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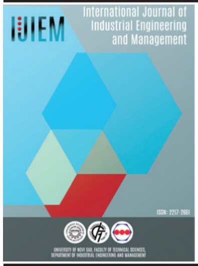

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Original research article

Micro downtimes management in the Lean perspective: An empirical research in a production bottleneck

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ABSTRACT

Nowadays, in the present dynamic industrial scenario characterized by shorter product lifecycles, customization, and uncertain demand, corporations should enhance their efficiency by reducing waste to remain competitive. This research addresses machine micro downtimes, which embrace a significant waste source that negatively affects Overall Equipment Effectiveness (OEE). Although the literature presents some studies suggesting methods to mitigate micro downtimes, contemporary approaches focus on isolated strategies, lacking an integrated methodology. Accordingly, a research gap remains in developing a comprehensive framework that holistically improves OEE and systematically decreases micro downtimes within processes with bottlenecks. In this context, the objective of this study is twofold. First, we aim to introduce a Lean-based framework to reduce micro downtimes in manufacturing processes. Second, we present the results of applying this framework in a Brazilian tire company through a practical research approach. The results demonstrate a 1.6% reduction in machine micro downtimes, amounting to potential savings of USD 750,000 annually. Additionally, the implementation led to the improvement project's completion three weeks ahead of schedule, showcasing the framework's effectiveness. Although validated in tire manufacturing, the adaptable framework shows potential for broader use in other industries, offering a flexible approach to enhancing efficiency and competitiveness.

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1. Introduction

The National Tire Industry Association (ANIP) reported that tire sales in Brazil dropped by 8.2% in 2023 compared to the year before, with total sales falling from 56.64 million to 51.97 million units [1]. According to [2], this decline may derive from factors such as high interest rates, economic instability, and shifts in the exchange rate, thus benefiting tire imports from China. Even in this scenario, specialists predict the market will rebound, hitting 2.09 billion USD by 2027, with an average Compound Annual Growth Rate (CAGR) of 4.5% per year between 2020 and 2027 [3].

In this context of instability, companies must continually enhance their effectiveness to remain competitive. Lean manufacturing, Agile, and DMAIC principles were developed to identify and eliminate

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wasteful practices, thereby improving manufacturing processes [4], [5]. Total Productive Maintenance (TPM), a core component of Lean, is an effective industrial methodology for enhancing plant productivity and operational efficiency, thereby minimizing the necessity for additional capital investments [6]. Overall Equipment Effectiveness (OEE) is the quantitative index of TPM that measures a combination of three parameters, (i) availability, (ii) performance, and (iii) quality, that highlight areas for process improvement [7]. Among these losses, machine downtime stands out. Downtime refers to intervals when production equipment is non-operational due to malfunctions [8]. When these intervals are short, such as momentary jamming of machine parts or speed reductions caused by workpiece blockages, are classified as micro downtimes [9].

Micro downtimes can lead to substantial productivity losses in manufacturing processes, as they are a significant source of waste that directly reduces OEE and increases operational costs. Addressing these inefficiencies is essential for industries to maintain their competitiveness. Previous research addressed the micro downtimes problem in manufacturing processes [8], [10]-[13]. Although these studies discuss methods for diagnosing or solving the problem, current approaches focus on isolated strategies, lacking an integrated methodology. Thus, a research gap remains regarding comprehensive framework development that holistically improve OEE and systematically reduce micro downtimes in bottleneck processes. This study aims to fill this gap by proposing a new Lean-based framework to reduce micro downtimes in manufacturing processes. Thus, the objectives of this paper are twofold: first, we aim to propose the Lean-based framework based on Agile and DMAIC concepts, and second, we seek to present the results of its application in a Brazilian tire company through a practical research approach.

2. Theoretical Background

This section aims to present the main topics related to the research theme. Initially, it examines the impact of downtime on production equipment. Subsequently, we provide a comprehensive review of Lean, Agile, and DMAIC methodologies, highlighting the significant contributions in each area. Finally, we discuss the research gap and problem identification, setting the stage for the proposed framework.

2.1 Downtime impact on production equipment

Mass production enterprises must aim for optimal efficiency in utilizing both equipment and human resources, as well as in managing input consumption. The adoption of OEE stands out as a crucial approach to tackling these challenges [14]. Designed by Seiichi Nakajima [15] as a component of TPM, the productivity metric has primarily been used within the TPM domain. However, it has developed into an autonomous operational improvement tool, which now applies to Lean Production and Six Sigma methodologies [16]. According to Figure 1, the OEE index consists of the multiplication of availability, performance, and quality [15].

Figure 1 illustrates that the components of OEE can be more effectively summarized as follows: Availability - measures the percentage of time equipment is running versus planned production time. It is affected by downtime, maintenance, plant shutdowns, setup time, changeovers, and interruptions [15], [16]. Performance - assesses the speed at which equipment operates compared to its ideal capacity. It is influenced by slow cycles, minor stops, and unoccupied time, leading to reduced throughput [15], [16]. Quality - Represents the proportion of products that meet quality standards. It is affected by defects, rework, and scrap, reducing the yield of high-quality products [15], [16].

Although an index for OEE of at least 85% is a reasonable objective [15], research conducted globally [16] has indicated that the average OEE in manufacturing firms typically falls around 60%. Several factors can affect the OEE index, such as (i) Downtimes (interruptions or breakdowns) and maintenance - planned or unplanned stoppages [17]. (ii) Plant shutdowns - halts operations, directly impacting availability [15], [17]. (iii) Setup time and changeovers - delay start of production or change in the product type

$$\text{OEE} = \underbrace{\boxed{\frac{\text{loading time} - \text{down time}}{\text{loading time}}}}_{\text{Availability}} \times \underbrace{\boxed{\frac{\text{ideal cycle time}}{\text{actual time}} \times \frac{\text{actual cycle time X output}}{\text{operating time}}}}_{\text{Performance}} \times \underbrace{\boxed{\frac{\text{total num. of production} - \text{rejections}}{\text{total num. of production}}}}_{\text{Quality}}$$

Figure 1. OEE calculation formula highlighting its role in identifying inefficiencies like micro downtimes

[17]. (iv) Unoccupied time and brief stops/ micro downtimes - reduce performance due to inefficiencies [8], [17]. (v) Rejections and defects - products that do not meet quality standards (defective items) reduce the proportion of high-quality products [17].

