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Optimization of Injection Mold Settings and their Impact on the Final Plastic Product (Cup) Quality Thermal Performance

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Abstract: Injection molding requires careful optimization of production parameters to achieve high quality plastic products. This research investigates optimizing injection mold settings, namely: mold temperature, injection speed, injection pressure, and cooling time as input parameters and their impact on the final plastic cup quality of thermal performance as the output parameter. Thermal performance refers to the cup's ability to maintain the temperature of hot or cold liquids inside. Thermal performance can be a significant indicator of a plastic cup's quality, particularly influencing its ability to insulate and retain desired temperatures. The aim of this study is to develop an optimal mold setting combinations to improve key cup quality metrics, namely: tensile strength, thermal performance and weight. This study utilizes response surface methodology design of experiments (DOE) with multiple iterative test molding trials varying the selected parameters to achieve the optimized product quality. The molded cup samples are quantitatively evaluated for the target quality attributes. Analysis of variance statistical analysis determined the optimized parameter settings that maximize quality metrics. The results provide guidance for plastic cup manufacturers to optimize their molding operations. This research demonstrates that a systematic DOE approach allows molders to economically determine the ideal production settings for their specific molds and materials to improve quality control. The methods could be applied to other injection molded plastic products to reduce defects.

Keyword: Plastic Cup, Injection Mold Settings, Response Surface Methodology (RSM), Tensile Strength, Thermal Performance, Weight.

INTRODUCTION

The plastic cup, seen in homes, restaurants, and offices around the world, is a marvel of modern manufacturing. Yet, the production relies on a crucial element, which is the production mold. This study focuses on the optimization of production molds and their influence on plastic cup quality. Production molds play a pivotal role in shaping the plastic cups' physical features and performance. Investigating how variations in-mold design, material, and manufacturing processes affect the final product quality, is essential for enhancing consistent product quality, minimal waste, sustainability, efficiency, and maintaining affordability of plastic cup production.

Injection molds are precision machined metal tools that enable high-bulk production of plastic parts through the injection molding process. They comprise of two main components - the core and cavity - that come together to form the mold cavity geometry. Intricate details are machined into the steel or aluminum mold blocks to impart shapes, textures, and features onto the plastic parts (Masato et al., 2022). The two halves are mounted into a molding machine where plastic is injected into the cavity under heat and pressure to form the parts. Mold designs include optimized runners, gates, cooling channels, and ejection systems to ensure efficient production (Cunha et al., 2025). Injection molds require extensive CNC machining, grinding, EDM, and polishing to achieve tight tolerances for precise plastic parts. Highly intricate mold geometries with conformal cooling channels, movable slides, and multiple cavities are possible through advanced machining methods (Kanbur et al., 2022). Injection molds support mass production of precision plastic components across almost all industries. Injection molds function by clamping the two mold halves together, creating a cavity into which molten plastic is injected under pressure through runner channels that lead to the entrance gate (Hossain et al., 2025). The plastic fills the cavity, taking the shape of the full mold geometry.

Cooling channels adjoining the cavity quickly cool and solidify the plastic. Once cooled, the mold will open and the ejector pins will push the solidified plastic part out of the opened cavity, and the mold would be now ready again for the next injection cycle (Minh et al., 2023). The mold design must balance efficient filling of the cavity before the plastic freezes, while enabling uniform cooling and easy ejection of the part. Keys to proper functioning include optimized runner placement to direct flow, adequate venting to release trapped gases, sufficient pressure to pack the cavity, coordinated timing of cooling and ejection, and robust ejector pins to remove the part once solidified, all while maintaining tight tolerances and minimal flash (Yang and Lin, 2025). Since its origins in the 1930s, injection molding has advanced tremendously, enabled by evolving mold materials and manufacturing methods that have increased mold complexity and proficiencies over the decades. 1930's – 1950's saw a growth and refinement of the injection molding techniques, while the 1960's – to date presented a more modern advancement of the technology. As noted by Changsheng (2025), "The 1940s and 1950s saw the development of stronger mold materials and more intricate mold designs". Multi-cavity molds radically increased productivity in the 1960s. According to Dabhi (2025), "The multi-cavity mold was an innovation that allowed much higher output rates".

Through the 70s-80s, computers assisted in analysis, design, and machining, improving precision. The introduction of CAD/CAM systems in the 1970's-80's revolutionized mold design and manufacturing (Titu and Pop, 2024). Currently, CNC machining, electrical discharge machines (EDM) and 3D printing permit rapid prototype and production mold making with conformal cooling and micro-molding abilities as highlighted in: "Design and Optimization of Conformal Cooling Channels for Increasing Cooling Efficiency in Injection Molding" (Wang. and Lee, 2023). For over 70+ years now, new technologies in materials, manufacturing, and analysis have expanded injection molding applications across industries by enabling sophisticated, high-volume production molds. Plastic injection molding is a global process presently, shaping everything from toys and cups to car parts and medical devices. But its journey from a niche technique to a universal production powerhouse is quite intriguing, expressed in: "Advanced Injection Molding Methods: Review" (Czepiel et al. 2023).

