

PARAMETRIC OPTIMIZATION OF INJECTION MOLD SETTINGS FOR THE WEIGHT EFFICIENCY OF POLYPROPYLENE PLASTIC CUPS USING RESPONSE SURFACE METHODOLOGY

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Abstract

This novel study focuses on the parametric optimization of injection mold settings to enhance the quality of polypropylene plastic cups. A model for the optimal injection mold settings, including cooling time, mold temperature, injection pressure, and injection speed (independent variables), was developed using the response surface methodology (RSM) to optimize the polypropylene plastic cup weight (dependent variable). Weight is an essential parameter in polypropylene plastic cups, directly influencing their durability, cost, and functional application. RSM was used for the experimental design, comprising multiple iterations of mold trial testings with variations in the input variables. The RSM model developed in this study produced the following optimal solutions for the input factors: cooling time – 15s; mold temperature – 57.270 °C; injection pressure – 95 MPa; and injection speed – 50 mm/s. The optimal solution for the response variable, weight, from the RSM analysis is 32.06g. The RSM analysis produced a global desirability (Dg) of 1 (100%) for achieving the optimal solutions. The RSM model explains 80.61% of the variance in the response variable, which is a strong contribution, as indicated by the coefficient of determination (R²). The selected model was the quadratic model, as indicated by the analysis of variance (ANOVA). The square (quadratic) term of the cooling time input factor and the interactive term between the cooling time and injection pressure were the two factors that had the most significant impact on the weight response variable of the finished polypropylene plastic cup product, as shown by the ANOVA. It is recommended that manufacturers implement the optimal solutions determined in this study in their production. This approach will mitigate waste and imperfections in plastic cups and allied products when implemented in injection molding. This study demonstrated the feasibility of determining optimal mold settings and materials to enhance product quality through the design of experiments (DOE).

1. Introduction

A common domestic item is the plastic cup, present in virtually every household worldwide. Though it may look simple and, in general, be inexpensive, its production is typically sophisticated and involves complex procedures to achieve high (optimal) quality while preserving efficiency and sustainability. This research study seeks to explain the relationship between injection mold settings and the high quality of plastic (cup) products, with a focus on illuminating processes to improve production efficiency, optimize mold settings, and, ultimately, achieve high (optimal) quality plastic (cup) products with improved attributes. These enhanced features are influenced by mold settings, which significantly contribute to the finished plastic cup's quality, e.g., dimensional precision, aesthetics, tensile strength, thermal performance, weight, and production cost. Imperfect mold designs result in defects such as imperfect shapes and weak points, which can lead to leaks, early failure, overweight, cracks, etc., seen in the finished plastic products, directly giving rise to increased

cost of production, increased rate of energy consumption, increased waste production, prolonged cycles of production, generation of environmental burdens, etc.

Weight is a vital factor that significantly impacts the feel and durability of plastic cups. Lighter cups may convey a sense of flimsiness, while heavier cups feel more substantial. Weight is a critical parameter in polypropylene plastic cups, directly influencing their durability, cost, and functional application. As a low-density, versatile material, PP cups are categorized by weight (light, medium, heavy-duty) to balance performance with material consumption.

The key aspects of weight importance in PP cups are: (i) Durability and Performance: Thicker-walled (higher weight) PP cups offer greater rigidity and resistance to deformation, making them ideal for heavier or more viscous beverages, such as milkshakes or soups. Medium-weight cups offer a balance between flexibility and sturdiness, suitable for general-purpose use. (ii) Cost Efficiency and Sustainability: PP is lightweight (density < 1 g/ml), allowing for high-yield, cost-effective production. Lighter cups require less material, reducing both manufacturing costs and the environmental impact by minimizing waste. (iii) Impact Resistance: While PP is generally flexible, increased thickness improves impact resistance, making the cups more durable in, for example, high-traffic food service environments. (iv) Logistics and Handling: The low density of PP makes the cups lightweight for transportation, reducing shipping costs compared to alternatives like glass or PET.

In terms of manufacturing, the weight of a cup is directly related to the amount of polymer used. Higher weight generally indicates a higher concentration of material, which can improve mechanical properties such as tensile strength and impact resistance. The weight is also influenced by the manufacturing method (e.g., thermoforming). Lightweight cups are used for high-volume, single-use, low-cost applications. The medium/heavy-duty is used for applications that require greater structural support and durability.

The thickness of the plastic material determines the weight of a plastic cup. Weight recommendations depend on the cup size and the intended use. Lighter-weight cups for short-term use can be thinner. Larger-volume tumblers, such as 32 oz. and above, benefit from thicker plastic and more weight. Heavier cups are generally perceived as higher quality, but weight needs to be balanced with other parameters like cost and ease of use. Ultra-light or ultra-heavy cups may be undesirable. The precise weight of plastic cups depends on balancing durability, insulation, cost-effectiveness, and ease of use for the specific application and customer preferences. Testing diverse weights is advisable. Optimizing the weight of plastic cups (often through a process called "lightweighting") offers significant economic, environmental, and operational benefits. The goal is to use the minimum amount of material necessary while maintaining the required strength and functionality.

The key benefits include: (A) Cost Reduction: (i) Lower Raw Material Costs: Directly using less plastic material significantly reduces raw material expenses, which is a primary cost driver in manufacturing. (ii) Reduced Transportation Costs: Lighter cups mean lighter shipments, which leads to lower fuel consumption and shipping per unit during distribution across the supply chain. (iii) Lower Production Energy Costs: Manufacturing plastic products with less material often requires less energy, cutting operational expenses. (iv) Optimized Storage and Logistics: Lighter, often better-designed, cups can be stacked more efficiently, maximizing storage and transport volume and reducing warehouse space needs. (B) Environmental Advantages: (i) Reduced Carbon Footprint: Less material usage and lower fuel consumption during transport significantly decrease greenhouse gas (GHG) emissions across the entire product life cycle. (ii) Resource Conservation: Minimizing the amount of plastic used helps conserve non-renewable fossil resources. (iii) Improved Recyclability: Optimized, single-material designs (such as mono-material solutions) are easier to sort and process in recycling facilities, supporting a circular economy. (iv) Compliance with Regulations: Reducing material weight helps companies meet increasingly strict environmental regulations and avoid potential taxes on single-use plastics. (C) Operational and Market Benefits: (i) Enhanced Brand Image: Aligning with sustainability goals and using less plastic appeals to environmentally conscious consumers, strengthening the brand's market position. (ii) Improved Manufacturing Efficiency: Optimized designs can lead to faster production cycles and less industrial waste, making the production process more streamlined. (iii) Maintained or Improved Performance: Through innovative design and material science (e.g. specific additives or topology optimization), cups can be

made lighter without compromising critical properties like strength, durability, or leak resistance. (iv) Enhanced User Experience: Lighter cups are easier for consumers to handle, carry, and use, improving convenience and portability.

