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Optimization of Mold Changeover Times in the Automotive Injection Industry Using Lean Manufacturing Tools and Fuzzy Logic to Enhance Production Line Balancing †

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Abstract

The main thrust of the study is the need to cut down the time taken for mold changes in plastic injection molding which is fundamental to the productivity and efficiency of the process. The research encompasses Lean Manufacturing, DMAIC, and SMED which are improved using fuzzy logic and AI for rapid changeover optimization on the NEGRI BOSSI 650 machine. A decrease in downtime by 65% and an improvement in the Process Cycle Efficiency by 46.8% followed the identification of bottlenecks, externalizing tasks, and streamlining workflows. AI-driven analysis could make on-the-fly adjustments, which would ensure that resources are better allocated, and thus sustainable performance is maintained. The findings highlight how integrating Lean methods with advanced technologies enhances operational agility and competitiveness, offering a scalable model for continuous improvement in industrial settings.

Keywords: fuzzy logic; line balancing; LSS approach; operational efficiency (PCE); mold injection

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1. Introduction

Manufacturers these days are focused on operational effectiveness to ensure competitiveness and continued profitability [1]. For example, in the case of injection-molded plastics, primarily in the automotive industry, frequent mold changeovers may pause operations and result in downtime that hampers productivity [2].

Hence, considerable emphasis must be given to deriving better mechanisms for reducing changeover times. The study gives practical consideration for the improvement of mold changeovers from the point of view of SMED in a Lean Manufacturing context. By employing the DMAIC process, it delineates various sources of waste and improves operations [3,4]. The introduction of fuzzy logic attends to uncertainties, thereby enabling quicker and smarter operational decisions on the shop floor [5].

The proposed methodology makes use of Value Stream Mapping (VSM), time-motion assessments, and statistical techniques to locate constrictions in the production flow and implement specific corrective actions [6]. It shortens changeover times and improves Process Cycle Efficiency (PCE) through the shifting of certain internal activities to external ones and the implementation of standardized procedures [7].

Besides them, the incorporation of fuzzy logic allows online tasks to reshape in jobs and subsequent reallocation of resources so that quite an adaptable and resilient manufacturing system continues in being. The findings presented in this publication illustrate the synergistic positives of combining Lean Manufacturing methods together with fuzzy logic, thereby reducing Manufacturing Cycle Time (MCT), improving line balancing and providing operational improvements in the long term. This forward-looking combination shows the significance of intelligent systems in modernizing the world of production, laying the foundation for enhanced and more robust manufacturing processes [8].

2. Material and Method

This research was based upon the fundamentals of DMAIC to reduce the Manufacturing Cycle Time (MCT) in plastic injection molding operations within a Lean Six Sigma framework. Because of its effectiveness in operational excellence, DMAIC has been inherently recognized as a very structured sequence because it aims to eliminate the bottleneck and remove non-value-added activities [9].

The Define phase explains the objectives of the project. The focus is to minimize the length of MCT, thereby increasing production output and operational flexibility in the molding activities, with offset factors established such as setup time and machine preparation. The Measure phase is the essence of analysis, where procedures and methods of measuring the baseline data depict the duration of plate changes and machine idle times, spurring down into detailed steps such as time-motion analysis to expose the process inefficiencies [10,11].

In the Analyze phase, the use of diagnostic tools such as Ishikawa (Fishbone) diagrams and value stream mapping is applied to identify the variables that are responsible for the lengthy changeover time. Prior research indicates that these methods are very effective in revealing inefficiencies with respect to tooling setups and production scheduling that usually cause delays during transitions. Tackling these root causes is what is most important because they directly impact production output and total capacity [12].

The Improve phase involves the implementation of corrective actions to systematically address the causes identified. Prior studies have indicated that incorporating Lean practices into the DMAIC methodology will streamline workflow and support line balancing, reduce interruptions, and increase productive time available [13]. The final Control phase consists of sustaining the improvements by ensuring that specific processes are rationalized and by establishing ongoing monitoring of performance, with artificial intelligence and fuzzy logic techniques (Figure 1) in support of maintaining process stability [8].