In the context of downtimes, micro downtimes refer to brief interruptions or stoppages in production processes that last very short durations, typically ranging from milliseconds to seconds. While traditional downtime events are more noticeable and can last minutes or even hours, micro downtime instances are often overlooked or underestimated due to their transient nature [8]. However, their cumulative impact can be significant, as micro downtimes may occur frequently throughout the production cycle. These micro interruptions may result from various factors, such as equipment malfunctions, sensor inaccuracies, material shortages, or minor adjustments in production settings. Despite their brevity, micro downtime events can disrupt workflow continuity, reduce OEE, and compromise productivity [17]. Therefore, identifying and addressing these micro interruptions is crucial for optimizing production efficiency and minimizing operational losses. A strategy used to reduce different types of waste since the 1980s, especially in the automotive industry, is the Lean approach.

2.2 Lean

Manufacturing companies confronted increasingly new challenges, such as market volatility, the demand for shorter delivery times, and reduced prices [18]. Thus, the manufacturing sector must deploy a range of strategic initiatives to maintain competitiveness. In this context, Lean emerges as a manufacturing strategy to improve processes [19]. Lean concepts originated with Japan's Toyota Production System around the 1980s, and from then on, they have gradually integrated into Western companies [20]. It comprises essential concepts like Muda (waste), Mura (variability) and Muda (overburden) [20]. Lean's underlying logic drives a dynamic process based on principles and practices that aim to achieve continuous improvement by eliminating waste [4]. Thus, it is a business strategy to improve quality and service, reduce time and cost, and enhance the overall organizational effectiveness [21]. Lean is not a standalone approach; typically, it's implemented alongside other associated Lean is not a standalone approach; typically, it is implemented alongside other associated practices, such as just-in-time, continuous improvement, TPM, Ishikawa Diagram, 5 Whys, Agile methodologies, DMAIC, and A3, among others [22]-[26]. The following paragraph will discuss the main Lean tools applied in this research.

The Ishikawa or Fishbone Diagram is a fundamental tool within the Lean approach. It is used to explore the potential causes of a problem by examining it from various perspectives, systematically identifying and categorizing the root causes of inefficiencies or defects in production processes [24]. This structured approach facilitates targeted interventions and continuous improvement efforts. Another fundamental tool of Lean is the 5 Whys methodology. It is a problem-solving approach that involves repeatedly asking "why" to identify the root cause of an issue, often reaching a deep understanding after about five iterations of the question [25]. By systematically probing the reasons behind a problem, the 5 Whys helps teams move beyond superficial symptoms and identify fundamental issues that can be addressed to prevent recurrence. The A3 framework is also a problem-solving tool from Lean. It is a method that involves detailing the background to set the context of an issue by outlining the current state, defining the objective or desired result, examining the root causes of the problem, suggesting corrective actions for enhancement, and developing plans for subsequent follow-up [27], [28]. Different tools mix enhance the effectiveness of continuous improvement and waste reduction, promoting a culture of systematic problem-solving and operational excellence, central to the Lean approach. Various authors have examined the integration of Lean tools and OEE concepts to enhance production processes across industries. This will be discussed in sequence.

Implementing TPM and lean tools like Jishu Hozen, Kaizen, and SMED has been shown to significantly increase OEE by addressing downtime, machine idle time, setup time, cycle time, and breakdown losses, leading to improved machine tool utilization and employee efficiency [29], [30]. Additionally, integrating Lean tools such as 5S and TPM with the DMAIC methodology in the automotive sector can result in substantial financial savings and improved key metrics like defect per unit and casting density [31].

Marinho et al. [32] developed a framework for Small and Medium Enterprises to implement TPM, demonstrating its effectiveness in reducing equipment stoppages and improving productivity in the cork industry. The study conducted by Suárez-Barraza and Rodríguez-González [24] involved an exploratory qualitative approach, analyzing Ishikawa diagrams from 40 Mexican companies and conducting in-depth interviews that revealed typical patterns that indicate foundational issues in these organizations. The findings emphasize the importance of quality control tools like the cause-and-effect diagram in addressing fundamental problems.

Combining Lean tools, such as the 5-whys analysis technique, has also been shown to be an efficient way to eliminate speed loss and generate significant annual savings in manufacturing industries [33].

For micro and small enterprises, methods developed to implement Lean practices using OEE as a guiding indicator have facilitated systematic operational enhancements [34]. Furthermore, integrating sustainability with Lean and OEE to measure environmental impact alongside equipment utilization has demonstrated significant sustainability improvements, particularly in tube fabrication companies [35]. Authors [36] used a simple moving average and Holt's double exponential smoothing methods to predict the future performance of OEE. As a result, Holt's double exponential smoothing method resulted in minimal error measured by mean absolute deviation.

In automotive component production lines, the standardization of operations and the elimination of non-value-added activities have led to a notable increase in OEE from 70% to 86% [37]. Enhanced OEE frameworks incorporating measures of Six Sigma process capability and asset management effectiveness have been successfully tested in factory settings manufacturing large batches of similar products, allowing for benchmarking internal performance against external competition [38]. Moreover, the importance of TPM and Lean manufacturing in improving OEE has been underscored through global surveys of manufacturing organizations, identifying critical managerial factors and linking successful OEE implementation to overcoming managerial barriers and leveraging key drivers [39].

