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15APPLYING A NEW PERFORMANCE EVALUATION METHOD TO A COMPANY SPECIALIZED IN TECHNICAL PRODUCT MANUFACTURING

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Rezumat. *Reducerea pierderilor în procesul de injecție mase plastice este un obiectiv esențial pentru maximizarea randamentului întregului proces. Acest lucru se realizează fie prin metode experimentale (ex. proiectarea experimentului – DOE), fie prin metode de simulare sau prin iterații directe în producție. În lipsa accesului la programe software avansate de simulare, optimizarea poate fi realizată prin planificarea și executarea riguroasă a testelor de injecție, analiza rezultatelor obținute și implementarea unor ajustări bazate pe cunoștințele tehnologice ale inginerului de proces. Astfel, optimizarea devine nu doar o activitate tehnică, ci și o componentă strategică a procesului de industrializare și lansare în fabricație.*

Abstract. *Reducing losses in the plastic injection molding process is an essential objective for maximizing efficiency of entire process. This can be achieved either through experimental methods (e.g., Design of Experiments – DOE) or through simulation methods and direct iterations in production. In the absence of access to advanced simulation software, optimization can be carried out through careful planning and rigorous execution of injection trials, analysis of the obtained results, and implementation of adjustments based on the process engineer's technological knowledge. Thus, optimization becomes not only a technical activity but also a strategic component of the industrialization and production launch process.*

Keywords: Design of Experiments, mold, plastic, improved process.

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1.Introduction

The plastic processing industry represents one of the most dynamic and innovative sectors of modern industrial production, with extensive applications in the automotive, packaging, electronics, medical equipment, and consumer goods industries. Due to the versatility of plastic materials and the ability to produce complex geometries, injection molding has become a dominant manufacturing technology, offering advantages such as high reproducibility, economic efficiency, and a high degree of automation.

However, optimizing injection molding parameters remains a significant challenge for the industry. Process performance is strongly influenced by several critical factors-such as injection temperature, holding pressure, injection speed, and cooling time-whose interactions directly affect both product quality and process stability. Improper parameter settings can lead to manufacturing defects, increased production costs, and material waste.

In the current context, where sustainability and cost reduction have become major priorities, optimizing the injection molding process is essential for enhancing industrial competitiveness. Improving process efficiency and minimizing material waste significantly contribute to both the economic performance and ecological impact of the manufacturing process.

2.Research Issues and Justification

Although plastic injection molding technology is well established and widely applied, its continuous optimization remains essential in order to address the current challenges of modern industry. The main factors affecting the process efficiency are:

- Defects in molded parts – such as air voids, porosity, excessive shrinkage, weld lines, or warpage. These defects can compromise product quality and significantly increase the rejection rate.
- High material consumption – the cost of plastic raw materials has increased considerably in recent years, making it necessary to reduce material losses through process optimization and improved material efficiency.
- Production cycle time – long injection and cooling times can reduce process efficiency, overall productivity, and production responsiveness.
- Low energy efficiency – injection molding machines often consume large amounts of energy; optimizing process parameters can lead to substantial energy and cost savings.
- Selection of the optimal equipment – for each new mold, choosing an appropriate injection molding machine is crucial to ensure both production quality and process efficiency.

Therefore, this research aims to analyze the process of developing an injection program for a new mold, to define the selection criteria for the appropriate equipment, to determine the optimal process parameters, and to propose improvement solutions for cost and efficiency optimization.

3.Optimization of the Plastic Injection Molding Process

Optimization within the plastic injection molding process is a systematic and scientific approach aimed at identifying the most suitable process conditions and technical configurations for producing high-quality parts with minimal resource consumption and the shortest possible cycle time. It involves the precise adjustment and correlation of essential parameters such as melt temperature, injection pressure, injection speed, cooling and holding times, and mold clamping force to achieve a stable, repeatable, and economically efficient process.

During the start-up phase of a new mold, optimization plays a crucial role, as the initially defined injection parameters have a direct impact on part quality, production cost, and equipment durability. The appropriate selection of the injection molding machine—based on mold and part characteristics such as dimensions, injection volume, clamping force, and cooling capacity—is an integral part of this optimization stage.