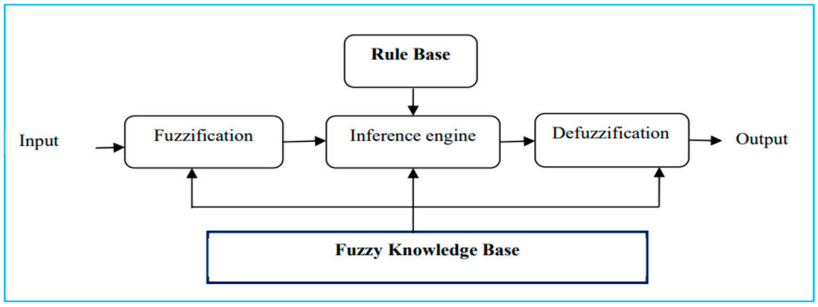


Figure 1. Fuzzy inference process.

3. Results and Discussion

3.1. Implementation of Lean Tools in the Mold Change Process

After Lean techniques have been introduced, the improvement phase will focus on mold changeover time reduction and process inefficiencies. Core methodologies, including SMED and 5S systems, were deployed to achieve considerable reductions in changeover times and to enforce general operational efficiency [3,14].

3.2. Implementation of SMED

After an elaborate study of the mold changeover process through time measurement and process flow evaluations, the SMED (Single-Minute Exchange of Die) technique was devised in an attempt to classify tasks into two categories: value-added and non-value-added. Non-value-adding steps especially those causing delay or causing waste of resources were identified for elimination. Value-adding tasks, in turn, were subdivided into internal (those carried out while the machine is down) and external (those carried out while the machine is running). The plan was to minimize internal activities, converting as many as practicable into external activities while lowering downtime and eliminating wasted time [15].

Specialist training was accorded to the equipment operators in order to empower them on the optimal procedures of carrying out mold changeovers and minimizing production operations. Each stage of the changeover process was then documented painstakingly into standard operating procedures so as to ensure uniformity of performance while minimizing variations. Workforce development was further boosted by Total Productive Maintenance, a set of skills that provides operators with knowledge on preventive and corrective maintenance which paves the way to reduced equipment downtime and consistent production flow.

3.3. Implementation of the 5S Methodology

The 5S methodology was applied in this study to address recurring machine stoppages and disorganized work areas that contributed to operational inefficiencies [16].

3.4. Improved VSM for Mold Change Operations

After implementing Lean tools, there were tremendous improvements in the value stream mapping (VSM) of the molding change process. It led to an increase in value-added time with a proportionate decrease in non-value-added time: a reduction of 86.72% of the latter. The updated VSM is shown in Figure 2.

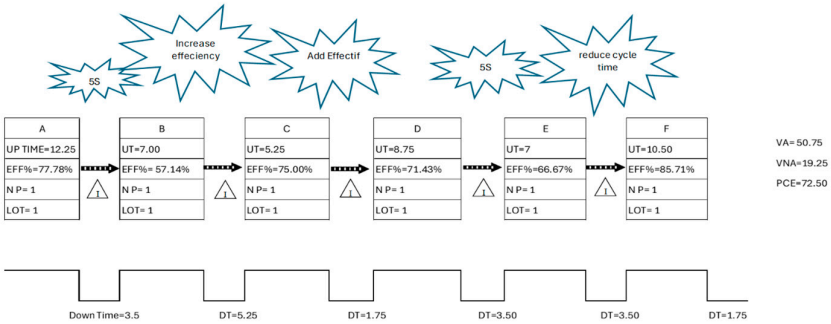


Figure 2. Improved value stream of the assembly operation.

The significant reduction in non-value-added time allowed for a more productive and efficient mold change process. Furthermore, a reduction of nearly 40% in human operators replaced by robotic systems will aid speed, precision, and consistency, to reduce cycle time and improve defects.

3.5. Future PCE of the Mold Change Process

Following the adoption of purposes Lean, the Process Cycle Efficiency (PCE) relating to mold changes was not only above the 25% minimum set by the industry at 27.50% and 72.50% after that but also was increased by 45.5% [17]. It is interesting to note that this had a positive effect on the PCE of 46.8% by resolving non-value-adding chores and optimizing resources. Furthermore, there has been an extraordinary reduction in lead time, with the lead time cut by 27.9% from the measured baseline. Another example of the successful utilization of Lean tools is the combination of the process time frame reduction and the operational efficiency increase [18].

The control phase is aimed at sustaining performance improvement continuity to check quality by regularly measuring system output against predefined benchmarks. This phase carried out some effective monitoring to keep track of performance and quickly reveal deviations from set standards. Control actions were taken to safeguard the improvements, including instituting a Standardized Work Plan (SWP), which was prepared for formal procedures, especially for mold assembly and components integration activities.