Overall, these studies illustrate that the assimilation of different Lean tools and OEE concepts can lead to significant improvements in equipment performance, reduction in various forms of losses, and overall enhancement of production efficiency. In this context, while Lean concepts have emerged to reduce waste and improve production processes, Agile methodologies emerged to speed up this process [40].

2.3 Agile

The Agile manufacturing concept emerged in the 1990s as a collaborative effort involving the US government, academia, and industrial sectors to better prepare North American companies to cope with global competition [41]. In the 2000s, the Agile Manifesto revolutionized the software engineering sector, inspiring developers to create business value by delivering software to end users promptly, thanks to its emphasis on technical excellence and simple designs [42].

Nowadays, Agile concepts encompass a suite of methods, frameworks, and practices aimed at evolving solutions iteratively through incremental stages, facilitated by self-organizing, cross-functional teams [43]-[45]. The Agile Manifestos stands on values and twelve principles that emphasize prioritizing individuals and interactions over processes and tools, delivering functional software over extensive documentation, fostering customer collaboration over contract negotiations, and maintaining adaptability to change rather than adhering strictly to a plan [45]. Thus, the Agile concept is characterized by an interactive, team-centric approach that fosters communication and collaboration, facilitating the organization and adaptation of work methods to suit project conditions [44], [46]. Agile represents a methodology characterized by dynamism, rapid iteration, and swift adaptation to evolving requirements and circumstances. It is implemented through frameworks such as Scrum, an approach designed for managing complex projects. Scrum operates through structured sprints and time-boxed iterations that enable teams to deliver incremental progress while fostering cross-functional collaboration and maintaining adaptability [44]-[46].

The literature regarding using Agile concepts to improve OEE is still sparse. However, authors like [47] investigated the use of Agile practices to improve the filling processes performance in the pharmaceutical industry, using simulation models to identify and evaluate nine improvement scenarios. Their findings revealed that applying Agile methodologies allows a labeler machine to improve the OEE by 13.5%, indicating substantial potential savings in production and quality costs.

In this work, we combine the Agile approach with the DMAIC methodology to make the cycles shorter and more dynamic, generating results throughout the project.

2.4 DMAIC

DMAIC seats for "define, measure, analyze, improve, and control". Identical to an algorithm, the DMAIC cycle follows several stages designed to help a company identify and solve problems using “both” statistical and non-statistical tools to reduce or eliminate waste [48]. Drawing from previous research [49],

[50], Table 1 outlines the five stages of the DMAIC process.

What distinguishes the DMAIC cycle from other approaches is its systematic methodology designed to facilitate reproducibility across diverse scenarios, providing a step-by-step framework for implementation [51].

The literature in the last two decades has shown the importance of integrating Lean, Agile, and DMAIC concepts to improve production processes. The application of DMAIC, Lean, and simulation tools in furniture manufacturing significantly increased production and reduced delivery times, showcasing the role of these methodologies in optimizing processes and minimizing waste [52]. Villacís and Burneo [53] employed a circular DMAIC methodology to address quality issues in a small drone assembly company. As a result, lead time was reduced, leanness increased from 23% to 60%, multifunctional worker rates rose from 75% to 83%, and motion waste decreased by nearly 50%, with line balancing and simulation techniques contributing to these improvements.

The Agile DMAIC cycle, which combines process mining and multi-criteria decision methods, enhances the agility and reliability of Six Sigma projects, resulting in better data acquisition and more accurate indicator determination [51]. The developed Integrated Manufacturing Business Excellence System framework by Paranitharan et al. [54], which incorporates Lean, Agile, and other management concepts, has driven manufacturing excellence, particularly in developing countries like India, where quality manufacturing environments are lacking. DMAIC's extension to additive manufacturing has shown the potential to enhance quality and sustainability, although customization remains necessary for broader applications [55], [56]. Applying Agile methodologies, such as Scrum, backlogs (a Prioritized list of tasks awaiting completion in a project), and Sprints, has provided the necessary flexibility to manage changing requirements, demonstrating its utility as a foundation for such initiatives [57].

2.5 Research Gap and Problem Identification

When reviewing the literature on Scopus, we found only a few papers that focus on the micro downtime problem. The reviewed studies collectively address the significant challenge of micro downtimes in manufacturing processes and propose several strategies for mitigation. The study by Ingaldi and Knop [10] emphasized the importance of machine component condition, operator training, and maintenance organization, proposing TPM and component modernization to reduce micro downtimes. Zennaro et al. [8] introduced a new micro downtime data collection and statistical analysis method, developing a Cost Performance Indicator (CPI) and a simulation model to enhance automated flow line efficiency. Another study utilized Discrete Event Simulation (DES) to optimize beer packaging systems, demonstrating productivity improvements through reduced micro-downtimes [11]. Previous studies explored buffer design in production lines, highlighting the

Table 1. DMAIC cycle

Step	Explanation
Define	The initial phase of this methodology involves comprehending and delineating the problem that demands resolution. The define stage purpose articulates the potential problem in a way that suits all stakeholders, from the CEO to the operator. Tools such as Pareto analysis and surveys have also been used, since they highlight critical issues that require attention.
Measure	After identifying the problem, the subsequent step involves gathering data, including metrics such as time, costs, units, and defects. The goal is to obtain quantitative values that enable the company to assess whether the implementation effectively addresses the identified issues.
Analyze	During this phase, the emphasis lies on identifying the root causes of the primary issues through the analysis of the collected data. The aim is to prioritize the most critical challenges and formulate an actionable response plan.
Improve	After concluding the analysis phase, it's essential to enumerate the root causes of the issues and develop a plan outlining potential solutions. Quantitative analysis should be carried out during this phase to assess the cost-effectiveness of prospective tools designed to solve the identified problems.
Control	Once the implementations are ended, Lean aims to sustain the achieved results in a solid way over time for the organization. Hence, it is vital for managers and operators to undergo training to identify and replicate project opportunities, fostering a culture of continuous improvement. The long-term success of Lean depends on the effectiveness of the control phase.

