comparisons essential for the method can be conveniently conducted through numerous free software options available for computing the weights. Each member of the analysis team is assigned the task of conducting pairwise comparisons, comparing each criterion against every other criterion, and assigning relative weights accordingly. Once each team member completes their pairwise comparisons, the average value for each weight is determined and adopted as the final weight for that criterion. This meticulous evaluation process provides a granular understanding of the potential gains in both efficiency and environmental sustainability across the changeover activity.

While time savings are invariably seen as positive due to the inherent nature of SMED projects, environmental impact savings might sometimes yield negative values. For example, identifying the absence of a duplication strategy implementation may clearly improve efficiency from a time perspective. However, when considering a life cycle perspective, it could exacerbate the environmental burden of the changeover activity. Understanding this dynamic underscore the necessity for a thorough analysis of this trade-off that will be addressed in Section 3.2.3.

3.2.3. Step 3

The next step envisages the clarification of the relationship between the savings. It is particularly important to understand the relationship between different savings because it enables the team to perform the efficiency evaluation more accurately thus leading to identifying the most promising changeover improvements. This analysis is carried out by compiling the CE-Matrix (Fig. 3). This matrix reports direct losses with the set-up phase where they occur in the row while indirect losses are located on the columns. A loss is categorized as direct if its removal through a corrective action enables the saving of time associated with that specific loss as well as other related losses. These related losses, which are dependent on the removal of the direct loss for their mitigation, are named indirect losses

For each direct loss, four distinct contributions are evaluated: two time-related contributions are directly obtained from the SSD, while the remaining two, associated with environmental impact, are derived using the same underlying logic. Considering a generic direct loss d_h in the set-up phase s , the CE-Matrix reports:

- Direct Saving Time ($DST_{d_h,s}$): time saving directly achievable by removing the direct loss d_h occurring in the set-up phase s .
- Indirect Saving Time ($IST_{d_h,s}$): sum of all indirect time savings ($T_{d_h,s}(i_j, k)$) achievable by implementing an action that removes/reduces the indirect loss i_j , in the set-up phase k , related to the direct loss d_h occurring in the set-up phase s .
- Direct Environmental Impact ($DEI_{d_h,s}$): environmental saving directly achievable by removing the direct loss d_h occurring in the set-up phase s .
- Indirect Environmental Impact ($IEI_{d_h,s}$): sum of all indirect environmental savings ($EI_{d_h,s}(i_j, k)$) achievable by implementing an action that removes/reduces the indirect loss i_j , in the set-up phase k , related to the direct loss d_h occurring in the set-up phase s .

Once $DST_{d_h,s}$, $IST_{d_h,s}$, $DEI_{d_h,s}$, and $IEI_{d_h,s}$ are available, it is possible to calculate the Total Saving Time ($TST_{d_h,s}$) and the Total Environmental Impact ($TEI_{d_h,s}$) as follows:

$$TST_{d_h,s} = DST_{d_h,s} + IST_{d_h,s} = T(d_h, s) + \sum_{j,k=1}^{J,K} T_{d_h,s}(i_j, k) \quad (2)$$

$$TEI_{d_h,s} = DEI_{d_h,s} + IEI_{d_h,s} = EI(d_h, s) + \sum_{j,k=1}^{J,K} EI_{d_h,s}(i_j, k) \quad (3)$$

After identifying and determining the interdependencies among the different types of losses, the evaluation of set-up efficiency becomes feasible through the utilization of two dedicated Lean indicators. These indicators offer a quick overview of the current changeover conditions (referred to as the “as is” state) and facilitate comparative analysis across multiple machines. The indicators are as follows:

$$Time\ Set - Up\ Efficiency_{as\ is} = TSUE_{as\ is} = \frac{Ideal\ set - up\ time}{Actual\ set - up\ time} \quad (4)$$

$$Env.\ impact\ Set - Up\ Efficiency_{as\ is} = ESUE_{as\ is} = \frac{Ideal\ set - up\ env.\ impact}{Actual\ set - up\ env.\ impact} \quad (5)$$

		Indirect losses																Direct Saving Time (DST)	Direct Env. Impact (DEI)	Indirect Saving Time (IST)	Indirect Env. Impact (IEI)	Total Saving Time (TST)	Total Environmental Impact (TEI)		
		Loss i_i								Loss i_l															
		P		E	M		C	F		P		E	M		C	F									
		Time	Env. Impact		Time	Env. Impact		Time	Env. Impact	Time	Env. Impact		Time	Env. Impact		Time	Env. Impact								
Direct losses	Loss d_i	P	$T(d_i,p)(i_i,p)$	$EI(d_i,p)(i_i,p)$		$T(d_i,p)(i_i,m)$												$T(d_i,p)$	$EI(d_i,p)$	$IST(d_i,p)$	$IEI(d_i,p)$	$DST(d_i,p) + IST(d_i,p)$	$DEI(d_i,p) + IEI(d_i,p)$		
		E																							
		M							$T(d_i,m)(i_i,f)$	$EI(d_i,m)(i_i,f)$							$T(d_i,m)(i_i,f)$	$EI(d_i,m)(i_i,f)$	$T(d_i,m)$	$EI(d_i,m)$	$IST(d_i,m)$	$IEI(d_i,m)$	$DST(d_i,m) + IST(d_i,m)$	$DEI(d_i,m) + IEI(d_i,m)$	
		C																							
		F																							
	...	...				$T(d_i,f)(i_i,m)$	$EI(d_i,f)(i_i,m)$	...					...	$T(d_i,f)(i_i,m)$	$EI(d_i,f)(i_i,m)$	...			$T(d_i,f)$	$EI(d_i,f)$	$IST(d_i,f)$	$IEI(d_i,f)$	$DST(d_i,f) + IST(d_i,f)$	$DEI(d_i,f) + IEI(d_i,f)$	
	Loss d_o	P	$T(d_o,p)(i_i,p)$					$T(d_o,p)(i_i,f)$					$T(d_o,p)(i_i,p)$						$T(d_o,p)$	$EI(d_o,p)$	$IST(d_o,p)$	$IEI(d_o,p)$	$DST(d_o,p) + IST(d_o,p)$	$DEI(d_o,p) + IEI(d_o,p)$	
		E																							
		M											$T(d_o,m)(i_i,p)$	$EI(d_o,m)(i_i,p)$			$EI(d_o,m)(i_i,m)$		$T(d_o,m)$	$EI(d_o,m)$	$IST(d_o,m)$	$IEI(d_o,m)$	$DST(d_o,m) + IST(d_o,m)$	$DEI(d_o,m) + IEI(d_o,m)$	
		C																							
		F	$T(d_o,f)(i_i,p)$	$EI(d_o,f)(i_i,p)$																$T(d_o,f)$	$EI(d_o,f)$	$IST(d_o,f)$	$IEI(d_o,f)$	$DST(d_o,f) + IST(d_o,f)$	$DEI(d_o,p) + IEI(d_o,p)$
		...																							
F		$T(d_o,f)(i_i,p)$	$EI(d_o,f)(i_i,p)$				$T(d_o,f)(i_i,m)$												$T(d_o,f)$	$EI(d_o,f)$	$IST(d_o,f)$	$IEI(d_o,f)$	$DST(d_o,f) + IST(d_o,f)$	$DEI(d_o,p) + IEI(d_o,p)$	