In addition, there was an established structured document review process under the compliance team's handling so as to guarantee traceability and back continuous improvement of operational practices. There were also routine trainings and refresher sessions organized for operators on continuous improvement techniques such as 5S and SMED so as to inculcate these concepts into daily work.

Process stability was reiterated by means of control charts of variations recorded in mold changeover durations with a view to ensuring appropriate fluctuation ranges. All these efforts add to the successful integration of Lean Six Sigma tools with an end result of successive reductions in changeover times and improved process reliability [9,10,19].

3.6. Estimated Cost–Benefit Analysis of the Fuzzy Logic-Enhanced SMED Method

In addition to performing the technical assessment, a cost–benefit assessment was completed to identify whether the proposed SMED method augmented with fuzzy logic is financially viable. The assessment identifies and quantifies the investments needed and the economic benefits yield from the method. With respect to costs, four groups of costs were approximate. First, operator training in Lean and SMED tools, which is needed so that the workforce can carry out the new routines in a productive manner, was approximated at EUR 5000 (Table 1). Second, the development and incorporation of a fuzzy logic decision-support system, which is one of the key innovations to the study, was well analyzed and thought to cost EUR 8000. This accounts for the time consultants charge to develop the algorithms and rule bases and integrate the system for real-time monitoring. Third, costs associated with standardization efforts such as developing standard operating procedures and 5S implementation are approximated to be EUR 3000. Fourth, partial automation of mold handling using robotic systems to replace nearly 40% of the manual labor was thought to be EUR 20,000.

There were three sources of annual savings listed as benefits. The time for changing over from one mold to another was reduced significantly; the survey reported the changeover time was reduced by 65% in this project. This increased equipment availability translates into a productivity gain in the estimated value of EUR 18,000 per year. Secondly, non-value-added actions were reduced by an estimated 71.9% and have lessened inefficiency valued at roughly EUR 12,000 annually. Finally, the Process Cycle Efficiency (PCE) increased overall from 27.5% to 72.5%, indicating the resource driving PCE improved, along with improved workflow, equating to a heartwarming estimated value of EUR 10,000 annually. In total, the total initial investment of EUR 36,000 is fully supported by nearly EUR 40,000 in returns annually. This indicates less than a 12-month payback

period or 111% return on investment (ROI). Therefore, these numbers support the proposed approach economically. Furthermore, while the financial returns can be quantified, the method itself provides intangible, but strategic benefits in process stability, decision making under uncertainty, and improved responsiveness to variation mix-ups in production. These benefits positively work towards further developing a more resilient, intelligent manufacturing environment—aligned with Industry 4.0 specifically.

Table 1. Estimated cost–benefit analysis.

Item	Estimated Costs (EUR)	Estimated Benefits (EUR/Year)	Comments
Operator training on Lean/SMED tools	5000	-	One-time cost for upskilling operators on standard procedures
Development of fuzzy logic decision-system	8000	-	Design and implementation of fuzzy inference for real-time changeover guidance
Standardization (5S, SOP documentation)	3000	-	Creating standardized work instructions for consistency
Partial automation (robotic replacement)	20,000	-	Approximately 40% of manual tasks replaced by robotic systems
Reduced mold changeover time	-	18,000	Increased machine availability boosts productivity
Reduction of non-value-added time	-	12,000	Less waiting, unnecessary movements, and manual errors
Process Cycle Efficiency (PCE improvement)	-	10,000	Better use of time and resources throughout the production cycle
Total	36,000	40,000	Break-even in less than one year (ROI = 111%)

3.7. Standardization and Continuous Optimization with Fuzzy Logic

During the Improve phase, what was put into place must be standardized and continuously monitored to stabilize improvements. Traditional monitoring mechanisms usually make use of fixed threshold limits, which can overlook variations in the molding changeover processes in progress. In mitigation of said limitation, a fuzzy logic-based SMED model was incorporated, which allowed a more flexible and intelligent way of making decisions and was better matched to dynamic production environment changes [20].

3.8. Implementation of the Fuzzy SMED Model

With the help of the fuzzy logic system, such things as mold changeover durations for a decision are considered, and in this way, based on some issues that deal with the parts, such as the following:

- **The size of the mold** (small, medium, large);
- **The hand of the robot** (completely adapted, partially adapted);
- **The complexity of the mold** (simple, complex).