The weight of plastic (cups) products are impacted significantly by the mold settings of cooling time, mold temperature, injection pressure and injection speed as seen from the following elaborations: (1) COOLING TIME: Cooling time in injection molding significantly affects the weight of plastic cups primarily by controlling the amount of shrinkage and molecular density (crystallinity) during solidification. Optimizing the cooling time during the production of plastic cups enhances weight efficiency by enabling a reduction in wall thickness without sacrificing structural integrity or quality. Proper, optimized cooling ensures that the polymer chains solidify in a stable, uniform structure, reducing the need for excess material (thicker walls) to prevent warpage, shrinkage, or defects during ejection. Key impacts of optimizing cooling time on weight efficiency include: (i) Enables Thinner Walls: By stabilizing the plastic more effectively, optimized cooling allows manufacturers to produce thinner-walled cups, directly reducing the weight per unit. (ii) Reduces Defects at Lower Weights: If the cooling time is optimized, thinner, lighter cups can be ejected without warpage, shrinkage, or sink marks, which often force the use of thicker, heavier, and more costly designs. (iii) Improved Structural Integrity: Controlled cooling allows for better crystallization of materials like polypropylene (PP), producing a stiffer and more rigid structure that requires less plastic to achieve the same strength as a thicker, poorly cooled cup. (iv) Increased Productivity: Reduced cooling times, often 60-80% of the injection molding cycle, improve production efficiency, allowing for higher, consistent output without sacrificing material efficiency. (v) Enhanced Material Distribution: Uniformly designed cooling channels, especially with conformal cooling, prevent "hot spots" that cause weak spots, enabling a consistent, lower weight across the entire cup. Conversely, insufficient cooling leads to higher defect rates, often requiring manufacturers to add more plastic (increasing weight) to ensure the cup can withstand the ejection process.

(2) MOLD TEMPERATURE: Optimizing mold temperature directly affects the weight efficiency of plastic cups by balancing flowability and material shrinkage, which allows manufacturers to achieve the minimum necessary material usage without sacrificing structural integrity or quality (e.g., preventing flash or warping). Proper optimization - typically finding the "Goldilocks" temperature - improves weight efficiency through the following mechanics. (A) Reduced Shrinkage and Consistent Weight - (i) The Problem: If the mold is too cold, the plastic solidifies too rapidly, causing high shrinkage and often requiring the operator to "pack" more plastic into the mold to fill it, leading to a heavier, less efficient cup. (ii) The Optimization: A higher, well-controlled mold temperature allows the polymer to fill the cavity more uniformly. As it cools, the material settles more consistently, reducing the need for excess pressure and excessive material packing. This creates a higher, consistent, and more efficient, stable product. (B) Improved Flow and Thin-Wall Capability - (i) Reduced Friction: Warmer mold temperatures reduce the viscosity of the molten plastic, allowing it to flow more easily and fill thin-walled areas of the cup more quickly. (ii) Weight Reduction: Easier flow allows manufacturers to reduce the injection pressure and optimize the overall part thickness, leading directly to a lower overall gram weight (weight efficiency) without incomplete filling (short shots). (C) Lowered Defect Rates (Less Scrap) - (i) The Problem: Improper temperatures often lead to defects like "flash" (excess plastic escaping the mold) or warping. (ii) The Optimization: A properly optimized mold temperature reduces and ideally eliminates these, reducing the amount of wasted material (scrap) that is produced. This makes the overall process much more efficient in terms of material usage per good, sellable cup. (D) Better Crystallinity (Strength-to-Weight Ratio): For semi-crystalline plastics (like Polypropylene -PP), a higher mold temperature improves crystallization. Increased crystallinity results in higher tensile strength and rigidity. (i) Weight Efficiency Connection: Because the cup is stronger due to better crystallization, you can design a thinner, lighter cup (lower total material) while still maintaining the same structural strength. Summary of Mold Temperature Effects - When the Mold Temperature Setting is: (a) Too Low: (i) Effect on Flow: Poor, causes short shots; (ii) Effect on Shrinkage: High/ Irregular; (iii) Effect on Cup Weight: Unstable (needs packing). (b) Too High: (i) Effect on Flow: Excess, Causes flash; (ii) Effect on Shrinkage: Excessive Contraction; (iii) Effect on Cup Weight: Higher potential, risk of deformation. (c) Optimized: (i) Effect on Flow: Perfect filling; (ii) Effect on Shrinkage: Controlled/ Uniform; (iii) Effect on Cup Weight: Lowest, consistent weight. (E) Improves Surface Finish and Stiffness: Better temperature control ensures a better replication of the mold surface, reducing the need for increased material to fix surface roughness, and enhancing the rigidity of thin walls.

(3) **INJECTION PRESSURE:** Higher injection pressure generally increases the weight of plastic cups by forcing more material into the mold cavity, increasing density, and reducing shrinkage. Excessive pressure can cause overfilling (higher weight), while insufficient pressure can lead to underfilling and lower weight. Proper control ensures consistent weight. The key effects of injection pressure on cup weight are: (i) **Increased Density and Weight:** Higher pressure compresses the melt, increasing its density within the mold, which directly results in a higher weight. (ii) **Reduced Shrinkage:** Increased pressure compacts the material, reducing the shrinkage that occurs during cooling, which helps maintain a higher, more stable part weight. (iii) **Filling Efficiency:** Sufficient pressure is required to fill the entire cavity, particularly for thin-walled cups. Insufficient pressure causes short shots (low weight), while excessive pressure can cause flash (excess material at edges), increasing weight. (iv) **Compensation for Viscosity:** High injection pressure allows for higher flow rates, enabling the plastic to fill thin, complex areas before premature cooling occurs. Relationship with related parameters: (a) **Holding Pressure:** Once the mold is filled via injection pressure, the holding (or packing) pressure continues to force more material into the cavity to compensate for shrinkage as it cools, heavily influencing final weight. (b) **Back Pressure:** Higher back pressure in the barrel ensures higher melt density before injection, contributing to more consistent, heavier, and more accurate, but sometimes excessive, part weights. In summary, increasing injection pressure is a primary way to increase part weight and density, provided it does not cause excess flash.

(4) **INJECTION SPEED:** Higher injection speeds in plastic cup molding generally increase product weight by improving cavity filling and increasing density before the material solidifies. Fast injection prevents premature cooling (short shots), while excessive speed may lead to flashing (extra weight) or, conversely, density variations due to turbulence. Impact of injection speed on weight is explained following: (i) **Faster Speeds:** Increase weight by filling the cavity more completely and allowing for higher pressure to be packed into the mold. This minimizes the risk of short shots (incomplete, light parts). (ii) **Slower Speeds:** Can result in lighter parts due to premature solidification of the plastic before the cavity is filled, leading to under-packed or short-shot parts. (iii) **Optimal Speed:** Proper speed settings ensure consistent weight by allowing the melt to flow evenly, filling the cavity before it cools and solidifies. (iv) **Density and Structure:** Fast injection helps in achieving a more consistent, higher-density part, but excessive speed can cause flashing, which technically increases the weight with excess. Key considerations are: (a) **Material Behavior:** Materials with high viscosity require faster, more precise, or higher-pressure injection to ensure proper, consistent weight. (b) **Defects:** If the injection speed is too fast, it can create burn marks (due to high shear) or flash. If too slow, it can lead to weld lines or sink marks. (c) **Multi-Stage Control:** Using multi-stage injection allows for high speed during the initial fill, followed by slower speeds to prevent defects, allowing for optimal, consistent weight.