A key objective of process optimization is to minimize losses—whether due to scrap, downtime, or excessive material and energy consumption—and to maximize process efficiency. These goals can be achieved through experimental methods, such as the Design of Experiments (DOE), simulation techniques, or iterative process adjustments during production. Even in the absence of advanced simulation tools, optimization can be successfully carried out through systematic planning of injection trials, thorough analysis of results, and process parameter refinement based on engineering expertise. In this sense, optimization becomes not only a technical activity but also a strategic component of industrialization and production launch

In the plastics manufacturing industry, production cost represents the totality of expenses incurred in transforming raw materials into a finished product ready for delivery. These costs can be divided into direct and indirect categories. Direct costs include raw materials (thermoplastic granules, masterbatch, additives), injection cycle time (determined by injection, cooling, and mold opening phases), direct labor, and specific energy consumption. Indirect costs involve machine depreciation, equipment maintenance, quality assurance activities, and administrative expenses related to production.

Production cost in injection molding is significantly influenced by process parameters such as the amount of injected material (including waste like runners and rejected parts), cycle time (which determines production capacity and unit cost), and defect rate (which generates additional costs due to scrap or reprocessing). Therefore, cost optimization requires the selection of process parameters that ensure the desired product quality with the lowest possible consumption of raw materials, energy, and time—while maintaining equipment reliability and production stability.

4.Definition of the Injection Process - Description of the Technology and Critical Process Parameters

Plastic injection molding is the most widely used method for manufacturing thermoplastic products. The process involves injecting molten plastic from a heated cylinder into a closed mold, where it cools and solidifies, forming the final part that is then ejected from the mold (see Figure 1).

Plasticizing is a key stage of the process that takes place inside the injection molding machine. It consists of transforming solid plastic pellets fed through the hopper into a viscous, homogeneous, and uniform melt, which accumulates in front of the screw during the dosing phase.

The plastic material, in the form of granules, is loaded into a hopper and fed into the heated barrel. Inside the barrel, the material is compressed, mixed, and melted, forming a homogeneous, bubble-free paste. This melt is pushed forward by the rotating screw and injected under pressure into the cooled, closed mold. Upon contact with the mold walls, the plastic takes the shape of the cavity, cools, and solidifies. The mold then opens to eject the finished part.

The advantages of injection molding lie in the ability to produce complex parts of various shapes and sizes using a wide range of polymers. The process is fully automated, ensuring high efficiency. This technology is commonly used to manufacture precision components, especially in the automotive, toy, and electronics industries.

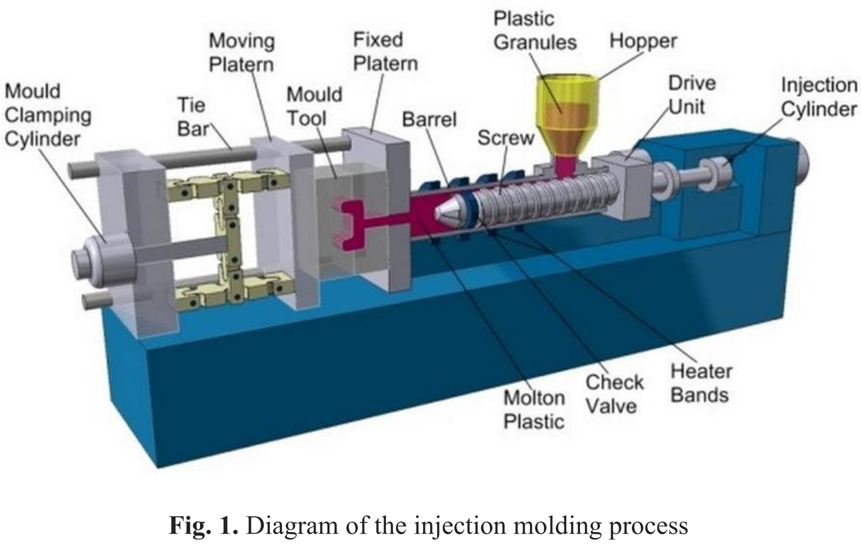

Fig. 1. Diagram of the injection molding process

5.Injection Process Parameters

The parameters described below have a significant influence on part quality and are generally responsible for the appearance of molding defects.

Material drying temperature and time before processing. These parameters are crucial for removing moisture from the plastic before it reaches the injection cylinder. They are particularly important for hygroscopic materials such as ABS, PA, PC, and PBT. As a general rule, the material should be dried separately and mixed with colorant only afterward.