Fig. 3 The CE-Matrix.

In both cases, the disparity between the ideal and current conditions arises from the proliferation of numerous losses, which not only prolongs set-up times but also elevate the environmental impact of the changeover process. Naturally, the objective is to achieve a set-up efficiency as close to 1 as possible, meaning optimal performance. However, it is essential to recognize the inherent trade-offs during the calculation of efficiency indicators. Reducing a specific inefficiency to save time might require corrective action that increases the environmental impact of the changeover, and vice versa. Therefore, the Time Set-Up Efficiency (TSUE) should only consider actions that result in time savings, while the Environmental impact Set-Up Efficiency (ESUE) should focus solely on those that reduce environmental impact.

For instance, employing the duplication strategy allows for the execution of multiple set-up activities while the machine remains operational, resulting in considerable savings. However, from an environmental perspective, this strategy increases the overall environmental burden of the process, considering all the environmental impacts associated with the production of duplicated material throughout its lifecycle. As a result, this strategy should be excluded from the ESUE calculation. Hence, when selecting corrective actions, it is crucial to carefully weigh the trade-offs between time efficiency and environmental performance, as discussed in Section 3.2.3.

These matrices serve to evaluate whether a changeover process is executed efficiently, considering both time and environmental impact. Measuring the total set-up time is insufficient. For instance, a set-up process taking 10 minutes might be completed in less than 1 minute, resulting in a TSUE of only 10%. Conversely, a set-up process lasting an hour could be completed in 55 minutes under optimal conditions, yielding a TSUE of nearly 92%. From an environmental standpoint, the situation is more complex, as detailed environmental assessments of changeover processes are often lacking.

To provide a more in-depth insight into the set-up process, in accordance with the SSD structure, both indicators can be obtained as the product of three sub-indicators, as shown below:

$$\begin{aligned}
 X \text{ SUE} = & X \text{ Standard Set - up Efficiency} \times \\
 & X \text{ Design Set - up Efficiency} \times \\
 & X \text{ Internal Set - up Efficiency}
 \end{aligned} \tag{6}$$

where, X represents either the *Time saving* or the *Environmental impact saving*.

The Standard Set-up Efficiency encompasses all losses stemming from deviations from standard procedures or the absence of standards altogether. A set-up process characterized by low Standard Set-up Efficiency indicates that a significant portion of activities are conducted while production units are halted, despite the potential to execute them during operation. The evaluation of Standard Set-up Efficiency is analytically conducted as follows:

$$X \text{ Standard Set – up Efficiency} = \frac{\text{Standard set – up } X}{\text{Actual set – up } X} \quad (7)$$

The Design Set-up Efficiency pertains to losses associated with changeover activities that could feasibly occur while the machine is in operation but, due to poor design, are not executed as such. An illustrative example of a loss impacting Design Set-Up Efficiency is the absence of advanced preparation for component operating conditions, such as temperature. This deficiency results in prolonged changeover times as machines idle during heating, leading to increased energy consumption and associated GHG emissions. The evaluation of Design Set-Up Efficiency is analytically expressed as follows (Formula 8):

$$X \text{ Design Set – up Efficiency} = \frac{\text{Target set – up } X}{\text{Standard set – up } X} \quad (8)$$

The Internal Set-up Efficiency assesses the execution of internal activities that cannot be shifted externally. Improved management and design of these internal operations often yield enhancements. A common example involves implementing positioning and locking systems, which can substantially reduce changeover times. From an environmental standpoint, selecting less harmful fluids for machine cleaning can readily enhance the environmental feasibility of the process. The evaluation of Internal Set-Up Efficiency is calculated as follows (Formula 9):

$$X \text{ Internal Set – up Efficiency} = \frac{\text{Ideal set – up } X}{\text{Target set – up } X} \quad (9)$$

The distinctive feature of this layered structure is its dual functionality in providing both a holistic perspective of current conditions and a detailed roadmap for enhancing set-up activities in terms of time and environmental impact saving. At this stage, it becomes feasible to pinpoint the most promising machines for SMED project implementation, as well as to identify specific activities necessitating focused efforts to accomplish optimal results.

3.2.4. Step 4

The final stage of EQC entails the selection of improvement techniques for implementation. This necessitates ranking potential corrective solutions and identifying a suitable subset thereof. Fulfilling this task is the responsibility of the R-Matrix (Fig. 4). In this matrix, the identified direct losses are listed along the rows, while improvement techniques are listed along the columns.