Buffer Design for Availability (BDFA) paradigm and the strategic role of intermediate buffers in maintaining system reliability and enhancing OEE [12], [13]. Collectively, these research underlined the critical role of advanced simulation, effective maintenance strategies, and optimized buffer capacity in mitigating micro downtimes and improving overall manufacturing efficiency.

Despite some studies addressing methods for diagnosing and solving micro downtimes, a research gap remains. Specifically, there is a lack of comprehensive frameworks to improve OEE and guide the reduction of micro downtimes in bottleneck processes. Current research primarily focuses on individual strategies or diagnostic methods rather than providing an integrated approach to tackle these inefficiencies holistically. This study aims to fill this gap by proposing a new Lean-based framework incorporating Agile and DMAIC concepts.

While DMAIC is well-documented for driving significant performance improvements in organizations, there remains potential for further enhancement [58]. One of the method's main limitations is its generality, which restricts its methodological support and does not fully leverage task-domain-specific knowledge. Adaptations tailored to specific domains partially resolve these shortcomings [59].

One of DMAIC's key advantages lies in its robust statistical techniques for uncovering facts and empirically validating concepts, as well as its stage model, which functions as a tool for organizing and solving problems [59]. Wheeler [60] suggested that one of DMAIC's main limitations is that it may fail to develop the process's full potential. Arguably, due to the linearity and rigid nature of DMAIC, which requires an improvement team to move through explicitly defined stages and carry out specific activities in every one of the phases, this may occur with a significant number of improvement projects guided by this approach [61]. Previous studies claimed that the DMAIC framework does not consider the sustainability of its implementation results, a core principle of the Lean approach [62], [63]. Pinedo-Cuenca et al. [64] pointed out that projects often suffer because project teams rush to finish them and, as a result, do not ensure sustainability. Most frameworks lack professionals or consultants, so a strict framework is needed to validate the project's benefits [65].

Considering the DMAIC framework's limitations discussed, integrating it into the Agile methodology could be a solution to increase its effectiveness. Although DMAIC offers a structured, data-driven approach to problem-solving strategies, sometimes it can be too inflexible and slow to adapt to fast-changing conditions. In contrast, Agile's dynamic and iterative approach can directly address the rigidity and linearity of DMAIC, providing a more flexible and responsive improvement process.

Agile's focus on continuous improvement and iterative feedback loops can ensure the sustainability of process improvements, addressing issues raised by authors [62] and [64]. Furthermore, Agile's emphasis on domain-specific knowledge and team collaboration can overcome the generality of DMAIC by providing more personalized methodological support and increasing the accuracy and reliability of process improvements. Thus, a combined framework may better handle rapid changes and unexpected variations in production processes, unlocking the full potential of DMAIC and making it more suited for complex and dynamic environments.

In sequence, the research methodology employed in this study will be presented.

3. Research Methodology

This study combines theoretical analysis and industrial practices to reach the proposed research objectives. This approach involves iterative exploration and collaboration between researchers and practitioners to address practical organizational problems [9] and develop the proposed framework [66]. This research consists of two phases: phase 1 focuses on developing the proposed framework, while phase 2 aims to understand how the framework performs in a real-case scenario.

In phase 1, the framework development begins with a comprehensive literature review on the subject and related methodologies to guide the framework design. The DMAIC cycle is integrated with Agile methodology to develop the proposed framework, which includes defining the scope, objectives, and key performance indicators (KPIs) and selecting appropriate tools from Lean, Agile, and Total Productive Maintenance (TPM) methodologies, as clarified in Table 2. This phase also involves identifying and selecting tools and techniques from these methodologies utilized within the framework.

Once the products or project objectives become defined in the Measure phase, the Analyze-Improve-Control (AIC) loop operates as an Agile management system, with sprints, backlog updates, and a focus on design, testing, and validation. This iterative process leads to incremental improvements in the project's key performance indicators (KPIs). To make the

Table 2. The methodologies' synergy

Step	Explanation
Project Structure	The choice to adopt a traditional methodology, such as DMAIC, is based on its well-defined steps, which facilitate comprehension, especially for stakeholders who are not directly involved in the project. Furthermore, DMAIC is widely applied in industry, as evidenced in the works of [51], [54], and [55]. The decision to adopt a traditional methodology, such as DMAIC, is based on its well-defined stages, which make it easier to understand, especially for stakeholders not directly involved in the project. Furthermore, DMAIC is widely applied in the industry, as evidenced in the research of [51], [54] and [55].
Define	The decision to use the traditional method in the Define phase is driven by the importance of understanding the problem thoroughly, outlining the scope, and gathering the perspectives of all relevant stakeholders. This is a fundamental factor for the project's success, as demonstrated in the research of [52] and [53].
Measure	We maintain the traditional approach in the Measure phase to ensure robust data collection, which will serve as the foundation for further analysis [59]. This phase is essential not only for gathering data but also to establish the first direction for solving the problem [56]. In the proposed framework, this is the phase where the methodologies begin to show synergy. The Measure phase is where the backlog and product functions for the project are defined and placed on the backlog, incorporating Agile terms and concepts.
Analyze, Improve, and Control	In the Analyze phase, we integrate Agile methodology, emphasizing incremental deliverables and continuous product improvement. To align this with the DMAIC methodology, we propose a "continuous loop" that combines the Analyze, Improve, and Control phases. This loop incorporates the Agile concept of small, iterative deliveries and gradual improvements in the project's results, which involves daily meetings by having the project leader as Scrum Master.

process replicable, we suggest organizing the sprints according to the CTA structure, emphasizing analysis, improvement, and control at each stage. Figure 2 provides details relating to the technical aspects of each stage.