Possible defects: silver streaks, black spots (in the case of excessive drying).

Dosing stroke and switchover point. These parameters determine the injected volume of material, directly influencing the weight and dimensions of the molded part.

Possible defects: burrs, short shots, sink marks (less frequent).

Dosing speed. This represents the speed at which the material is dosed during the process. It has a significant impact on process stability and on material degradation.

Possible defects: black spots, flow marks, unmelted particles.

Back pressure. This is the pressure applied opposite to the screw's rotation, used to improve mixing and melt homogenization, thus reducing air entrapment. It also affects the degree of thermal degradation and the amount of material dosed.

Possible defects: black spots, flow marks, unmelted fragments, burrs, incomplete parts.

Screw Temperature. This refers to the temperature at which the injection unit (barrel and screw) is heated. It is essential for melting and homogenizing the plastic material. Typically, the barrel is divided into four heating zones, each controlling the gradual melting of the material. The nozzle temperature is controlled separately and only ensures the material flow, without directly affecting plastification.

Possible defects: black spots, flow marks, unmelted fragments.

Injection Speed. This is the rate at which the molten material is injected into the mold cavity. It has a strong influence on the surface appearance and structural quality of the part. This parameter is difficult to stabilize because the cross-sectional thickness of the part often varies.

Possible defects: surface defects, warpage, sink marks.

Holding Pressure and Time. This phase compensates for material shrinkage during solidification inside the mold. It begins immediately after injection and continues until the start of the cooling phase.

Possible defects: sink marks, dimensional variations, deformation.

Cooling Time. Represents the duration required for the complete cooling of the molded part. It is one of the main factors determining the total cycle time.

Possible defects: dimensional instability, warpage, ejector marks.

Mold Temperature. This is the controlled thermal condition of the mold, maintained to prevent excessive temperature rise during repeated molding cycles. The mold temperature must be high enough to allow proper flow of the melt but low enough to ensure adequate cooling.

Possible defects: poor surface finish, dimensional inaccuracies, deformation.

Clamping Force. This is the force applied to keep the mold closed during injection. It is expressed in tons or kiloNewtons (1T = 10kN). The required clamping force depends on the projected area of the part and the injection pressure of the material.

Possible defects: flash at the parting line, burns.

Cushion (Material Cushion). This is the amount of material remaining in the injection unit after the injection and holding phases. A stable cushion value indicates process consistency; therefore, it should be controlled within ±10%.

Possible defects: part weight fluctuations, dimensional instability.

Switchover Pressure. This is the pressure at which the process changes from the injection phase to the holding phase. It corresponds to the pressure at the tip of the screw when the mold cavity is full. The pressure must be maintained consistently within ±10% to ensure uniform mold filling during each cycle.

Possible defects: sink marks, dimensional variations, flash.

Injection Time. This is the time required to fill the mold cavity with molten material. Like other parameters, it should be kept within ±10% to maintain process stability.

Possible defects: short shots, uneven surface, sink marks.

Melt Temperature (also called plasticizing or melt temperature). This is the temperature at which the thermoplastic polymer becomes sufficiently fluid to be injected into the mold while maintaining its chemical integrity and rheological properties. It is controlled through the heating zones of the plasticizing cylinder and depends on:

- the type of material (e.g., PP, PA, ABS, PC);
- its viscosity;
- the geometry of the part and mold.

Possible defects: material burning, streaks, flow marks, incomplete filling.

6.Optimization methods: analysis of existing optimization techniques and proposal of efficient strategies

What is a design of experiments plan and what is it used for?

In industrial processes, variations or instabilities in product characteristics frequently occur, especially during the introduction of new products into mass production. To reduce these variations and improve process stability, structured investigation methods such as the Design of Experiments (DoE) are used.

A design of experiments plan represents a scientific method for investigating the influence of process variables on a measurable response (e.g., shrinkage, weight, porosity, cycle time, etc.). Through a well-organized and controlled series of tests, causal relationships between parameters can be identified, allowing valid conclusions to be drawn with a minimum number of trials and maximum accuracy.