These improvement measures are categorized into two groups: organizational-procedural improvements and engineering improvements. The former involves managerial actions, such as the implementation of Lean practices to optimize personnel, equipment, and activities within the

changeover process. On the other hand, engineering improvements entail technical activities aimed at redesigning production units. Consequently, the nature of these improvements varies significantly depending on the specific circumstances.

The analysis team is tasked with identifying at least one improvement measure for each direct loss, although it is more likely that multiple corrective measures will be envisioned for a single loss. Consequently, there arises a need for a tool that is both easy to evaluate and sufficiently reliable to compare these improvements. With this objective in mind, we introduce the Green Set-up Index (GSI), defined as the ratio between the total time savings achievable by implementing a specific corrective action and the residual environmental impact following the implementation of said corrective action. This index is expressed as follows:

$$GSI_{d_i,s,r} = \frac{1}{1 - \Delta EI_r} \times \Delta t_r \quad (10)$$

where, $GSI_{d_i,s,r}$ is the GSI of the improvement measure r aimed at addressing the direct loss d_i in the set-up phase s , Δt_r denotes the achievable time saving, and ΔEI_r indicates the achievable environmental impact saving resulting from the implementation of improvement measure r . Interpreting this index is straightforward: the higher its value, the better the improvement measure. Considering two different improvements a and b , if $GSI_a > GSI_b$, the improvement a is better than improvement b . The coefficient $\frac{1}{1 - \Delta EI_r}$ functions as a multiplier that rewards improvements with greater environmental savings. In this way, the index can be understood as a "corrected" time-saving metric that accounts for the environmental benefits of a particular measure. A corrective measure that not only reduces set-up time but also cuts down environmental impact is considered more valuable. By employing this index to compare different corrective measures, it becomes feasible to select the most optimal option for each direct loss.

			Improvement techniques									
			Organizational-Procedural improvement							Engineering improvement		
			TPM	Standardized work	...	Poka-Yoke	Visual management	The 5S method	Six Sigma	Design modification of the equipment	...	Fast clamping system
Losses	Loss <i>i</i>	P		GSI ₁								
				IT ₁								
		E										
		M								GSI ₄	GSI ₅	
										IT ₄	IT ₅	
		C										
		F										
		...										
	Loss <i>j</i>	P					GSI ₂					
							IT ₂					
		E										
		M										GSI ₆
												IT ₆
		C							GSI ₃			
									IT ₃			
		F										

Fig. 4 The R-Matrix.

Once each direct loss is paired with its corresponding improvement, the analysis team can rank these improvements based on their GSI. However, the actual implementation of corrective measures is often subject to various constraints, such as budget limitations. At this point, caution is warranted as three critical scenarios may arise:

- $\Delta t_r = 0$ and $\Delta EI_r \neq 1$. This means that the improvement r reduces the environmental burden of the changeover process without affecting the time, resulting in a GSI value of 0. A practical example is the substitution of a cleaning hazardous fluid with water. The time required to perform the process remains the same while the environmental impact is clearly reduced.
- $\Delta t_r \neq 0$ and $\Delta EI_r = 1$. In this case, the improvement r reduces set-up time and accomplishes the maximum environmental saving. For instance, eliminating a set-up activity decreases the time while achieving zero environmental impact for that activity. The corresponding GSI tends towards infinity, representing a mathematical singularity.

The analysis team is tasked with thoroughly investigating these situations, as they may signify significant opportunities for optimizing changeover processes. Considering the aforementioned special scenarios and the GSI-based ranking, the company in question may adopt several implementation strategies. Firstly, it could opt to directly implement improvements based on the rankings provided by the GSI. Alternatively, the company might choose to implement one improvement per phase. In situations constrained by budget considerations, a cost-benefit analysis of the improvements could be conducted, incorporating costs as a decision criterion. The policy adopted by the company will likely prioritize one strategy over another to maximize benefits in the implementation process. Lastly, to offer a quantitative overview of achievable results, the team can calculate the $TSUE_{to\ be}$ and $ESUE_{to\ be}$, representing the time and environmental efficiency within the chosen strategy.

3.2.5. Continuous improvement

To achieve long-term excellence, the analysis team must implement a continuous improvement process that ensures sustained progress rather than a one-time effort. Regular audits help monitor improvements, while structured performance reviews identify new opportunities for enhancement. Effective feedback mechanisms enable stakeholder input, fostering ongoing refinement. Tailored elements such as training, workshops, and cross-functional collaboration further strengthen this approach. Without a well-defined process, improvements from lean implementation may deteriorate over time. By embedding continuous improvement into daily operations, the organization can prevent regression, drive innovation, and cultivate a culture focused on ongoing enhancement and operational excellence.

4. Case study

The methodology has been applied within an Italian company specialized in the production of plastic water bottles. The company was selected for three primary reasons. First, our previous collaboration with the management ensured a close working relationship and granted us full access to data on set-up operations. Second, operating in a highly competitive market, the company faces significant pressure to reduce set-up times, which are among the most time-consuming activities. By reducing set-up time, the company can decrease lead times and enhance overall product quality. Additionally, the company is aware of the growing consumer focus on the environmental impact of industrial practices. As a result, it has set ambitious environmental targets and established strategies to mitigate its environmental footprint.

Given that this was the first deployment of the EQC, the focus was placed on a well-established machine: an injection molding machine suitable for a wide range of plastic processing applications used for producing plastic water bottles which, for the case at hand, produces 500ml cylindrical plastic water bottles (Fig. 5).