At the start of the membership, all the inputs should be presented as the monotonous function of system membership functions which allows smooth transitions between categories instead of crisp boundaries. The system through these inputs will evaluate fuzzy rules that allocate the anticipated changeover time to one of the three ranges: short, medium, or long. Thus, it serves as an operational decision-support tool, the trueness of which is borne out by ways to simplify the tool necessary for mold-changeover durations to reduce.

3.9. Fuzzy-Based Decision Support for SMED

The fuzzy inference rule base development that needs to be carried out is both discussing expert insights and historical production data.

- When the mold is still small, the robotic hand is fully optimized, and the mold design is quite straightforward, the changeover time can be expected to be short.
- However, if the mold is large, the robot hand will adapt poorly, and the design is complex, the changeover time is more likely to be long.
- In other words, a situation that lies between these extremes aims for assessments that do not dictate strict and rigid categorical groupings but rely on flexible approaches.

This adaptive system makes sure that the different states' defining errors in real production environments are accounted for during the standardization phase, which results in more exact changeover time forecasts as well as better responsiveness to the process variations.

3.10. Control System Integration

These are some of the key actions taken in an ordered manner in the execution of fuzzy control systems:

- Real-time assessment, based on fuzzy logic, of mold changeover durations gives the chance to identify deviations in their initial stage of development which then may develop into production bottlenecks
- Integration with monitoring systems (for instance, Qi Macros in Excel) to impart visual tracking results in live mode of mold change-over performance.
- Support in decision-making for the operator, by providing advice that would lead to the right settings of related variables before any issues start to progress or even before they emerge and cause the delay.

3.11. Benefits of the Fuzzy SMED Model

The addition of fuzzy logic in the Control phase provides several benefits: Adaptive Decision Making—Performance of the changeover is measured automatically on a real time basis instead of performing against fixed-time targets, enabling decisions to be made based on continuous changes in process conditions.

- **Real-time monitoring:** The system facilitates the identification of inefficiencies and helps to take corrective actions in time so there is no future disruption.
- **Sustainable changes:** By consistently characterizing changeover activities, we can analyze the root reasons for inefficiency and address them swiftly.

The Control phase combines fuzzy logic with SMED to hold improvements in place, while continuously adjusting them based on real-time process data from the factory. This philosophy intellectualizes decision making, reduces variability in operation, and assists in executing the mold changeover process to a sustained level of efficiency.

3.12. Interpretation of Results

The fuzzy logic membership curves depicted in Figure 3 provide a detailed representation of how the system processes input and output variables to support decision-making, as well as the distribution of input variables, where mold size is classified into small, medium, and large; robot hand adaptation is categorized as either adapted or unsuitable; and mold complexity is defined as either simple or complex. These membership functions facilitate smooth transitions between categories, accommodating the inherent uncertainties and variations often encountered in manufacturing environments.

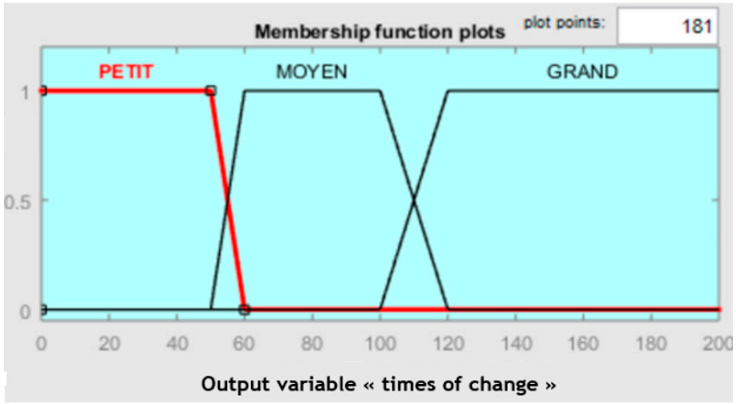


Figure 3. Output variable "time change".

Figure 4, in contrast, displays the output variable representing changeover time, segmented into short, medium, and long durations. By combining these input variables with fuzzy inference rules, the system can generate flexible and adaptive changeover time predictions. This enhances the accuracy of setup time estimation and contributes to improving process flow efficiency.