Methodological approach – steps in applying a design of experiments plan

The implementation of a DoE plan involves the following steps:

- Phase 1: Define the technological problem and formulate the objective (e.g., minimizing the shrinkage of an injected part).
- Phase 2: Select the relevant process parameters based on a thorough technical analysis. Parameters that have no significant influence are excluded.
- Phase 3: Establish the variation levels for each parameter and select the experimental design (e.g., full or fractional factorial matrix). Constant parameters remain unchanged throughout the tests.
- Phase 4: Conduct the tests according to the experimental plan and record the results in a predefined table.
- Phase 5: Perform statistical analysis to identify the influence of each factor and their interactions.
- Phase 6: Formulate conclusions and define further actions – parameter adjustments, technological modifications, and validation of the optimal result.

To ensure the success of a DoE plan, strict compliance with technical, organizational, and methodological conditions is required. Success depends not only on rigorous planning but also on the operational context and team involvement.

Essential Conditions:

- Experimental parameters must be defined in advance and kept constant throughout the testing series.
- Results must be quantifiable, objectively measurable, and repeatable.

Key Success Factors:

- Formation of a multidisciplinary team composed of specialists with diverse technical backgrounds, actively involved and motivated to contribute to process improvement.
- Appointment of an experimental coordinator (also known as a “facilitator” or “animator”) trained in DoE methodology, responsible for managing the implementation and ensuring consistency.
- Careful selection of execution personnel capable of precise equipment handling and accurate measurements.
- Development of a clear experimental strategy aligned with the objectives, available resources, and operational constraints.
- Strict adherence to the established experimental plan, avoiding deviations that may affect the validity or reproducibility of results

Objectives

To ensure and improve product quality, it is essential to identify and understand the factors that influence manufacturing process outcomes. Design of Experiments (DoE) provides systematic answers to key questions such as:

- Which process factors have the greatest influence on part characteristics?
- Which parameters have little or no significant effect on the analyzed result?
- What is the magnitude of each factor’s effect, and how can it be measured and modeled?
- Are there interactions between process parameters, and if so, are they statistically significant?
- Can mathematical models be developed to describe the relationships between main parameters and obtained responses?

1.Experimental Study and Analysis

Practical Example: Windshield Wiper Assembly (see Figure 2).

Main components:

1. Wiper arm – made from a polyamide and glass fiber blend (PA66 GF30), ensuring rigidity and mechanical strength.
2. Motor cover – made from polypropylene (PP), selected for impact resistance and weather stability.
3. Connectors and pivots – made from acetal (POM) for dimensional stability and low friction.