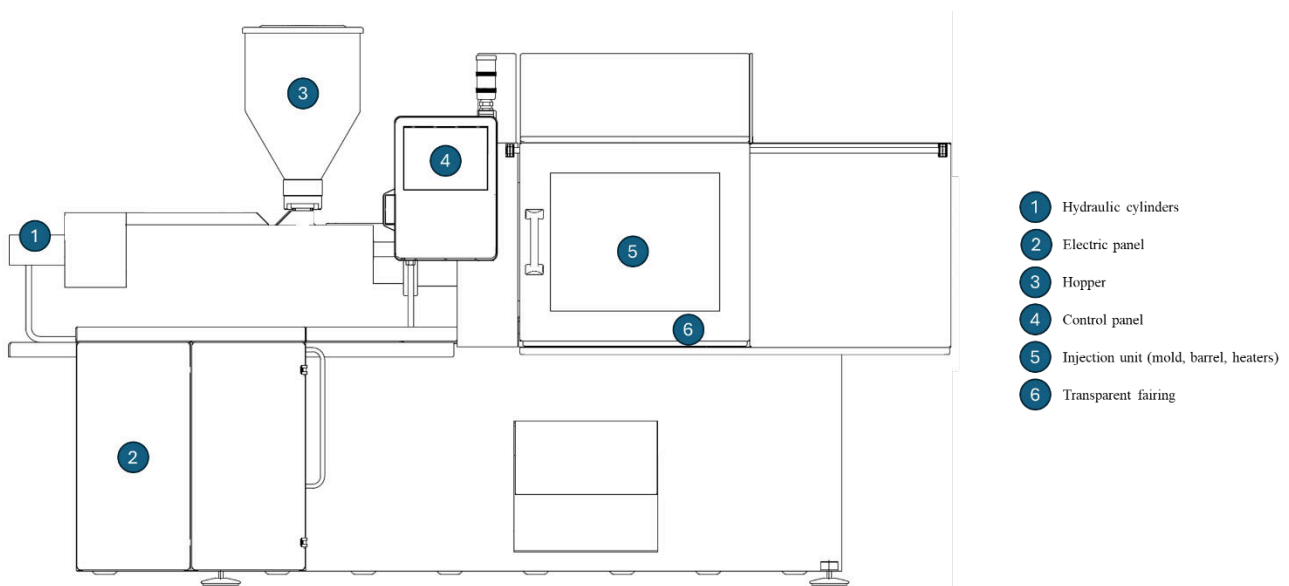


Fig. 5 Injection molding machine under analysis.

4.1. Changeover process

The injection molding process begins with feeding plastic granules, often mixed with additives, into the machine's hopper. These granules are heated and melted by a rotating screw inside the barrel, ensuring a homogeneous molten plastic. The molten plastic is then injected into a clamped mold cavity, where it takes the desired shape. The mold remains closed while the plastic cools and solidifies, after which the mold opens, and ejector pins release the finished part. This cycle is then repeated for continuous production.

The changeover process is as follows:

- Pre-staging. Gather necessary tools, materials, and documentation.
- Mold removal. Remove the old mold from the machine.
- Mold cleaning. Clean the mold and machine interface.
- Mold installation. Install the new mold into the machine.
- Mold clamping. Securely clamp the mold in place.
- Injection parameter set-up. Adjust injection pressure, temperature, and time.
- Cooling parameter set-up. Set the cooling water temperature and flow rate.
- Material loading. Load the required plastic resin into the hopper.
- Machine startup. Start the injection molding machine.

Through a detailed observation of the changeover process, each activity has been clocked, and the overall environmental impact has been assessed. The set-up process takes a total of 60 minutes to complete, consuming 120 kWh of energy and 600 liters of water. Additionally, it generates approximately 2.3 kg of waste and results in the emission of 54 kg CO₂-eq.

4.2. EQC application

The results of the EQC application are presented below, along with a detailed description of each step. The initial step involved assembling an analysis team comprising both industrial practitioners and academic personnel. The team, led by the head of the production department, ensured comprehensive knowledge of the entire process. It included a design engineer from the technical office and personnel from operations and maintenance. Academic experts were involved to provide insights into the environmental impact of the process and leveraging their expertise in changeover efficiency approaches.

The team began by adopting the 7 Green “Muda” as environmental impact categories and applied to the AHP to determine their relative weights. Poor health and safety were excluded from the scope of analysis, as they are not directly related to environmental issues. The team decided to exclude environmental categories with weights below 0.1, enabling the company to focus on areas more closely aligned with its environmental goals, such as GHG mitigation and improvements in water and energy efficiency. The resulting weights from the pairwise comparison are presented in Table 2. As shown, the weights for Eutrophication, Resource Usage, and Pollution are below the threshold and have been excluded from further analysis, with GHG, Power and Water Usage, and Waste Generation identified as key environmental impact categories.

Environmental Impact Category	Relative weight
Greenhouse gases	0.350
Eutrophication	0.025
Resource usage	0.025
Power usage	0.210
Water usage	0.210
Pollution	0.025
Waste generation	0.155

Table 2 Environmental impact category weights.

The second step involved identifying potential time and environmental losses within the changeover process. Through a thorough analysis, the team identified several losses that could be eliminated to enhance process efficiency (Fig. 6). The team provided estimates for both time savings and environmental impact reductions. A critical factor in these estimations is the sensorization of the machinery and auxiliary systems involved in the changeover process. Without adequate measurement equipment, the accurate quantification of EICs can be significantly compromised. During the experimental activities, all relevant equipment was equipped with appropriate sensors to monitor power and water consumption, as well as waste generation. For the estimation of GHG emissions, the analysis team adopted an indirect approach, calculating emissions based on the measured energy consumption and applying an emission factor corresponding to the specific energy mix used by the company.

An example of calculation of EI is reported below. The general formula applied to calculate the EI of the i loss is:

$$EI_i = w_{GHG} \times \frac{GHG_i}{GHG_{set-up}} + w_{Power} \times \frac{Power_i}{Power_{set-up}} + w_{Water} \times \frac{Water_i}{Water_{set-up}} + w_{Waste} \times \frac{Waste_i}{Waste_{set-up}} \quad (11)$$

For instance, the loss n°1 can be treated as follow:

Loss: Standardize Tooling and Setup Procedures.