Existing literature by various scholars has delivered pragmatic solutions to the enhancement of the efficiency of the injection molding process and product quality via process optimization, but no work has been done by any previous scholar precisely to address the process efficiency improvement and plastic cup weight optimization via the optimization of the mold variables to the best of our knowledge. And this is the gap that this innovative research study covered. Various factors, including the cooling time, mold temperature, injection pressure, injection speed, melt temperature, holding/packing pressure, and time, etc., impact the complex injection molding process.

Injection molding is an efficient and economical process for the large-scale commercial manufacturing of complex parts, such as automotive components and consumer goods (Trivedi et al., 2023). Plastic injection molding is widely used to produce a variety of plastic products. Nevertheless, defects can arise during the production process due to improper settings of process variables, which are critical to ensuring the quality of the molded parts. In the injection molding process, important concerns include the strength, warpage, and weight of the molded parts (Aslam et al., 2025).

The injection molding process principally involves a systematic order that converts plastic pellets into molded parts. This method produces identical components by repeatedly melting resin pellets or powder and injecting the molten polymer into a hollow mold cavity under high pressure. The injection molding process poses challenges for manufacturers and researchers seeking to produce cost-efficient products that meet stringent criteria.

The research study focused on designing, analyzing, and manufacturing injection molds for plastic components used in biomedical applications, emphasizing cost-effectiveness while overcoming common challenges to achieve high-quality components. In view of this, mold design was optimized through strategic gate placement, weld-line management, elimination of gas traps, pressure-drop equalization, and stress reduction. Implementing these optimized parameters during production led to improved component quality, with fewer defects and better dimensional accuracy. Also, this research helps minimize manufacturing costs by reducing rejections and rework. This multifaceted method not only refines the process but also enables the efficient, cost-effective production of high-quality plastic parts for biomedical applications (Krishnappa et al., 2025).

A study developed a multi-objective optimization procedure to minimize surface roughness and volumetric shrinkage in injection-molded products. Surrogate models for both responses were constructed using Kriging, based on experimental data and seven input parameters: packing pressure, mold temperature, cooling time, injection speed, injection pressure, melt temperature, and packing time. A multi-objective optimization problem was developed and solved using the pattern search algorithm, generating a Pareto front that highlights the trade-off between the two objectives. The proposed approach offers an experimentally validated tool for plastic engineers, enabling informed parameter adjustments to realize optimal trade-offs in surface quality and dimensional stability within practical manufacturing constraints (Mukras et al., 2025).

Some scholars studied the optimization of the process parameters in plastic injection molding. They employed the Taguchi method. The research focused on minimizing defects, such as shrinkage, in polypropylene containers. Crucial variables like melt temperature, injection pressure, packing pressure, and packing time were analyzed through a series of 27 experiments based on the L27 orthogonal array. The findings show that melt temperature was the most impactful factor, followed by injection pressure, packing pressure, and packing time. The optimal conditions determined are a melt temperature of 2600 °C, an injection pressure of 65 MPa, a packing pressure of 50 MPa, and a packing time of 10 seconds. Implementing these conditions would decrease the plastic jar's defect rate (Kumar and Bairwa, 2025).

The increasing demand for thinner products, lower production costs, and higher product quality has driven a surge in research on plastic molding processes. A key branch of such research focuses on the mold cooling system (Martowibowo, 2017).

A study found that additive manufacturing offers significant design freedom for injection mold tooling, particularly for optimizing cooling performance and reducing mass. The study presented a comprehensive framework for the topology optimization of mold inserts, incorporating design-for-additive-manufacturing principles and essential boundary conditions from mold-making, injection molding, and post-processing operations. The results show up to 60% savings in mass and cost while maintaining structural integrity under operational and misuse conditions. Maximum displacements – only a 4 µm increase compared to the reference – remained within DIN ISO 20457 tolerances, and stresses did not exceed 170 MPa under operational conditions, confirming industrial applicability. The study concludes with a proposed framework for incorporating topology optimization into mold design workflows (Redeker et al., 2025).

Cooling channels play a crucial role in mold performance and product quality, as they strongly influence cycle time. Designs incorporating conformal cooling channel (CCC) geometries that conform to or align with the part contour are being explored as an alternative to conventional cooling channel designs in injection molding. A study simulated CCC geometries and their effects on mold temperatures and warpage. Two cross-sectional geometries, circular and square, were selected for a three-parameter design of experiments (DOE) analysis. The response parameters were mold temperatures and part warpage. A cup-shaped part with upper and lower diameters of 54mm and 48mm, respectively, a height of 23mm, and a thickness of 3mm was used for the injection-molded part. The final element simulation results show a 9.26% reduction in final warpage in the cup-shaped part using CCCs compared with conventional cooling methods in steel. For parts with lower geometric stiffness, CCCs reduced final part warpage by 32.4% in metal molds and by 59.8% in polymer molds (Vargas-Isaza et al., 2023).

A study was conducted in a typical plant to investigate the effects of cooling time and colorant type on dimensional and weight deviations in plastic closures during injection molding. High-density polyethylene (HDPE) was used as the raw material, and the samples were injection-molded using a 32-cavity mold. Three cooling times (1.6, 2.6, and 3.6 seconds) and four colorants (black, blue, white, and colorless) were used in the research. A full factorial design of experiments (DOE) was adopted, and twelve experiments were conducted. For each sample, the dimensional and weight deviations were determined. The investigation found that the dimensional stability of plastic closures, driven by contraction rate, is influenced by cooling time and colorant type during injection molding. It was observed that the contraction rate, especially along the transverse axis (diameters) of the closures, was inversely proportional to cooling time and significantly dependent on colorant type. The effect of these factors on contraction along the lateral axis (height) and on weight loss was insignificant (Njagi et al., 2023).

The aim of the study was to optimize injection molding process parameters to minimize warpage of plastic glass. The optimization process was divided into two sections. The Finite Element Method (FEM) was employed in the first section to simulate 32 experiments under various factors. The process factors were melting temperature in the range of 180 to 230°C, mold temperature in the range of 20 to 45°C, filling time from 0.82 to 0.92 s, packing time from 5.88 to 7 s, and cooling time from 14 to 18 s. In the second section, an Artificial Neural Network (ANN) combined with a Genetic Algorithm (GA) was employed to predict warpage and to optimize the parameter values. The combination of the intelligent methods revealed that ANN and GA effectively identified optimal process parameters that reduced the product's warpage by 35.73% from the maximum value (Nitnara and Tragangoon, 2023).

The primary feature of the single-use container used for sample collection in the medical industry is transparency, which is achieved only with virgin polypropylene (PP). Proper selection of injection molding variables leads to better product quality. In a research study, the objective was to optimize injection molding process variables. The selected variables were injection pressure, melting temperature, cooling time, packing time, and packing pressure. Optimizing these variables for sample collection containers made from recycled polypropylene helped reduce production costs, cycle time, and virgin material costs (Kumar et al., 2025).