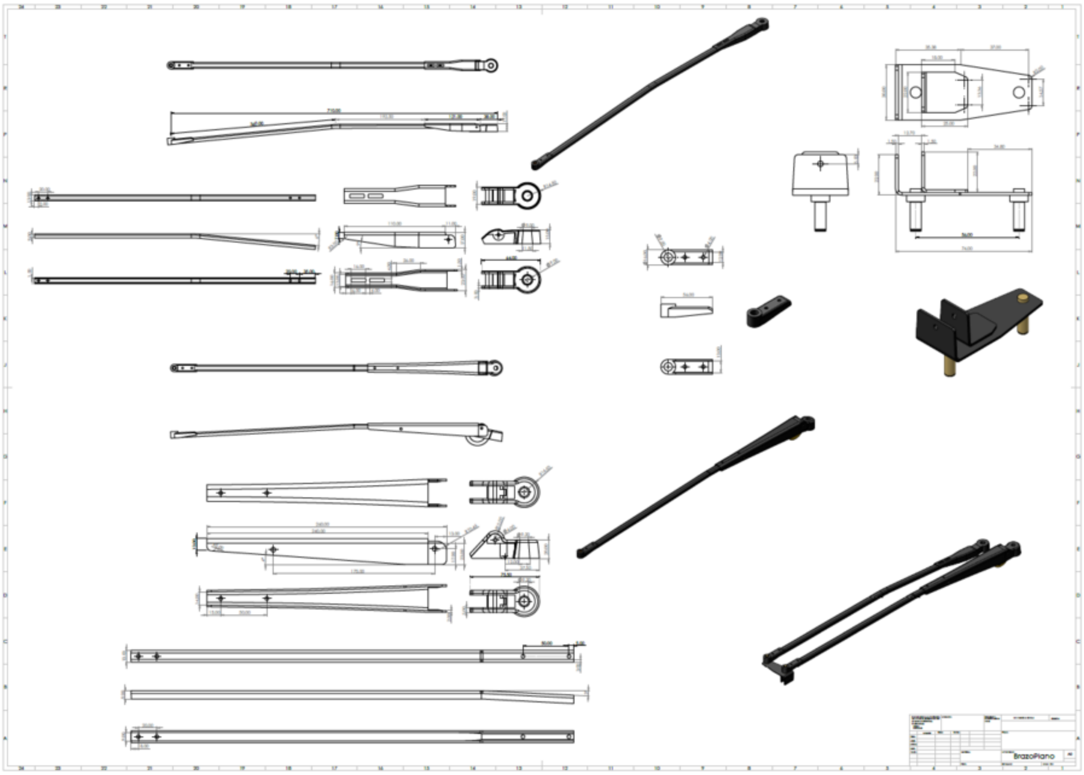

Fig. 2. Assembly drawing of the windshield

Analyzed component: Sliding flange of the wiper arm (pivot joint)

This component:

Is produced by injection molding;

Is part of the articulation area (between arm and blade);

Is subject to mechanical stress and wear;

Is dimensionally critical, as variation may affect blade fixation and correct functioning.

Material: Acetal (POM) – chosen for dimensional stability, wear resistance, and low friction.

Analyzed parameter: inner diameter of the pivot housing – the area where the pivot shaft is inserted. This dimension is critical for the correct operation of the joint.

Phase 1 – Problem description

The sliding flanges used in the windshield wiper assembly show dimensional deformations after injection molding, leading to deviations from functional tolerances, especially in the pivot housing area.

Such deformation affects proper blade assembly, reducing wiping efficiency and increasing the risk of premature wear. The main cause is the influence of process parameters on material shrinkage. The Design of Experiments (DoE) method was applied to minimize these variations.

Phase 2 – Selection of study factors

Three main factors were selected for their potential influence on dimensional stability:

Mold temperature: 30°C – 70°C;

Injection speed: 150 mm/s – 300 mm/s;

Material temperature (POM): 210°C – 250°C.

Phase 3 – Experimental matrix

The full factorial experimental plan 2^3 includes 8 distinct combinations of factors, shown in the table below:

Table 1. Applied Experimental Plan – Full Factorial Design 2^3

Trial No.	Mold Temperature	Injection Speed	Material Temperature
1	1(30°C)	1(150 mm/s)	1(210°C)
2	1(30°C)	1(150 mm/s)	2(250°C)
3	1(30°C)	2(300 mm/s)	1(210°C)
4	1(30°C)	2(300 mm/s)	2(250°C)
5	2(70°C)	1(150 mm/s)	1(210°C)
6	2(70°C)	1(150 mm/s)	2(250°C)
7	2(70°C)	2(300 mm/s)	1(210°C)
8	2(70°C)	2(300 mm/s)	2(250°C)

These combinations were chosen within the recommended POM processing ranges to allow observation of part behavior under realistic technological conditions.

Phase 4 – Method of Performing the Tests

Each combination of factors was tested individually and successively, monitoring the inner dimension of the pivot housing (critical functional dimension).

Table 2. Result of the critical functional dimension

Trial No.	Mold Temperature	Injection Speed	Material Temperature	Average result (mm)
1	1(30°C)	1(150 mm/s)	1(210°C)	8.03
2	1(30°C)	1(150 mm/s)	2(250°C)	7.97
3	1(30°C)	2(300 mm/s)	1(210°C)	8.03
4	1(30°C)	2(300 mm/s)	2(250°C)	7.97
5	2(70°C)	1(150 mm/s)	1(210°C)	7.92
6	2(70°C)	1(150 mm/s)	2(250°C)	7.94
7	2(70°C)	2(300 mm/s)	1(210°C)	7.92
8	2(70°C)	2(300 mm/s)	2(250°C)	7.94

To ensure data representativeness, at least ten injections were carried out for each combination, and the considered result was the average value of these ten measurements.

To avoid the influence of parameter instability at the beginning of the cycle, a waiting time of 10 minutes was allowed after each setting, before extracting and measuring the part.