Details: Lack of detailed work instructions and operator training.

Where: Preparation phase.

Type: Direct Loss.

Description: The changeover process is predominantly managed by senior operators who rely on their extensive experience. This reliance often results in a longer and more variable setup process, particularly when performed by less experienced or new operators. Without clear, standardized instructions, these operators may proceed without a defined sequence, leading to an iterative and inefficient approach.

Environmental Impact:

$$EI_1 = 0.378 \times \frac{9}{54} + 0.227 \times \frac{20}{120} + 0.227 \times \frac{50}{600} + 0.168 \times \frac{0.5}{2.3} = 0.16$$

Calculations for all the identified losses are provided within the Supplementary Information file.

The analysis revealed several key insights regarding potential savings. Many of the identified losses, such as the lack of detailed work instructions and operator training, offer opportunities for both time and environmental savings. However, there are actions that impact only one aspect. For example, optimizing the cooling system and implementing water-saving equipment provide clear environmental benefits but may not improve - and could even worsen - set-up times. Conversely, optimizing mold cleaning by using fast-acting chemical solvents can reduce set-up time, but it may negatively impact the environment due to the production of chemical waste.

The CE-Matrix was then constructed to illustrate the relationships between these losses, enabling the identification of direct losses whose resolution in a specific set-up phase could also eliminate related indirect losses (Fig. 7). By addressing these direct losses with targeted corrective actions, additional improvements can be achieved, resulting in further reductions in both time and environmental impact. The matrix also outlines the expected time and environmental savings achievable by eliminating these losses. For instance, externalizing set-up activities allows for better organization of work operations and minimizes operator movements during the extraction and mounting phases. Additionally, installing a flow control system for the cooling process necessitates first implementing a closed-loop cooling system to recycle water.

			Set-up phases									
Loss category	Loss type	Details	Preparation (P)		Extraction (E)		Mounting (M)		Control (C)		First Run (F)	
			Time [min]	Environmental Impact	Time [min]	Environmental Impact	Time [min]	Environmental Impact	Time [min]	Environmental Impact	Time [min]	Environmental Impact
Process Losses	Standardize Tooling and Setup Procedures	Lack of detailed work instructions and operator training	8	0.16								
	Externalize Setup Activities	Tools and materials are gathered while the machine is stopped. New mold is heated while the machine is stopped.	12	0.11								
Design Losses	Implement Quick-Change Tooling	Lack of hydraulic or pneumatic systems for fast and secure mold clamping					10	0.17				
	Optimize Cooling System	Absence of a closed-loop cooling system to recycle cooling water									-5	0.18
	Water-Saving Equipment	Absence of flow restrictor to control the amount of water									0	0.05
Internal Activity Losses	Implement Quick-Change Tooling	Lack of reference systems for part positioning							3	0.03		
	Improve Work Environment	Disorganised working area and lack of operator movements optimisation			2.5	0.03	2.5	0.03				
	Optimise mold cleaning	Use of water in place of fast-acting chemical solvents to clean molds			10	-0.01						

Fig. 6 Industrial application L-Matrix.

					Indirect Losses						Direct Saving Time (DST)	Direct Env. Impact (DEI)	Indirect Saving Time (IST)	Indirect Env. Impact (IEI)	Total Saving Time (TST)	Total Environmental Impact (TEI)
					Water-Saving Equipment		Improve Work Environment									
					Absence of flow restrictor to control the amount of water		Disorganised working area and lack of operator movements optimisation									
				Phase	F		E		M							
	Loss Type	Details	Phase		Time	Environmental Impact	Time	Environmental Impact	Time	Environmental Impact						
Direct Losses	Standardize Tooling and Setup Procedures	Lack of detailed work istructions and operator training	P								8	0.16			8	0.16
	Externalize Setup Activities	Tools and materials are gathered while the machine is stopped. New mold is heated while the machine is stopped.	P				2.5	0.03	2.5	0.03	12	0.11	5	0.07	17	0.17
	Implement Quick-Change Tooling	Lack of hydraulic or pneumatic systems for fast and secure mold clamping	M								10	0.17			10	0.17
	Optimize Cooling System	Absence of a closed-loop cooling system to recycle cooling water	F		0	0.05					-5	0.18	0	0.05	-5	0.24
	Implement Quick-Change Tooling	Lack of reference systems for part positioning	C								3	0.03			3	0.03
	Optimise mold cleaning	Use of water in place of of fast-acting chemical solvents to clean molds	E								10	-0.01			10	-0.01

Fig. 7 Industrial application CE-Matrix.

To provide a better understanding of the changeover process, it is possible to evaluate the set-up efficiency indicators both for time and environmental impact (Fig. 8).