Phase 2 focuses on implementing and evaluating the framework in a real-case scenario, involving collaboration between academic researchers from a federal university in Brazil and practitioners from a multinational tire company. The process includes conducting training sessions to familiarize the company's staff with the proposed framework and selected tools, collecting baseline data on micro downtimes and other relevant KPIs using the OEE metric, and applying the framework iteratively.

Tools such as the 5-Whys analysis, root cause analysis, A3, and continuous improvement techniques are used. We monitored the implementation process, made adjustments as necessary, and evaluated the framework's performance by comparing pre- and post-implementation data on micro-stoppages and other KPIs.

4. Results

This section presents the proposed framework and the main results of its application in a real-case study.

4.1 Proposed DMAIC framework

Agile concepts have been incorporated into the classical DMAIC cycle to diagnose problems and suggest solutions earlier. The developed framework is composed of three major phases: (i) Define, (ii) Measure and (iii) Analyze, Improve, and Control. Figure 2 shows the phases of the proposed DMAIC-Agile framework in detail. The figure presents the "Traditional DMAIC" path and the proposed Agile path with its characteristics.

In the Define phase (i), a comprehensive description of the project's scope outlined its objectives, deliverables, and expected results. Key members are selected based on expertise and experience, ensuring a diverse skill set conducive to project success.

Concurrently, the parameters and constraints of the project are delineated, providing a structure for subsequent activities. Thus, has been developed a detailed schedule to allocate resources effectively and set clear milestones to guide the project's progression.

In the Measure phase (ii), measuring standards and reliable sources of information are established. This phase provides the basis for informed decision-making and establishes the foundations for accurate data collection and analysis. Additionally, we create follow-up reports, which facilitate continuous improvement initiatives. Furthermore, standards for visual representation of processes are defined, provid-

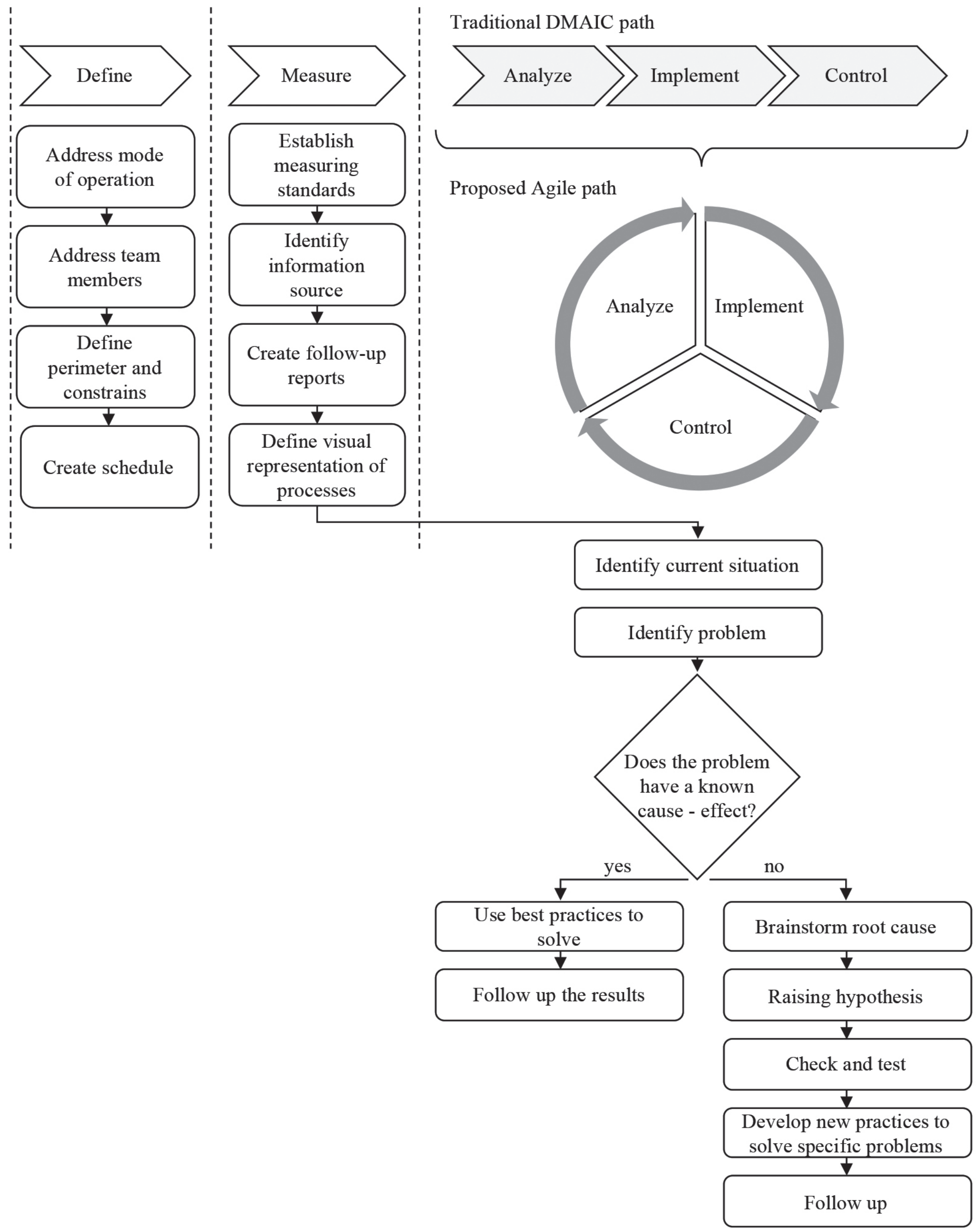

Figure 2. Proposed DMAIC-Agile framework illustrating the integration of Agile concepts to enhance adaptability, real-time analysis, and iterative problem-solving within the DMAIC cycle

ing stakeholders with clear insights into the project's progress and performance metrics.

Finally, in the Analyze, Implement, and Control phase (iii), Agile methodologies are integrated with the classical DMAIC cycle, increasing adaptability and faster response capabilities. This phase encompasses a dynamic approach to problem-solving, where iterative cycles of analysis, experimentation, and implementation drive changes.