Table 3. Standard deviation results

Experiment	Average dimension (mm)	Standard deviation (mm)
1	8.03	0.01479827317253257
2	7.97	0.012931013537658664
3	8.03	0.017310561965330595
4	7.97	0.023828321151287347
5	7.92	0.023167266179293246
6	7.94	0.019949937343259973
7	7.92	0.019570101913094155
8	7.94	0.017101007117840867

Phase 5 – Analysis of the Effects of Factors on the Functional Result

Calculation of the global mean

The overall mean of the obtained values for the analyzed dimension (inner pivot) is:

$$I = \frac{8.03 + 7.97 + 8.03 + 7.97 + 7.92 + 7.94 + 7.92 + 7.94}{8} = 7.965mm \quad (1)$$

Calculation of mean values by levels for each factor

Mold temperature

- Level 1 (30°C):

$$T_{mat,1} = \frac{8.03 + 7.97 + 8.03 + 7.97}{4} = 8mm \quad (2)$$

- Level 2 (70°C):

$$T_{mat,1} = \frac{7.92 + 7.94 + 7.92 + 7.94}{4} = 8mm \quad (3)$$

Injection speed

- Level 1 (150 mm/s):

$$V_{inj,1} = \frac{8.03 + 7.97 + 7.92 + 7.94}{4} = 7.965mm \quad (4)$$

- Level 2 (300 mm/s):

$$V_{inj,2} = \frac{8.03 + 7.97 + 7.92 + 7.94}{4} = 7.965mm \quad (5)$$

Material temperature

- Level 1 (210°C):

$$T_{mat,1} = \frac{8.03 + 8.03 + 7.92 + 7.92}{4} = 7.975mm \quad (6)$$

- Level 2 (250°C):

$$T_{mat,2} = \frac{7.97 + 7.97 + 7.94 + 7.94}{4} = 7.955mm \quad (7)$$

Calculation of the global effects of the factors

Mold temperature:

$$E_{Tmat} = 8 - 7.93 = 0.07mm \quad (8)$$

Injection speed:

$$E_{Vinj} = 7.965 - 7.965 = 0mm \quad (9)$$

Material temperature:

$$E_{Tmaterial} = 7.975 - 7.955 = 0.02mm \quad (10)$$

Table 4. Calculation of deviations from the global mean (mean effects)

Factor	Level	Mean effect from global mean (mm)
Mold temperature	1	+0,035
	2	-0,035
Injection speed	1	0,000
	2	0,000
Material temperature	1	+0,010
	2	-0.010

Preliminary Conclusion

The data analysis indicates that (see Figure 3).:

- The mold temperature has the most pronounced effect on the analyzed functional dimension, being an influential factor in this stage.
- The material temperature shows a secondary, but still significant effect.
- The injection speed does not influence the measured result within the tested range, showing a neutral effect.