			"As is" set-up efficiency indicators
Time [min]	Set-up process	60	Time Set-Up Efficiency = $\frac{\text{Ideal set-up Time}}{\text{Actual set-up Time}} = \frac{60 - 20 - 10 - 18}{60} = 20\%$
	Process Losses	20	Time Standard Set-up Efficiency = $\frac{\text{Standard set-up Time}}{\text{Actual set-up Time}} = \frac{60 - 20}{60} = 67\%$
	Design Losses	10	Time Design Set-up Efficiency = $\frac{\text{Target set-up Time}}{\text{Standard set-up Time}} = \frac{60 - 20 - 10}{60 - 20} = 75\%$
	Internal Activity Losses	18	Time Internal Set-up Efficiency = $\frac{\text{Ideal set-up Time}}{\text{Target set-up Time}} = \frac{60 - 20 - 10 - 18}{60 - 20 - 10} = 40\%$
Environmental impact	Set-up process	1.00	Env. impact Set-Up Efficiency = $\frac{\text{Ideal set-up Env. impact}}{\text{Actual set-up Env. impact}} = \frac{1.00 - 0.26 - 0.41 - 0.10}{1.00} = 23\%$
	Process Losses	0.26	Env. i. Standard Set-up Efficiency = $\frac{\text{Standard set-up Env. impact}}{\text{Actual set-up Env. impact}} = \frac{1.00 - 0.26}{1.00} = 74\%$
	Design Losses	0.41	Env. i. Design Set-up Efficiency = $\frac{\text{Target set-up Env. impact}}{\text{Standard set-up Env. impact}} = \frac{1.00 - 0.26 - 0.41}{1.00 - 0.26} = 44\%$
	Internal Activity Losses	0.10	Env. i. Internal Set-up Efficiency = $\frac{\text{Ideal set-up Env. impact}}{\text{Target set-up Env. impact}} = \frac{1.00 - 0.26 - 0.41 - 0.10}{1.00 - 0.26 - 0.41} = 69\%$

Fig. 8 "As is" set-up efficiency indicators.

Regarding time efficiency, poor performance is primarily due to slow internal activities and poorly organized set-up procedures, as indicated by the respective metrics of 40% and 67%. To reduce changeover time, the company should focus on speeding up activities that must be completed while the machine is offline, such as adjustments, and standardizing tasks to minimize reliance on the experience and intuition of workers. Conversely, the environmental impact of the changeover process is significantly affected by outdated machine design, reflected in a 44% indicator. This is common in many companies where older machines were not designed with environmental considerations in mind. Therefore, implementing technical improvements could greatly reduce the environmental impact of the changeover process.

The final step of the methodology involved identifying tailored solutions and prioritizing them based on the results presented in the R-Matrix (Fig. 9). The company, limited by budget, implemented the top five GSI-ranked improvements, highlighted in green in the R-Matrix.

				Improvement techniques				
				Organizational-Procedural improvement		Engineering improvement		
				Standardize work	Set-up cycle redesign	Reference system introduction	Replacement of washing fluid	Equipment redesign
	Loss Type	Details	Phase					
Losses	Standardize Tooling and Setup Procedures	Lack of detailed work instructions and operator training	P	9.48				
	Externalize Setup Activities	Tools and materials are gathered while the machine is stopped. New mold is heated while the machine is stopped.	P		13.44			
	Implement Quick-Change Tooling	Lack of hydraulic or pneumatic systems for fast and secure mold clamping	M					12.10
	Optimize Cooling System	Absence of a closed-loop cooling system to recycle cooling water	F					-6.13
	Implement Quick-Change Tooling	Lack of reference systems for part positioning	C			3.11		
	Optimise mold cleaning	Use of water in place of fast-acting chemical solvents to clean molds	E				9.87	
	Water-Saving Equipment	Absence of flow restrictor to control the amount of water	F					0.00
	Improve Work Environment	Disorganised working area and lack of operator movements optimisation	E	2.59				
			M	2.59				

Fig. 9 Industrial application R-Matrix.

Once the improvement techniques had been selected, the team evaluated the $TSUE_{to\ be}$ and $ESUE_{to\ be}$, and other intermediate indicators (Fig. 10). A critical aspect during this phase is the calculation of these indicators, which are obtained by subtracting the estimated savings (resulting from the selected interventions) from the “*as is*” values. Specifically, the Actual set-up Time under the “*to be*” scenario is 17 minutes (i.e., 60 – 43), and the Actual set-up Environmental impact is 0.54 (i.e., 1 – 0.46). As a result, the remaining losses represent the portion of the initial time and environmental impacts that have not yet been mitigated.

			“To be” set-up efficiency indicators	
Time [min]	Set-up process	17	Time Set-Up Efficiency = $\frac{\text{Ideal set-up Time}}{\text{Actual set-up Time}} = \frac{17 - 5}{17} = 71\%$	
	Process Losses	0	Time Standard Set-up Efficiency = $\frac{\text{Standard set-up Time}}{\text{Actual set-up Time}} = \frac{17}{17} = 100\%$	
	Design Losses	0	Time Design Set-up Efficiency = $\frac{\text{Target set-up Time}}{\text{Standard set-up Time}} = \frac{17}{17} = 100\%$	
	Internal Activity Losses	5	Time Internal Set-up Efficiency = $\frac{\text{Ideal set-up Time}}{\text{Target set-up Time}} = \frac{17 - 5}{17} = 71\%$	
Environmental impact	Set-up process	0.54	Env. impact Set-Up Efficiency = $\frac{\text{Ideal set-up Env. impact}}{\text{Actual set-up Env. impact}} = \frac{0.54 - 0.24 - 0.07}{0.54} = 43\%$	
	Process Losses	0	Env. i. Standard Set-up Efficiency = $\frac{\text{Standard set-up Env. impact}}{\text{Actual set-up Env. impact}} = \frac{0.54}{0.54} = 100\%$	
	Design Losses	0.24	Env. i. Design Set-up Efficiency = $\frac{\text{Target set-up Env. impact}}{\text{Standard set-up Env. impact}} = \frac{0.54 - 0.24}{0.54} = 56\%$	
	Internal Activity Losses	0.07	Env. i. Internal Set-up Efficiency = $\frac{\text{Ideal set-up Env. impact}}{\text{Target set-up Env. impact}} = \frac{0.54 - 0.24 - 0.07}{0.54 - 0.24} = 77\%$	

Fig. 10 “*To be*” set-up efficiency indicators.