A study establishes a standard process setup procedure and an adaptive process control system based on data generated by a nozzle pressure sensor and a tie-bar strain gauge to stabilize product quality affected by these process factors in injection molding. The V/P switchover point, injection speed, packing pressure, and clamping force were successively optimized based on the pressure profile characteristics. At the end of the optimization process, the study defined the standard quality characteristics using the optimized process factors and integrated them with the adaptive process control system to achieve automatic machine adjustment and maintain high-quality production. Three materials with different viscosities were used to validate the optimization process and the adaptive control system. Thus, the variations in the product's weights were reduced by 0.079%, 0.106%, and 0.092%, respectively, with the system (Liou et al., 2023).

Mulge and Kalashetty (2019) provided insight into the literature on recent research on optimization methods for determining the optimal process factors in injection molding of plastics using the Taguchi technique. A study reviewed the application of injection molding parameter optimization. The fundamental principles and features of various optimization techniques were described. Optimization techniques chiefly include Taguchi-based optimization, numerical simulation-based optimization using CAE technology, genetic algorithm-based optimization, and artificial neural network-based optimization. The types of optimization problems applicable to different optimization methods were deliberated (Zhu et al., 2021). In an experiment, the parameter selection for injection molding was studied using Taguchi and ANOVA. Since many parameters are involved in the process, the study investigated the impacts of melting temperature, injection pressure, cooling time, and injection speed. A composite matrix material of Linear Low-Density Polyethylene (LLDPE) and Flyash as a reinforcing material (LLDPE + Flyash) was used in the experiment to determine optimal injection molding settings for tensile strength and hardness, minimizing defects and maximizing strength and toughness. The analysis was conducted using Minitab 17. The output features analyzed and indicated the good and optimal results (Reddy et al., 2017).

The theoretical basis of this research study centers on optimizing the injection mold parameters to investigate their impact on the optimal weight of the plastic cup using the response surface methodology (RSM). RSM is a mathematical and statistical tool employed for the optimization of systems and product quality, and for studying the interrelationship between input and output variables. This is supported by existing literature, as numerous scholars have employed the response surface methodology to enhance product quality by optimizing injection mold settings. This research study builds on the existing literature to contribute to knowledge in the science of enhancing plastic cup product quality and weight through the optimization of injection mold settings.

To optimize injection molding for efficient, lightweight plastic cups, focus on reducing material usage (weight) by 2-5% while maintaining structural integrity using DOE (Design of Experiments). Key settings include minimizing pack/ hold pressure, slightly increasing molding/ barrel temperatures to improve flow, optimizing cooling time, and using high injection speeds (Aslam et al., 2025). Key parameter optimization for Lightweighting includes: (a) Packing and Holding Pressure/ Time (Reduce): Lowering these parameters reduces the amount of material pushed into the mold after filling, decreasing part weight. (b) Melt and Mold Temperature (Optimize/ Increase): Higher temperatures reduce viscosity, allowing easier thin- wall filling with less material. (c) Injection Speed (Increase): Faster injection speeds (high injection rate) are essential for thin- walled, lightweight parts, ensuring the mold fills completely before the plastic cools. (d) Cooling Time (Reduce): Optimizing cooling time is often the most significant factor in cycle efficiency, enabling faster production and reduced material consumption. (e) Venting (Clean/ Enlarge): Good venting prevents air entrapment, which can cause defects and lead operators to over- pack the part. Optimized Setting Profile Example: Based on studies for efficient production and quality (e. g., Taguchi/ RSM methods): (i) Melt Temperature: 210- 230 ° C (depending on material, e. g., PP or PET). (ii) Mold Temperature: 40- 60 ° C. (iii) Injection Speed: High (to prevent short shots). (iv) Holding Pressure: Reduced by 5- 10% from standard to cut weight, provided it doesn' t cause sink marks (Kumar and Bairwa, 2025). Key Considerations: (a) Weight Consistency: Utilize machine features like IQ WEIGHT CONTROL to automatically compensate for viscosity fluctuations, maintaining a weight variation of 0. 0.1-0. 4%. (b) Thin- Wall Technology: If designing a new cup, reduce the average wall thickness toward 1-2mm to significantly reduce material usage. (c) Verification: Utilize RSM or Taguchi L 27 or similar DOE methods for robust optimization of these factors (Aslam et al., 2025).

Several existing literature reviews have indicated that many scholars have conducted research on enhancing plastic product quality through the optimization of injection mold settings. However, none of these previous studies was specifically focused on enhancing the weight quality of a plastic cup product by optimizing the cooling time, mold temperature, injection pressure, and injection speed (mold parameters) as input variables, to investigate the impact of their optimal values on the resultant weight (response variable) of the polypropylene (PP) plastic cup product, using the experimental design of the response surface methodology. This is the novelty of this research and the gap this study addresses.

1.1. The key objectives of this study include:

- (i) To develop a Response Surface Methodology (RSM) model relating injection mold setting to the weight of polypropylene plastic cups.
- (ii) To estimate the significance and interaction effects of optimal cooling time, mold temperature, injection pressure, and injection speed on the optimization of the weight response.
- (iii) To determine the optimal combination of process input parameters, namely: cooling time, mold temperature, injection pressure, and injection speed that minimizes the weight response of the polypropylene plastic cup.
- (iv) To make recommendations for enhancing production efficiency and product quality in injection mold plastic cup production.

2. Materials and Methods

The strategic methodology employed to accomplish the aims and objectives of this experimental study relies primarily on identifying the fundamental plastic cup qualities, selected with respect to structural and durability perspectives and user experience. The following identifies the fundamental injection mold factors that impact the selected plastic cup qualities. Experimental trials were conducted with varied mold variables to study their performance and assess their influences on the

weight factors of the polyethylene plastic (PP) cup product. The investigation of the interrelationships among the various mold variables relative to the weight-quality metric, as well as the individual variables' effects on plastic cup weight, followed. The critical mold settings selected for optimization based on their influence on the weight attributes of plastic cups are: cooling time, mold temperature, injection pressure, and injection speed. These mold variables were selected for optimization based on common knowledge of injection mold factors and dynamics and their impact on the finished plastic cup's weight. Probable interactions among these mold factors were considered in their selection. The RSM design of experiment (DOE) was used for the experimental design, and the response modeling focused on these mold factors (input parameters) and the weight response, with the single objective of identifying the efficient process variables that significantly influence the plastic cup weight and need to be optimized. RSM is a multi-input, multi-output process factor design analytical method. Its objective is to find the optimal combination of input parameters that results in the target response. It uses response plots and contour plots to visually represent the interactions between the input factors and the responses. The visual representations offer intuitive insights and help decision-makers understand the system's behavior. RSM has been successfully used in engineering design, pharmaceuticals, chemical process optimization, product development, etc. It's a method for addressing real-world problems. Hence, a major advantage of RSM is that it is a preferred choice for multi-objective optimization and the challenges posed by non-linear systems. The general second-order (quadratic) RSM model used in this study is expressed as:

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_{i < j}^k \beta_{ij} X_i X_j + \epsilon$$

Minitab Statistical Software (Version 20.3.3.0) was the analytical tool employed for this research study. It's a strong analytical tool employed for Six Sigma projects, process optimization, and data analytics. Its attributes include a user-friendly interface that makes it accessible to both statisticians and non-statisticians. It offers the full RSM suite of powerful data analysis and visualization, making it a common choice across various fields and settings. Generally, it is deployed across engineering design, engineering production, construction, and research for optimization, analytical modeling, product quality enhancement, and cost reduction. It is known to provide various predefined experimental designs, such as Box-Behnken, Central Composite, and Doehlert designs, suitable for various objectives and constraints. The design can be customized with precise variables, levels, and midpoints, and Minitab will automatically generate the experimental trials and run the data analysis. Minitab provides various regression analytical tools to fit data models, including Linear, Quadratic, and Cubic models, which are commonly used in RSM modeling. Minitab software always provides an interface for easily assessing the model's fit through diagnostic plots and statistical tests. The Pareto chart was used in this study. A swift visual impression of the few factors that impact most significantly on the target response(s) is permitted by the Pareto chart. The Pareto chart bars are well-arranged from most impactful to least impactful on the target response. The assessment of the relative and statistical significance of the impacts on the target response is facilitated by the Pareto chart. The central composite design (CCD) of the response surface methodology (RSM) was used for the design of the experimental (DOE) matrix in this study, and the Minitab Statistical Software (Version 20.3.0. 3. 0) was employed to generate twenty- four (24) experimental trial runs. For its simplicity and flexibility in adjusting variables and analyzing process interactions across process factor combinations, the central composite design (CCD) was used in this study. The experimental matrix was made up of the process input and output parameters, and the results noted from the experimental trial tests comprising the variations of the process parameters made up the dat.

The main process parameters (inputs and responses) in this research study are identified in Table 1 below.

Table 1: The Process Variables (Inputs and Responses) under Investigation.

Mold Settings (Input Parameters) Under Investigation	Plastic Cup Qualities (Response Parameters) Under Investigation
Cooling Time (sec)	Weight (g)
Mold Temperature (°C)	Tensile Strength (MPa)
Injection Pressure (MPa)	Thermal Performance (W/mK)

Injection Speed (mm/s)

Table 1 above shows the plastic cup mold settings, i.e. the input parameters and the quality metrics, i.e. the response parameters under study.

Table 2. Central Composite Design (CCD) Experimental Matrix for the Data and Results.

Input Parameters				Response Parameter
Cooling Time (sec)	Mold Temp. (°C)	Injection Pressure (MPa)	Injection Speed (mm/s)	Weight (g)
16	60	80	70	33.2
25	80	90	50	36.8
15	50	70	80	32.6
20	70	50	50	34.5
15	60	70	60	32.9
18	50	60	70	33.0
30	80	90	110	36.5
15	50	60	70	32.3
25	80	75	80	34.6
23	70	60	50	35.0
17	60	90	80	32.2
15	50	95	55	32.5
18	50	80	70	34.7
20	60	70	50	35.5
16	50	50	60	33.7
19	70	60	80	34.2
30	80	90	60	36.3
17	50	90	70	36.0
19	60	50	60	36.4
21	60	70	100	32.1
23	50	70	70	33.3
30	90	80	90	38.5
16	60	80	50	34.1
27	70	90	70	36.8
15	57	95	50	32.06

3. Results and Discussion

In this study, the response surface methodology used for data analysis indicated that the selected models are quadratic. The central composite design (CCD) used suggests the use of quadratic models for the ease and flexibility of model analysis. The process input variables, namely: cooling time, mold temperature, injection pressure, and injection speed, were compared against each of the quality metrics (response variables), namely: weight, tensile strength, and thermal performance, to determine the significance and influence of the process input variables on each response. In Table 3 below, the coded coefficient table, the “coeff.” column indicates whether the impacts on the responses are positive or negative. A positive coefficient value indicates that the input variable is directly proportional to the response (i.e., an increase in the input factor will automatically give rise to an increase in the response), while a negative coefficient indicates that an increase in the input factor will lead to a decrease in the response.

The regressions analysis from the comparison of the impact of the input variables, namely: cooling time, mold temperature, injection pressure, and injection speed, against the weight response factor and their results are presented in Table 3 below.

Table 3. Coded Coefficient Table for Weight Response Variable.

Term	Coeff.	SE Coeff.	T-Value	P-Value	VIF
Constant	35.21	1.02	34.66	0.000	
Cooling Time (s)	1.22	2.69	0.46	0.659	3.88
Mold Temperature (°C)	1.08	2.20	0.49	0.635	2.86
Injection Pressure (MPa)	1.36	1.35	1.00	0.342	1.80
Injection Speed (mm/s)	-1.68	1.22	-1.38	0.201	1.14

Cooling Time (s) * Cooling Time (s)	4.37	2.17	-1.92	0.047	1.33
Mold Temperature (°C) * Mold Temperature (°C)	-0.91	2.66	-0.34	0.740	1.64
Injection Pressure (MPa) * Injection Pressure (MPa)	-0.250	0.909	-0.27	0.790	1.55
Injection Speed (mm/s) * Injection Speed (mm/s)	-1.23	1.85	-0.67	0.521	1.70
Cooling Time (s) * Mold Temperature (°C)	4.29	3.65	1.17	0.070	2.35
Cooling Time (s) * Injection Pressure (MPa)	3.30	2.31	1.43	0.058	1.94
Cooling Time (s) * Injection Speed (mm/s)	1.23	3.66	0.35	0.734	2.86
Mold Temperature (°C) * Injection Pressure (MPa)	-2.04	1.86	-1.09	0.302	1.36
Mold Temperature (°C) * Injection Speed (mm/s)	0.60	3.68	0.16	0.873	2.33
Injection Pressure (MPa) * Injection Speed (mm/s)	0.65	1.35	0.49	0.639	3.38

The results of the coded coefficient for the weight variable shown in Table 3 above portrays that the independent variables have little or no significance on the weight response, while the square term of cooling time and the interaction between cooling time and injection pressure are the most significant factors impacting on the weight response among all the factors. The square term of the cooling time has the highest impact on the response.

Table 4. Model Statistics Summary of the Weight Response Variable.

S	R2	Adj. R2	Pred. R2
1.25667	80.61%	50.45%	0.00%

The model statistics summary in Table 4 above shows that the standard error of regression (S) is relatively low at 1.257, indicating a good fit between the model predictions and the actual data points. The model's Coefficient of Determination (R2) of 80.61% explains the variance in the response variable. This very high R2 indicates that the model fits the data well. The Adj. R2 value of 50.45% is lower than the R2 value but still quite high. The Pred. R2 value of 0.00% is remarkably low and indicates that the model is poor at predicting future values of the response variable or fitting new data. Overall, the analysis shows a good model. The P-value indicates it is statistically significant. The R2 value shows it explains a large share of the variation in the response variable.

Table 5. Analysis of Variance (ANOVA) Table for Weight Response Variable.