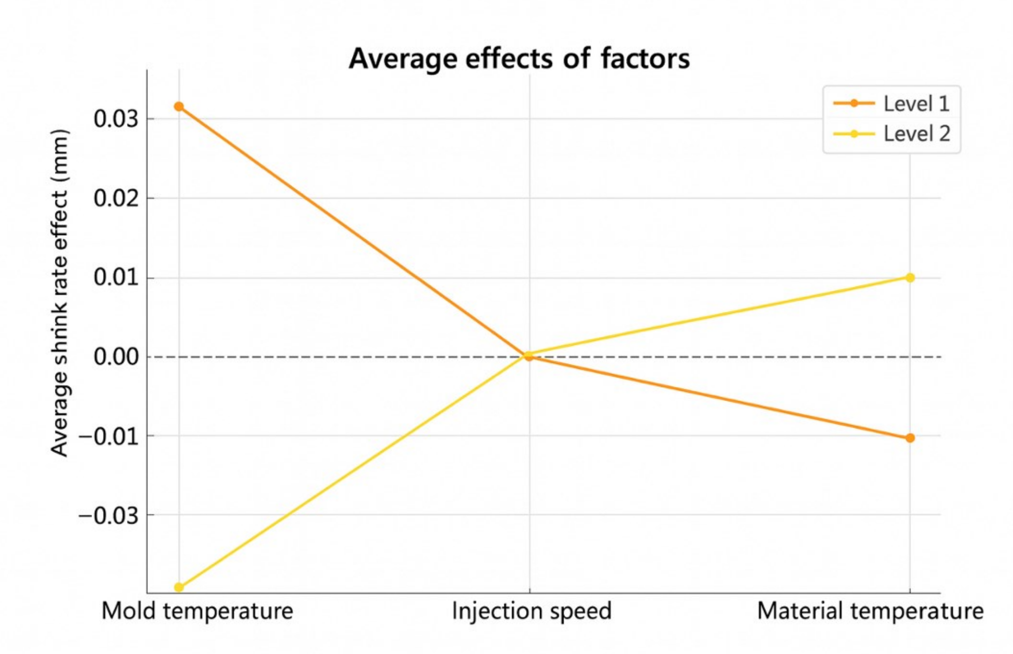

Fig. 3. Graph of the mean effects of the three factors

Main Results

- Mold temperature proved to be the factor with the greatest influence on the analyzed functional dimension.
- Injection speed did not have a significant influence within the tested range.
- Material temperature had a moderate but clearly measurable effect.
- The predictive model obtained showed residuals below 0.5%, confirming the validity and accuracy of the method used.

Phase 6 – Validation of the Theoretical Model Obtained through DoE

To validate the predictive model obtained after applying the DoE method, the theoretical estimated value was compared with the average experimental values resulting from the eight combinations of factors

Methodology:

- For each combination of technological parameters (mold temperature, injection speed, and material temperature), at least 10 successive injections were performed.
- The average of the measured values of the critical functional dimension (pivot slot) was calculated.
- This average was considered the reference experimental value for each trial.

Model Use:

The theoretical model was defined as follows:

Y = I + ∑ (average effects of factors at the respective levels)

Where:

- I = 7,965 mm is the overall mean of all measured values;

The effects of each factor were extracted from the analysis in Phase 5:

- Mold temperature: ±0.035 mm
- Injection speed: ±0.000 mm
- Material temperature: ±0.010 mm
- Calculation example (Trial 1):

Factor combination:

Mold temperature = Level 1 (30°C)

Injection speed = Level 1 (150 mm/s)

Material temperature = Level 1 (210°C)

Y = 7.965 + 0.035 + 0.000 + 0.010 = 8,010mm

- Measured value: 8.03 mm
- Absolute residual: |8.03 − 8.010| = 0.02 mm
- Percentage residual: $\frac{0,02}{8,03}$ x 100 = 0,25%

Table 5. Results of the model and experimental values

Trial	Mold temperature (°C)	Injection speed (mm/s)	Material temperature (°C)	Average result (mm)	Theoretical model (mm)	Residual (%)
1	30	150	210	8.03	8.01	0.25
2	30	150	250	7.97	7.99	0.25
3	30	300	210	8.03	8.01	0.25
4	30	300	250	7.97	7.99	0.25
5	70	150	210	7.92	7.92	0
6	70	150	250	7.94	7.9	0.5
7	70	300	210	7.92	7.92	0
8	70	300	250	7.94	7.9	0.5

Interpretation

In general, a result is considered:

- Between 0% and 2% → good
- Between 2% and 4% → acceptable
- Between 4% and 6% → medium (verify if all press parameters are stable)
- Above 6% → unsatisfactory
- All percentage residuals are below 0.50%, which means:
- The model is very well calibrated;
- The deviations are far below the 2% threshold, considered “very good” in the technical literature;
- Variability between executions is minimal, and part reproducibility is stable.

Main Results

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- The injection speed did not have a significant influence within the tested range.
- The material temperature had a moderate but clearly measurable effect.
- The predictive model obtained showed residuals below 0.5%, confirming the validity and accuracy of the method used.

Conclusion

Observations from the Tests

- Increasing the material temperature (250°C vs 210°C) did not bring significant quality benefits but implied higher energy costs.
- The residual values and dimensional stability were excellent even at lower temperatures, indicating efficient operation with reduced energy consumption.
- Injection speed did not affect quality, so the level that minimizes machine wear can be chosen, ensuring that cycle time is not negatively affected.

The predictive model developed using the DoE method can be reliably used to estimate the functional result of the part depending on the process parameters, without requiring extensive experimental tests or complex software simulations.

This is essential for improving industrial process efficiency under real operating conditions.

Economic Conclusion

By combining the quality results with the cost analysis, the optimal combination is: Mold temperature = 30°C, Injection speed = 150 mm/s, Material temperature = 210°C

This ensures high quality, low energy cost, and very good reproducibility, being suitable for industrial production without significant losses.

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