4.3. Sensitivity analysis

To evaluate the robustness of the GSI-based rankings, a sensitivity analysis was conducted using a Monte Carlo sampling method with 10,000 iterations. This approach is widely adopted in the literature for assessing the stability of multi-criteria decision-making outcomes. For example, similar applications can be found in the work of [32]. In each iteration, random perturbations were applied to the values of time savings and environmental impacts (Power, Water, and Waste), excluding GHG due to its direct dependency on Power. Two levels of variability were considered: $\pm 5\%$ and $\pm 10\%$ of the original recorded values. For each scenario, the EI and the resulting GSI were recalculated, followed by a re-ranking of the solutions. Table 3 reports the results of the analysis. Under the $\pm 5\%$ variation scenario (Table 3a), the rankings remained remarkably stable: solutions n°2 and n°3 consistently occupied the top positions, while solutions n°4, n°5, and n°7 maintained their respective ninth, fifth, and eighth places. Minor internal shifts were observed between solutions n°1 and n°6 (third and fourth ranks) and between n°8 and n°9 (sixth and seventh ranks), though solution n°1 ranked fourth in over 80% of the iterations.

The $\pm 10\%$ variation scenario (Table 3b) confirmed the robustness of the method, with the top five solutions remaining unchanged in composition. Although more internal switches occurred within the top-ranked group, the only exception was a marginal (0.7%) appearance of solutions n°8 and n°9 in fifth place, replacing n°5.

The sensitivity analysis demonstrates that the GSI-based ranking is robust against moderate fluctuations in the input parameters, thereby reinforcing the reliability of the methodology for decision-making purposes.

			Ranking (5%)								
	Loss Type	Phase	1	2	3	4	5	6	7	8	9
Losses	Standardize Tooling and Setup Procedures	P	0	0	1859	8141	0	0	0	0	0
	Externalize Setup Activities	P	10000	0	0	0	0	0	0	0	0
	Implement Quick-Change Tooling	M	0	10000	0	0	0	0	0	0	0
	Optimize Cooling System	F	0	0	0	0	0	0	0	0	10000
	Implement Quick-Change Tooling	C	0	0	0	0	10000	0	0	0	0
	Optimise mold cleaning	E	0	0	8141	1859	0	0	0	0	0
	Water-Saving Equipment	F	0	0	0	0	0	0	0	10000	0
	Improve Work Environment	E	0	0	0	0	0	4928	5072	0	0
		M	0	0	0	0	0	5072	4928	0	0

(a)

			Ranking (10%)								
	Loss Type	Phase	1	2	3	4	5	6	7	8	9
Losses	Standardize Tooling and Setup Procedures	P	0	0	3189	6811	0	0	0	0	0
	Externalize Setup Activities	P	8789	1211	0	0	0	0	0	0	0
	Implement Quick-Change Tooling	M	1211	8787	2	0	0	0	0	0	0
	Optimize Cooling System	F	0	0	0	0	0	0	0	0	10000
	Implement Quick-Change Tooling	C	0	0	0	0	9930	67	3	0	0
	Optimise mold cleaning	E	0	2	6809	3189	0	0	0	0	0
	Water-Saving Equipment	F	0	0	0	0	0	0	0	10000	0
	Improve Work Environment	E	0	0	0	0	40	5010	4950	0	0

		M	0	0	0	0	30	4923	5047	0	0
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(b)

Table 3. Results of Sensitivity analysis under the $\pm 5\%$ variation scenario (a), and $\pm 10\%$ variation scenario (b).

5. Results and Discussion

The EQC methodology has yielded significant results, reducing both changeover time and environmental impact. Prior to implementing the methodology, the set-up process required 60 minutes to complete, consuming 120 kWh of energy and 600 lt of water. Additionally, it generated approximately 2.3 kg of waste and resulted in the emission of 54 kg of CO₂-equivalent. Following the implementation of the improvement techniques identified through the EQC methodology, the changeover time was reduced to 17 minutes. Energy consumption decreased by 75 kWh, and water usage was reduced by 115 lt. Furthermore, CO₂-eq emissions were cut by 34 kg, and waste production decreased by 0.5 kg. The new set-up process is 72% faster, consumes 62% less energy, and uses 20% less water. Additionally, carbon emissions have been reduced by over 60%, and waste production has decreased by nearly 22%. More details about the calculation can be found in the Supplementary Information file.

This significant result was achieved by implementing five corrective measures identified by the EQC methodology. The improvement techniques were selected based on the ranking provided by GSI and the budget constraints of this pilot project. The chosen techniques, in order of priority, are:

1. Redesigning the set-up cycle to externalize activities that can be performed while the machine is running.
2. Redesigning the clamping system by introducing pneumatic fast clamping.
3. Substituting water with a fast-acting chemical solvent for mold cleaning.
4. Preparing detailed work instructions to ensure the changeover process does not rely on operator experience and intuition.
5. Introducing a pin-based reference system to speed up part positioning.

Notably, the substitution of water with a chemical solvent is the only action that improves one aspect at the expense of another. While it decreases set-up time, it also increases waste production, thereby worsening the environmental impact of the process. Nevertheless, the changeover time and environmental impact have been significantly improved.

Regarding the efficiency indicators, the TSUE increased from 20% to 71%, while the ESUE improved from 23% to 42%. The enhancement in time efficiency is particularly notable. Time

Standard and Design Set-up Efficiency reached 100%, indicating that any further improvements can only be achieved by optimizing internal activities, those that must be carried out while the machine is stopped. Although environmental improvement is significant, there is still room for further enhancement. The primary opportunities for improvement lie in the design of the machine itself, which was not conceived of environmental considerations for the changeover process in mind.