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value
Model	14	59.0934	*****	59.0934	4.22095	2.67	0.007
Linear	4	45.9391	62.67%	29.7765	7.44414	4.71	0.025
Cooling Time (s)	1	8.6148	11.75%	0.3283	0.32831	0.21	0.659
Mold Temperature (°C)	1	34.8163	47.50%	0.3812	0.38121	0.24	0.635
Injection Pressure (MPa)	1	0.7598	1.04%	1.5876	1.58760	1.01	0.342
Injection Speed (mm/s)	1	1.7477	2.38%	3.0075	3.00749	1.90	0.201
Square	4	3.3221	4.53%	7.2009	1.80022	1.14	0.397
Cooling Time (s) * Cooling Time (s)	1	0.1306	0.18%	5.8185	5.81849	3.68	0.047
Mold Temperature (°C) * Mold Temperature (°C)	1	1.9585	2.67%	0.1856	0.18556	0.12	0.740
Injection Pressure (MPa)*Injection Pressure (MPa)	1	1.2263	1.67%	0.1191	0.11912	0.08	0.790
Injection Speed (mm/s) * Injection Speed (mm/s)	1	0.0066	0.01%	0.7045	0.70447	0.45	0.521
2-Way Interaction	6	9.8321	13.41%	9.8321	1.63869	1.04	0.461
Cooling Time (s) * Mold Temperature (°C)	1	2.3272	3.17%	2.1785	2.17846	1.38	0.270
Cooling Time (s) * Injection Pressure (MPa)	1	3.2265	4.40%	3.2265	3.22650	2.04	0.058
Cooling Time (s) * Injection Speed (mm/s)	1	1.0613	1.45%	0.1936	0.19358	0.12	0.734
Mold Temperature (°C) * Injection Pressure (MPa)	1	0.0806	0.11%	1.8898	1.88983	1.20	0.302
Mold Temperature (°C)*Injection Speed (mm/s)	1	2.5194	3.44%	0.0425	0.04246	0.03	0.873

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value
Injection Pressure (MPa) *	1	0.6171	0.84%	0.3718	0.37184	0.24	0.639
Injection Speed (mm/s)							
Error	9	14.2129	19.39%	14.2129	1.57921		
Total	23	73.3062	100.00%				

From the ANOVA table above, the developed model is highly significant (P-value = 0.0071). The contribution of 80.61% is also the expression of the percentage of the total variation in the model or the R-sq. value. The high R-sq. The value indicates that the model is a good fit for the data and can therefore be used to predict the weight response variable. The linear source makes a significant contribution to the model, with a value of 62.67% and a P-value of 0.025. The square source expresses a low contribution to the model with a value of 4.53% and a P-value of 0.397. Only the square (quadratic) term of the cooling time in this relationship shows a low P-value (0.047), which is still significant. The 2-Way (interactive) source contributes 13.41% to the overall model, which is more significant than the linear source. The injection pressure and cooling time source contributes the most to this model. The error or the unexplained variation in the overall model is 19.39%. Overall, the weight response ANOVA table, Table 5 above, suggests that the RSM model is a good fit for the data and can be used to predict the response variable. The most significant factors affecting the weight response are the square term of the cooling time factor and the interaction between the cooling time and injection pressure factors.

Regression Model of the Actual Factors for the Weight Response Variable

$$\begin{aligned} \text{Weight (g)} = & 43.2 - 0.023 \text{ Mold Temperature (}^\circ\text{C)} - 0.105 \text{ Injection Speed (mm/s)} \\ & - 0.053 \text{ Injection Pressure (MPa)} - 0.33 \text{ Cooling Time (s)} \\ & - 0.000228 \text{ Mold Temperature (}^\circ\text{C)} * \text{Mold Temperature (}^\circ\text{C)} \\ & - 0.000137 \text{ Injection Speed (mm/s)} * \text{Injection Speed (mm/s)} \\ & - 0.000049 \text{ Injection Pressure (MPa)} * \text{Injection Pressure (MPa)} \\ & - 0.0741 \text{ Cooling Time (s)} * \text{Cooling Time (s)} \\ & + 0.00101 \text{ Mold Temperature (}^\circ\text{C)} * \text{Injection Speed (mm/s)} \\ & - 0.00452 \text{ Mold Temperature (}^\circ\text{C)} * \text{Injection Pressure (MPa)} \\ & + 0.0286 \text{ Mold Temperature (}^\circ\text{C)} * \text{Cooling Time (s)} \\ & + 0.00097 \text{ Injection Speed (mm/s)} * \text{Injection Pressure (MPa)} \\ & + 0.0057 \text{ Injection Speed (mm/s)} * \text{Cooling Time (s)} \\ & + 0.0195 \text{ Injection Pressure (MPa)} * \text{Cooling Time (s)} \end{aligned}$$

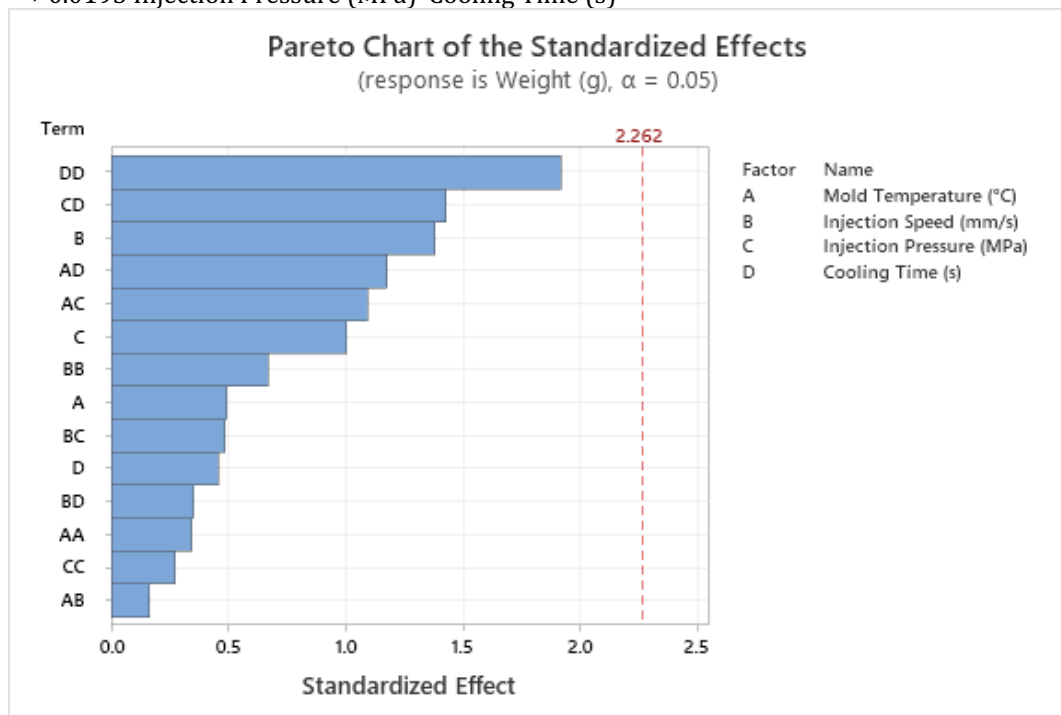


Fig 1. Weight Response Variable Pareto Chart.