By harnessing the principles of agility, the project team has been empowered to swiftly adapt to evolving circumstances and capitalize on emerging opportunities, thereby enhancing the overall efficacy and resilience of the improvement process.

Adopting Agile concepts in the Analysis, Implementation, and Control phase aims to make the process more dynamic by shortening the cycles. This allows each stage to be analyzed and verified in real time rather than waiting until the project's completion. Figure 2 depicts this concept.

The proposed framework allows the improvement team to take initiatives based on real-time data concerning production processes. Therefore, after identifying the current situation and the problem, the team must check whether a clear cause-effect correlation exists. If so, established best practices—those already implemented with known gains—can be adopted. Otherwise, the improvement team may need to develop new practices to address a novel problem.

Therefore, the process involves holding brainstorming sessions, formulating and testing hypotheses, and developing new practices (or actions) to solve these problems. By introducing the concepts of the Agile method, this process can be carried out using short improvement cycles.

The following section will present the application of the proposed framework in a real-case scenario.

4.2 Using the proposed framework to reduce micro downtimes

An improvement team comprising researchers and practitioners used the proposed framework to identify root causes and develop actions to improve a specific process of the OEE index in a Brazilian tire company.

4.2.1 Define Phase

Meetings involving management and the operational team have been set up to define the focus of the research. We collected data from a specific process in the tire assembly area, where the machines manufacture both the tire frame and its top section, which are later merged into a unified product using heat in another field. The assembly department consists of eight machines. Each machine underwent analysis, and their micro downtimes were measured. Figure 3 illustrates the micro downtimes for each machine.

Similar to the challenges discussed by [8], [67], [68] regarding distinguishing between cycles with degraded speed and micro downtimes, our study encountered a similar issue. To address this, we conducted a deeper analysis and established two criteria for selecting a machine: (i) a consistent cycle and (ii) the presence of micro downtimes. This approach aimed to improve the company's performance by targeting priority issues rather than only addressing common errors. As a result, machine #8, with micro downtimes of 8,83%, was chosen for intervention, deviating from the traditional method of selection based solely on Pareto chart analysis.

Machine #8 comprises seven operating stations (designated FS1, FS2, ... FS7). We examined each station and measured the inactivity. Focus has been placed on stations FS4 and FS2, which had total micro downtimes of 1.73% and 1.53%, respectively. The improvement team aimed to reduce the micro downtime on this machine by 0.5%, which could save the company USD 230,000 annually if applied across all eight machines in the process. A four-month timeline has been set for the project's conclusion.

4.2.2 Measure Phase

The second phase involved gathering data and ensuring its reliability and accuracy. Previously, there wasn't a robust system for managing micro downtimes or detailed follow-up methods. Therefore, the most important outcome of this phase was creating a performance panel to monitor and control these shutdowns, along with measures to ensure data accuracy. It's worth noting that the data presented in sequence underwent adjustments due to industrial secrecy, but their accuracy and relevance remained intact.

To manage micro downtimes effectively, the team brainstormed and identified key monitoring needs, including tooling, product type, machine, and process stages. The entire bandage assembly process takes approximately 2.94 minutes, with the extended station, which acts as a bottleneck, requiring about 30 seconds. That restricts production to two bandages

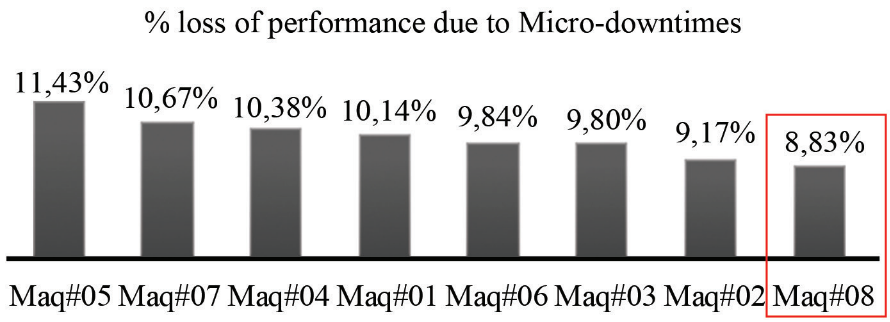

Figure 3. Micro downtimes for each assembly machine, highlighting machine #8 as the focus for intervention due to its consistent cycle and significant presence of micro downtimes (8.83%)

per minute. Due to the subtle and often unnoticed nature of micro downtimes, precise management is crucial. Consequently, data collection depends on the machine automation system, which provides stoppage information, alerts, and speed irregularities to the performance management system.

Settings on the machine's automation program have been made to ensure the necessary information to the improvement team. Thus, to handle the extensive data and numerous data points, we applied Microsoft Power BI, which led to the development of the visual tool that incorporates all identified needs from the initial brainstorming session, as shown in Figure 4.

The developed tool allows to view in real-time: (1) machines with the highest stoppage rate, (2) information from different dates, (3) process stage distribution, (4) the number of stops categorized by product type, (5) proportional representation based on tooling usage, (6) trends displayed through daily charts over time, (7) catalog of failures and their representation at the machine automation level, (8) ongoing and future support, including a list of potential causes and solutions for investigated micro downtimes.

4.2.3 Analyze, Implement and Control phase

During this phase, we employed the Agile methodology and the DMAIC cycle. This approach involved executing the Analyze, Implement, and Control steps iteratively rather than in a linear sequence where all stations must complete the Analyze phase before progressing to the subsequent steps. By operating in cycles and with daily sprint meetings, it is possible to establish standards and quickly implement actions that produce immediate results in the project. This cyclical approach also facilitated effective workload distribution among the project team, allowing the Analyze phase of the second cycle to start while the first cycle was still in the Control phase. The combination of these strategies reduced the initial project timeline by three weeks.