Compared to existing studies in the literature, the EQC methodology advances the state of the art by quantitatively integrating multiple environmental aspects simultaneously. For instance, the study by Leme et al. [9] laid the groundwork for incorporating environmental considerations into SMED analysis, but its scope was limited to carbon footprint. In contrast, EQC is capable of accounting for GHG emissions as well as energy, water, and material consumption, thereby enabling a more comprehensive environmental assessment. Similarly, the work of Ebrahimi et al. [25] presents a tool based on VSM and SMED that considers aspects beyond time, such as energy use and inventory consumption. However, EQC distinguishes itself by encompassing a broader range of environmental factors and by offering practitioners a set of lean performance indicators to evaluate current efficiency and support the selection of improvement techniques. Finally, the findings of our study are consistent with the conclusions of Queiroz et al. [27], reinforcing the idea that SMED can be effectively enhanced by incorporating environmental considerations. This integrated approach enables improvements in production processes not only from a time-efficiency standpoint but also from a broader sustainability perspective.

The successful implementation of the EQC methodology has led to significant improvements in efficiency and sustainability, aligning with multiple SDGs and prompting its expansion across the production floor. In line with SDG 6, water usage decreased by 115 liters, supporting sustainable water management. SDG 7 is addressed through a 62% reduction in energy consumption, enhancing efficiency. The methodology improves productivity under SDG 8 by making the set-up process 72% faster without increasing labor strain, while standardized work instructions enhance reliability and working conditions. By optimizing changeover processes through lean techniques, SDG 9 is supported. Reductions in energy, water, and waste contribute to SDG 12. Finally, a 60% decrease in CO₂ emissions aligns with SDG 13, promoting low-carbon manufacturing. These results demonstrate how industrial efficiency and sustainability can coexist, providing a model for responsible production.

Despite the strengths of the proposed approach, certain limitations must be acknowledged. First, the methodology has been validated on a single case study. While this case effectively demonstrated the approach's capabilities and functionality, broader validation is required before it can be systematically implemented in industrial settings. For instance, it should be tested in diverse industrial environments, such as the changeover process of a production line involving multiple machines

simultaneously. From an operational perspective, one potential limitation concerns the composition of the implementation team. Conducting a comprehensive analysis of the changeover process, considering both operational and environmental factors, demands extensive expertise. Consequently, assembling a team with the necessary knowledge presents a challenge, particularly when aiming for an in-depth assessment. In this sense, the main limitation of the proposed CE-Matrix lies in its qualitative nature, as the identified relationships are based on expert perception rather than statistical validation, which may affect the objectivity and reproducibility of the findings. Nevertheless, EQC methodology remains valuable in real-world industrial settings, where quick and structured decision support is often needed even in the absence of statistically validated data. Furthermore, the definition of the target (“to-be”) state is significantly influenced by the judgment of production managers. Balancing environmental and operational objectives remains a complex task, as decision-making is inherently shaped by corporate pressures to optimize economic performance. The methodology partially addresses this issue through the development of the R-matrix, which ranks solutions by integrating both environmental and operational considerations. To further support the robustness of the EQC methodology, a sensitivity analysis was conducted on the GSI to evaluate the impact of input data fluctuations on the final prioritization of improvement techniques. This analysis confirmed the relative stability of the GSI rankings, reinforcing the consistency of the methodology under different decision-making scenarios.

6. Conclusions

This paper introduces an innovative Lean methodology called EQC, designed to achieve two critical objectives: minimizing the environmental footprint of changeover processes while simultaneously reducing set-up times through the principles of SMED. This dual focus is accomplished by integrating environmental considerations into the SSD.

EQC follows a structured, step-by-step process. The first step involves assembling a diverse analysis team, comprising individuals from various disciplines such as environmental management, production, maintenance, and operations. This multidisciplinary approach ensures that both production efficiency and environmental impacts are effectively addressed. The subsequent steps are organized around three specific matrices that guide the process and provide clarity on the results. In the second step, potential savings in time and environmental impact are identified and quantified. In the third step, the relationships between these savings are analyzed to determine how one improvement can enable further savings. Finally, a list of potential improvement techniques is generated and ranked using a novel metric (Green Set-up Index) which evaluates both time and environmental savings associated with each loss in the changeover process.

The EQC methodology was successfully applied in a company producing plastic water bottles to optimize the changeover process for an injection molding machine. The set-up process became 72% faster, energy consumption decreased by 62%, water usage dropped by 20%, carbon emissions were reduced by over 60%, and waste production declined by nearly 22%. EQC also introduced tailored efficiency indicators, which provided a comprehensive assessment of the set-up process. Time efficiency rose from 20% to 71%, while environmental efficiency increased from 23% to 42%.

The company recognized the strength of the EQC methodology in its ability to quantify both time and environmental impacts, a critical feature for making informed decisions. This quantitative approach proved essential in situations where trade-offs between time savings and environmental benefits had to be carefully weighed. The methodology enables decision-makers to evaluate and prioritize improvements based on both dimensions, supporting a more practical and effective decision-making process.

Future developments may include the integration of empirical data and statistical techniques to validate the relationships highlighted by the CE-Matrix, thereby enhancing the robustness and generalizability of the methodology. Moreover, future work could focus on integrating economic considerations into the improvement process. At present, the methodology does not account for detailed cost-benefit analyses of the proposed improvements. Incorporating this dimension would significantly enhance its value for industrial practitioners, who often face budgetary constraints while striving to make their operations greener. Additionally, the methodology could be expanded to include other key dimensions of sustainability beyond environmental impacts, most notably, the health and safety of workers. Integrating these factors would allow for a more holistic evaluation of changeover efficiency, taking into account not only resource consumption and emissions, but also ergonomic risks, operator well-being, and overall workplace safety. This broader perspective would align the methodology with the principles of sustainable manufacturing and corporate social responsibility, increasing its relevance for practical applications.

Competing Interests

The authors have no relevant financial or non-financial interest to disclose.

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Author Contributions

All the authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Francesco Di Paco and Leonardo Marrazzini. Supervision and control were performed by Marcello Braglia, Mohamed Afy-Shararah and Konstantinos Salonitis. The first draft of the manuscript was written by Francesco Di Paco and Leonardo Marrazzini. All authors read and approved the final manuscript.

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