The chart shows that the square (quadratic) term of the cooling time, and the interactive term of the cooling time and the injection pressure factors are the predominant influences, and the length of their bars confirms their statistical significance for the weight response. Injection speed is the most significant independent mold factor for the response.

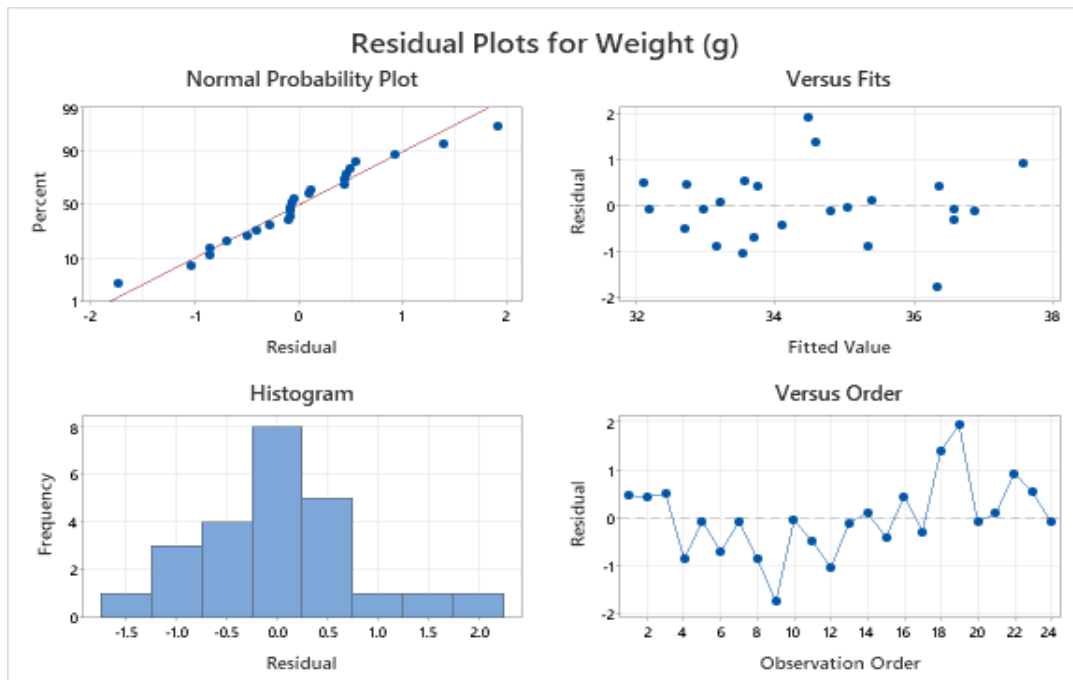


Fig 2. Weight Response Variable Residual Plots.

The residual plot of the variations of the predicted and the residuals are shown in Fig. 2. above. It is used to confirm the constant errors in the system. Fig. 2 above reveals that the errors in the predicted and the residuals are within values of errors that are limited and insignificant in the system as can be seen that all the data points in the figures lie within the acceptable ranges/ limits, and at 45° diagonal line.

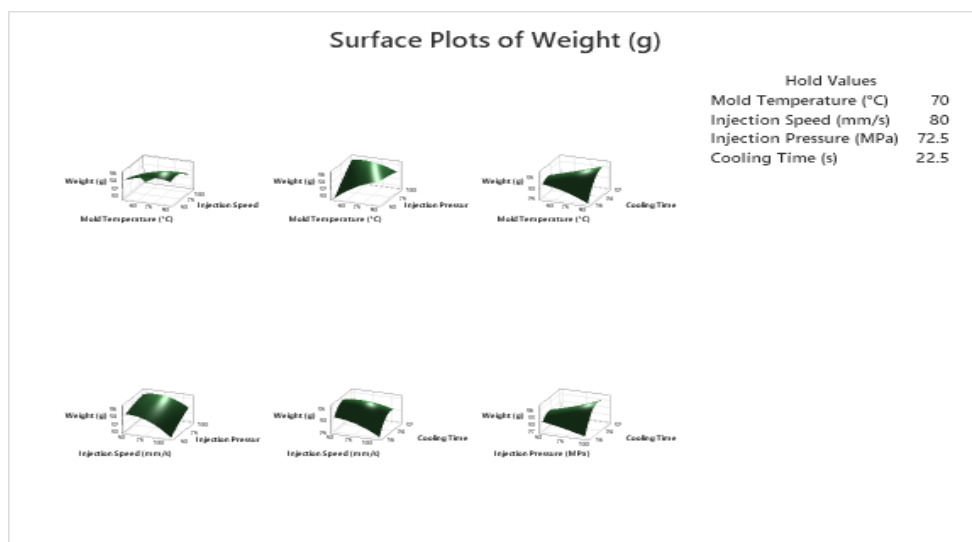


Fig 3. Weight Response Variable Surface Plots.

The surface plots above visually depict the 3D response surface with two factors on the axes. It typifies the shape of the response surface and the interaction effects. It also identified the optimal parameter settings and the operating zones.

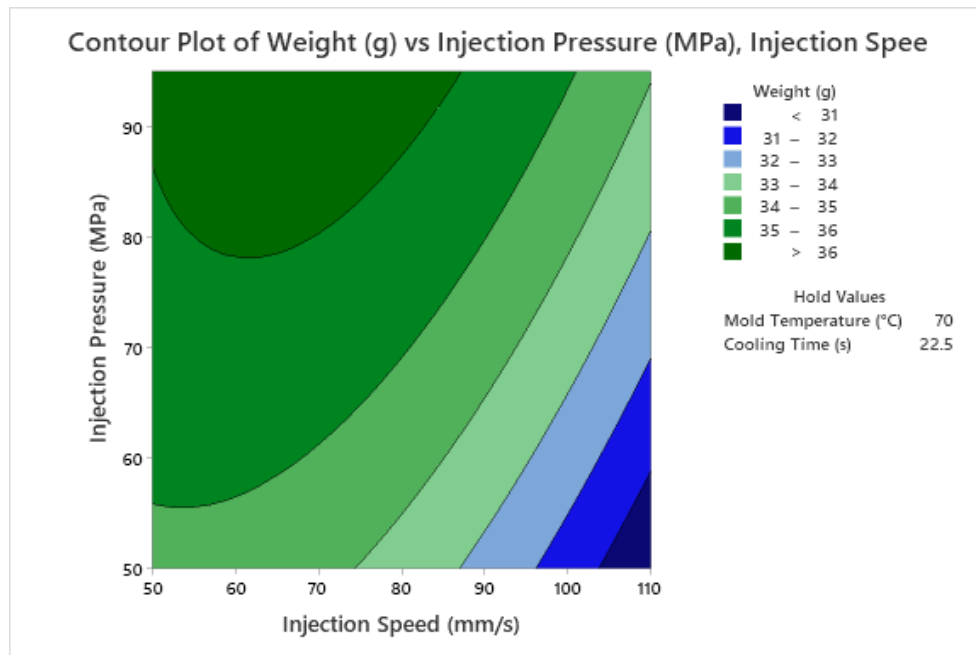


Fig 4. Contour Plot of the Weight Response Variable: Injection Pressure vs. Injection Speed.