Following this, two cycles of improvements are displayed.

4.2.4 First Cycle

This cycle focused on resolving and enhancing the FS4 process, the one identified as having the highest frequency of micro downtimes in the plant. Therefore, the A3 methodology was employed to lead the problem-solving process.

After collecting data and thoroughly understanding the current situation, the team conducted an Ishikawa Diagram to identify potential root causes of the issues within the FS4 process. By aligning the Ishikawa Diagram with the Pareto analysis of causes, the team categorized the issues into three main areas for treatment: (i) Method/Labor – adjustments and corrections performed by operators; (ii) Material – various forces and

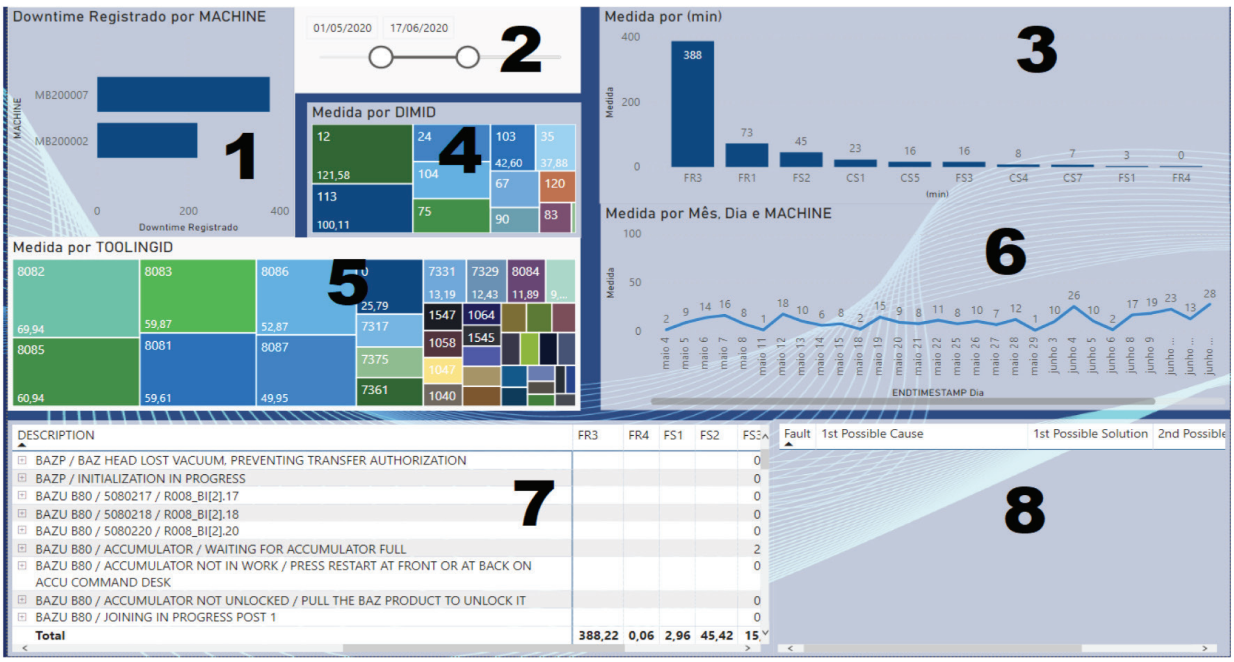

Figure 4. Visual tool developed for monitoring tire production, displaying real-time data on stoppage rates, process stages, product types, tooling use, failure trends, and potential solutions to address micro downtimes effectively

tensions experienced by the product during processing; and (iii) Machine – precision issues and problems with the cutting block accumulator.

Upon examining the method/labor aspect, the team concluded that it was a consequence rather than the root cause, as the differences in reactivity have been noticed since the problem occurred. From the material perspective, a study on plastic deformation during product manufacturing revealed that the product's weight, when wound onto the bobbin, caused crushing. Thus, this led to a loss of rubber elasticity, making it necessary to address the issue immediately in a palliative way while a long-term solution remains to be defined.

To solve the machine-related problems with the cutting block and accumulator, our team used the 5 Whys methodology to identify the root cause. This analysis revealed that seam variation was due to insufficient heat treatment on the cutting blade. After replacing the blade and applying the correct heat treatment, the variation in the seam decreased significantly. Thus, this confirmed that inadequate heat treatment was the root cause of the problem. Consequently, micro downtimes reduced from 1.73% to 0.73% per day, leading to a 1% increase in daily production time.

4.2.5 Second Cycle

While the implementation phase of the previous cycle was ongoing, the analysis phase of the second cycle began concurrently. During this cycle, actions were implemented, and results were monitored and controlled. The second process examined was the FS2 station, chosen for its high potential for replication across other machines.

The issues within this station were classified as complex, indicating that the root cause was not immediately apparent to everyone. Therefore, the improvement team conducted several brainstorming sessions to generate hypotheses for potential micro downtimes in the station. We found that multiple factors contributed to the machine's resulting micro downtime.

The hypotheses have been tested, and their effectiveness evaluated during the daily meetings, highlighting the importance of continuous monitoring and the systematic identification of cause-and-effect relationships. In one specific Sprint, we identified that machine vibrations during data collection were the root cause of misreadings, which emerged as a key source of waste. To resolve the problem, we relocated the sensor and installed a stabilizing support to absorb the vibrations, improving the accuracy of the readings. Consequently, micro downtimes reduced from 1.53% to 0.93% per day, leading to a 0.6% increase in daily production time.

4.2.6 Main results

In the first cycle, insufficient heat treatment on the cutting blade has been identified as the primary source of issues. Implementing the correct heat treatment reduced micro downtimes by 1%. In the second cycle, the team found that an incorrectly activated switch was the root cause of micro downtimes. Correcting this issue, we reduced micro downtimes by 0.6%. In summary, after improvements, total micro downtimes in machine #8 have been reduced from 8.83% to 7.20%. Figure 5 shows these results.