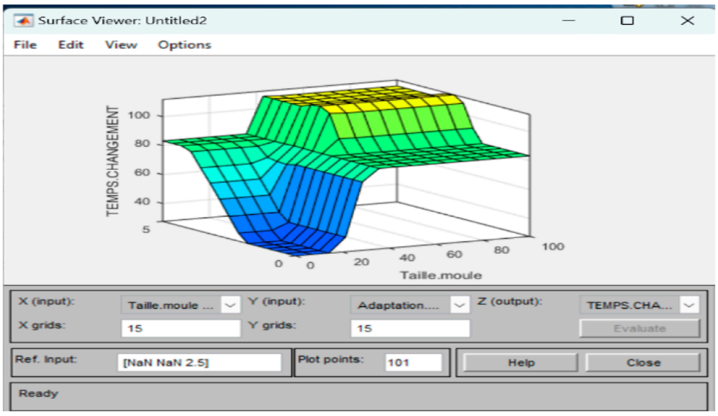


Figure 4. Surface visualization of mold size, adaptation size, and changeover time.

Figures 4–6 provide a clear visual representation of how key factors influence mold changeover time.

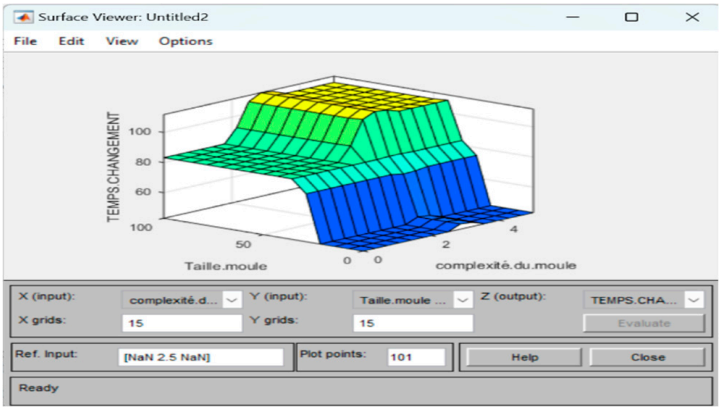


Figure 5. Surface visualization of mold size, complexity, and changeover time.

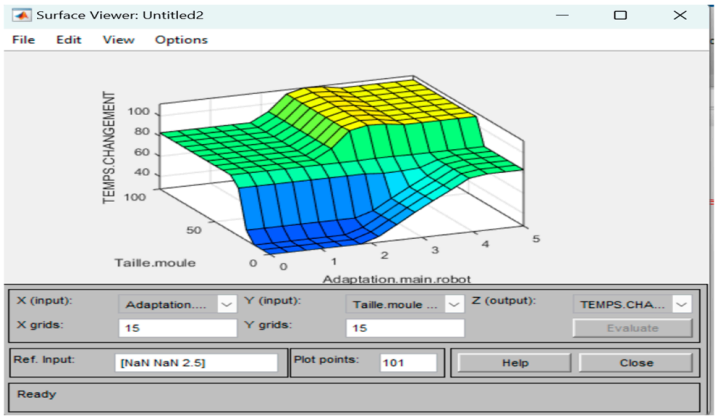


Figure 6. Surface visualization of mold size, robot adaptation, and changeover time.

Figure 4 illustrates the relationship between mold size and the degree of robot hand adaptation, showing that larger molds and poorly adapted robot hands generally result in extended changeover durations. Figure 5 builds on this by demonstrating the combined effect of mold size and complexity, revealing that increased complexity—particularly when dealing with larger molds—further prolongs the changeover process.

Lastly, Figure 6 emphasizes the positive impact of improved robot hand adaptation, showing that it can significantly reduce changeover times, even when working with larger molds. These 3D visual representations provide a clearer understanding of the interactions between key variables, highlighting the value of fuzzy logic in addressing real-world manufacturing challenges by effectively capturing and analyzing such process complexities.

3.13. Limitation of Study

The study has certain limitations that may restrict the broader application of its findings. It was carried out on a specific machine within a single company, meaning the results might not fully apply to other manufacturing settings. Data limitations also posed difficulties, preventing the use of simulation tools that could have provided a more detailed validation of the improvements. Furthermore, the scope of the research was confined to mold changeovers, without examining other related processes within the production line. A wider study covering various machines and stages of production would offer a more complete view of the approach's effectiveness.

4. Conclusions

This study showed that combining Lean Six Sigma (LSS), SMED, and fuzzy logic can greatly improve mold changeover times in plastic injection molding. The approach led to a 65% reduction in changeover time and increased Process Cycle Efficiency (PCE) from 27.5% to 72.5%. Value-added time rose by 59.3%, while non-value-added tasks dropped by 71.9%. These improvements boosted equipment availability and streamlined production. The findings confirm that blending Lean methods with modern tools can enhance manufacturing performance. Future work could apply this approach to other production stages or explore the use of simulations for broader validation [3].

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