Contour plots represent the 3D response surface in 2D by plotting contour lines of constant response. They indicate variable interactions and locate the optima. These visual analyses check assumptions, identify significant effects, assess model adequacy, and explain the response surface model for optimizing parameter settings..

3.1. Optimization Analysis

Optimal solutions for both the input variables and the target responses were obtained via Response surface optimization using 24 experimental runs. The optimal input parameter values are: cooling time - 15 s; mold temperature - 570 °C; injection pressure - 95 MPa; and injection speed - 50 mm/s. The optimal value for the weight response variable is 32.06 g. The composite or global desirability (Dg) for achieving these optimal solutions, as revealed by the response surface methodology (RSM) used, is 1 (100%).

Table 6. Optimization Solution's Table

Solution	1
Cooling Time (s)	15
Mold Temperature (°C)	57
Injection Pressure (MPa)	95
Injection Speed (mm/s)	50
Weight (g)	32.06
Tensile Strength (MPa)	31.44
Thermal Performance (W/mK)	0.360
Global Desirability	1

3.2. Analysis of Prediction

When the developed models were subjected to an accuracy test in real-world applications through a conformity test, during which different values of the process input variables were assigned within their working limits but outside the design matrix, the response surface methodology (RSM) produced predicted responses from the regression analysis. The predicted values are: cooling time - 28s; mold temperature - 750C; injection pressure - 85MPa; and finally, injection speed - 105mm/s. These values were substituted into the regression model, and the model produced a predicted value for the weight response of 32g.

Table 7. Predicted Values from the Accuracy Test in Actual Application.

Parameters	Settings
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Cooling Time (s)	28
Mold Temperature (°C)	75
Injection Pressure (MPa)	85
Injection Speed (mm/s)	105

Table 8. Prediction Results of the Weight Response Variable

Fit	SE Fit	95% CI	95% PI
45.0862	7.13667	(28.9419, 61.2304)	(28.6935, 61.4788) XX

XX denotes an extremely unusual point relative to predictor levels used to fit the model

Using the design of experiments (DOE) within the response surface methodology (RSM), this study was conducted to optimize the weight of a polypropylene plastic cup based on injection mold settings. The primary objective is to determine the optimal proportion of the weight response variable, along with the optimal values of cooling time (s), mold temperature (°C), injection pressure (MPa), and injection speed (mm/s), that will effectively optimize the weight of the finished polypropylene plastic cup. The final objective is to determine the optimal proportions of the three response variables: weight, tensile strength, and thermal performance, in the finished polypropylene plastic cup, along with the optimal values of the four input parameters: cooling time, mold temperature, injection pressure, and injection speed, that would be required to effectively optimize (maximize) the tensile strength and thermal performance response variables and effectively optimize (minimize) the weight response variable in the finished plastic cup.

A multiple iterative test molding approach, varying the process input factors, was used for the design of experiment (DOE) within the response surface methodology in this study. The objective is to evaluate the performance of the varied process input factors on the responses. The impact of variations in the mold variables on the weight factor and the performance of the finished polypropylene plastic cup was evaluated. During the experimental trials, experimental values of the process variables (input and response) were observed and recorded. A statistical design of experiment (DOE) using the central composite design (CCD) was generated for twenty-four (24) experimental runs. The process variables (input and response) make up the experimental matrix (see Table 2). The statistical software used for the experimental design (DOE) of the response surface methodology (RSM) is the Minitab Statistical Software (Version 20.3.0). For its simplicity and flexibility in variable adjustment and analysis of process interactions relating to process factor combinations, the central composite design (CCD) was employed for this research study.

The full quadratic model was employed in Minitab Software for the analysis, as suggested by the central composite design (CCD); this produces the best-fitting model for the data. Optimal solutions for each of the process variables were obtained from the analysis. The optimal solutions for the input factors are: cooling time – 15 s; mold temperature – 570°C; injection pressure – 95 MPa; and injection speed – 50 mm/s. Likewise, the optimal solution for the response variable, weight, is – 32.06 g. The Global Desirability (Dg) was 1 (100%), as revealed by the RSM for attaining the optimal solutions. From Table 5 (ANOVA table), the model is highly significant, with a p-value of 0.007. The low p-value indicates a good model fit for the data and for statistical modeling of the weight response variable.

The coefficient of determination (R²) of 80.61% indicates the proportion of variation explained by the model. The ANOVA model indicates that the square (quadratic) term of the cooling time input factor has the most significant impact on the weight response, with a p-value of 0.047. Also, from the ANOVA table, it is shown that the interaction term between the cooling time and the injection pressure input factors has a close impact on the response, with a p-value of 0.058. Generally, the ANOVA model indicates that the RSM model is good and fit for the data analysis and for the statistical modeling of the data.

The efficient optimization of the injection mold settings can be achieved using RSM, as revealed in this study. The injection mold settings (as input factors) were designed to determine optimal solutions for each response (quality attribute) of the finished polypropylene plastic cup. Conformity tests were performed to assess the models' accuracy. Various values were assigned to the input factors within their working limits, but they differed from the design matrix. Using this approach, the response surface methodology (RSM) produced new regression models to predict the responses. The

input factor values used for the conformity tests were: cooling time - 28s; mold temperature - 750 °C; injection pressure - 85MPa; and injection speed - 105mm/s. The predicted values of the response variables are: weight - 45g; tensile strength - 45MPa; and thermal performance - 0.36W/mK.

4. Conclusion

This study investigates the optimization of key injection molding parameters—cooling time, mold temperature, injection pressure, and injection speed—using Response Surface Methodology (RSM) to enhance the quality of polypropylene plastic cups. A Central Composite Design (CCD) with 24 experimental runs was employed using Minitab software to systematically evaluate the effects of these parameters on three critical quality responses: weight, tensile strength, and thermal performance. The experimental results were analyzed using full quadratic models, which enabled the identification of both main and interaction effects among variables. The optimal processing conditions were determined as follows: cooling time of 15 seconds, mold temperature of 57.27°C, injection pressure of 95 MPa, and injection speed of 50 mm/s. Under these conditions, the optimized responses were a cup weight of 32.06 g, tensile strength of 31.44 MPa, and thermal performance of 0.36 W/mK, achieving a global desirability value of 1 (100%). Statistical validation confirmed the robustness of the models, with p-values below 0.05, Variance Inflation Factor (VIF) values less than 4, and a coefficient of determination (R^2) of 80.61%, indicating strong model significance and fit. The analysis also revealed that the quadratic term of cooling time and its interaction with injection pressure significantly influenced weight optimization. Overall, the study demonstrates that RSM is an effective tool for simultaneously minimizing weight while maximizing mechanical and thermal properties, and provides practical guidance for improving plastic cup production efficiency and quality.

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