5. Discussion

The current research was conducted in a tire company in Brazil, but our findings may be applied to other sectors. Thus, this research offers significant contributions to both researchers and practitioners in the field of industrial operations and process improvement.

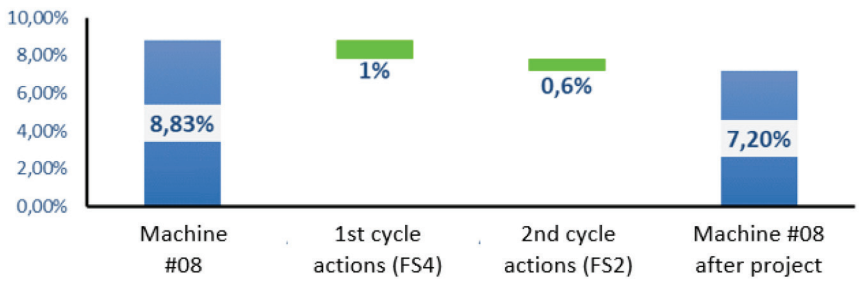

Figure 5. Final results of implemented improvements, highlighting a reduction in micro downtimes on machine #8 from 8.83% to 7.20% through actions addressing heat treatment and switch activation issues

Our literature review revealed only a few studies focusing specifically on micro downtimes. These studies mainly addressed diagnosing downtimes [8], using DES to optimize production systems [11], implementing TPM concepts [10], [69], and focusing on buffer design to enhance OEE [13], [12]. While these works propose valuable methods for addressing micro downtimes, they are more likely to concentrate on isolated aspects of the issue, leaving a gap in holistically addressing these inefficiencies [70]. Our study addresses this gap by introducing a Lean-based framework that integrates Agile and DMAIC principles, providing a more comprehensive and robust approach to resolving micro downtimes.

Regarding the DMAIC methodology, it was possible to identify certain limitations within the framework. Notably, it lacks adaptability to task-domain-specific knowledge and tends toward linearity and rigidity, as stated by [59]. It also fails to develop the full potential of processes [60], struggles with its linear nature [61], and does not adequately ensure the sustainability of improvements [62], [63]. This study proposes an innovative solution by integrating Agile methodologies into DMAIC to address these shortcomings and provide a more dynamic and responsive improvement process. By integrating the structured problem-solving framework of DMAIC with the iterative and collaborative nature of Agile, organizations can significantly improve their ability to address challenges and adapt more efficiently to changes in production processes. In addition, Agile's focus on continuous improvement and adaptability aligns with Lean principles, ensuring that process improvements are not only effective, but also sustainable in the long term.

5.1 Theoretical contribution

This research offers valuable insights by demonstrating the efficacy of integrating Lean, Agile, and DMAIC methodologies in real-world industrial settings for researchers. By applying a practical, field-based approach, the study presents a systematic framework for developing and implementing improvement strategies, thus expanding the methodological toolkit available to researchers studying process optimization. This approach creates opportunities for further research into hybrid methodologies, advancing theoretical understanding in the industrial engineering and operations management field.

Moreover, integrating Agile principles into the DMAIC cycle represents a theoretical advancement, enriching the discussion on process improvement strategies. Researchers can apply the proposed framework in various industrial contexts, investigating its effectiveness in addressing operational challenges and enhancing organizational performance.

5.2 Practical implications

For practitioners, the proposed hybrid framework can enhance operational efficiency and productivity in different industries by successfully reducing micro downtimes, minimizing production losses, optimizing resource utilization, and improving OEE, which results in measurable cost savings and increased competitiveness. Incorporating Agile principles into the DMAIC cycle offers practitioners a more flexible, systematic, and iterative approach to process improvement. This agility allows quick adaptation to changing production environments, identification of emerging issues, and timely implementation of solutions, fostering continuous improvement and innovation.

While the study has been conducted in a large multinational company, we believe that the proposed framework can be adapted and used by small and medium-sized industries in different segments. Given its modular, it's also possible to customize the proposed framework according to the industrial scenario or could be used in the manufacturing processes of other kinds of organizations. In the context of Industry 4.0, incorporating AI, machine learning, and big data analytics allows for predictive identification of micro downtimes, creating a proactive continuous improvement system. Tools like Microsoft Power BI can be scaled for real-time monitoring, improving OEE and decision-making.

6. Conclusion

This empirical research identified challenges and solutions for addressing micro downtimes, which were previously unrecognized due to the lack of a control and management system. The proposed framework proved effective in tackling OEE issues of this nature. Despite relying on empirical knowledge for hypotheses and potential causes, this study clarified the topic, established a management approach, and successfully reduced the overall downtime rate. In addition, the intelligent alerts application has transformed the report into an active tool, enhancing its effectiveness.

The hybrid approach introduced considerable agility to the project execution, enabling the delivery of a complex project three weeks ahead of the original deadline in a company that typically experiences delays between two and three months for projects of similar complexity. This achievement was made possible by the implementation of Agile methodologies, which represented a significant shift from the company's traditional practices. The remarkable improvement results achieved throughout the project were decisive for keeping the human resources available until completion.

The results surpassed the initial objective threefold, reducing micro downtimes by 1.6% instead of the targeted 0.5%, even amid the challenges posed by the COVID-19 pandemic. This reduction represents an annual savings of around 750,000 USD for the company and should increase annual production capacity by 76,000 units per year.

The study's scientific contribution to the operations and process management field demonstrates the empirical validation of the proposed framework in a realistic context. By quantitatively assessing the impact of micro downtime reduction and showcasing a systematic approach to process enhancement, this research provides valuable insights and a replicable model for other industries facing similar challenges.

Looking forward, introducing machine learning to identify potential problems seems appropriate for future developments, in line with emerging topics such as Industry 4.0 or Industry 5.0, as standards have been established and recognized.

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