Bahreini et al. (2013) conducted research directly related to optimizing the manufacturing process parameters for plastic cups. They focused specifically on injection molding parameters for polystyrene (PS) cups and modeled the effects on cup compressive strength. A central composite design was used to vary three injection molding factors - injection velocity, pressure, and cooling time. PS cups were molded based on the design and tested for compressive strength. Quadratic regression models were developed to correlate the process parameters to the compressive strength response. The models showed cooling time having the most significant effect, with an optimum combination of parameters identified to maximize compressive strength. Khan et al. (2015) analyzed how changes in injection molding parameters affect the quality of molded polypropylene plastic cups using design of experiments. The researchers varied five factors - melt temperature, mold temperature, injection velocity, packing pressure, and cooling time - and evaluated their influence on responses including cup weight, wall thickness distribution, tensile strength, and surface defects. Statistical analysis of the DOE results found injection velocity and packing pressure had the most dominant effects, with lower velocities and moderate packing reducing defects. There were also significant interactions between factors.

Optimization determined the ideal combinations of velocity, pressure, temperatures, and cooling to minimize quality issues like variation in weight and tensile strength. The research demonstrated that systematically optimizing process parameters using DOE allows identification of optimal settings for injection molding quality plastic cups. In 2013, Karaağaç conducted research on optimizing the injection molding process, but focused on a different plastic product - a plastic dustpan. Their work is still relevant though as they used a similar experimental optimization approach. They studied the effects of injection molding settings like melt temperature, packing pressure, and cooling time on the mechanical properties of plastic dustpans made from polypropylene copolymer. A Taguchi L27 orthogonal array was used to design the combinations of parameters. Dustpan samples were manufactured and tested for flexural strength, impact strength, and other properties. The Taguchi analysis identified optimal process parameter settings that maximized the measured responses. Kamaruddin (2020) tackled the multi-faceted challenge of optimizing injection molding parameters for polypropylene (PP) cups. Seeking to simultaneously improve tensile strength, reduce wall thickness, and minimize cycle time, their research employed a powerful tool, Grey Relational Analysis (GRA). This method helps prioritize and optimize multiple, sometimes conflicting, quality characteristics.

The study focused on four key parameters: injection pressure, melt temperature, holding time, and cooling time. Utilizing an experimental design, the researchers measured their impact on the three chosen quality measures. Notably, interactions between parameters were observed, requiring a sophisticated approach to optimization. GRA effectively analyzed these complex relationships, assigning "grey relational coefficients" to each parameter combination based on its desirability regarding the target quality values. Higher coefficients indicated better performance. Through optimization analysis, the researchers identified the setting that maximized the overall grey relational grade, representing the "sweet spot" for balancing the conflicting objectives. This optimal setting delivered improved tensile strength while reducing wall thickness and cycle time compared to conventional settings. This translates to stronger, lighter cups produced in a shorter time, leading to potential cost savings and increased efficiency. However, the authors acknowledged the limitations of their study, primarily focusing on a single cup design and material. They encouraged further research on optimizing diverse cup configurations and plastic types to expand the applicability of their findings. In conclusion, Kamaruddin et al.'s work showcases the effectiveness of GRA for optimizing injection molding parameters for PP cups. Their findings pave the way for producing stronger, lighter, and faster-produced cups, demonstrating the potential of this approach for improving quality and efficiency in the plastic cup industry.

The theoretical foundation of this research project centers on the principles of optimization and quality management. Optimization, as defined by Dung. (2025), is “the process of finding the conditions that give the maximum or minimum value of a function”. In the case of plastic cup production, the optimization process involves selecting and manipulating mold parameters to maximize the quality of the finished product. He et al. (2024) opined that “Optimization techniques are essential tools for finding the optimal combinations of variables to meet these objectives”.

The theoretical underpinnings of this research integrate optimization and the application of Response Surface Methodology. According to Kim et al. (2025), “Response Surface Methodology is a collection of mathematical and statistical techniques for empirical model building and system optimization”. These concepts are foundational to enhancing the quality of plastic cups through systematic optimization of the mold process parameters, as highlighted by Taguchi: “Optimizing process parameters leads to improved product quality”. (Kim et al., 2025). Previous research emphasizes the importance of optimizing mold parameters to improve plastic cup manufacturing. These studies also highlight using Response Surface Methodology for injection mold optimization. The existing literature provides a foundation for the current study. Response Surface Methodology (RSM) is a powerful statistical and mathematical technique used for optimizing processes, improving product quality, and understanding the relationships between input variables and response variables. RSM is particularly valuable in industries where experimentation and optimization are essential, such as manufacturing, engineering, chemistry, and product design. RSM is valuable for finding the best combination of factors that lead to the desired results while minimizing experimentation and resource use. This study aims to expand on prior work by looking specifically at optimizing input materials. The goal is gaining new insights into how materials affect plastic cup quality. In summary, earlier research establishes injection molding process optimization and various methodologies as key to better plastic cup production. The current study will contribute additional knowledge focused on injection mold settings optimization to build on this prior work. The aim is advancing the field's understanding of optimizing injection molding for improved quality and performance.

The manufacturing industry continuously seeks to find a balance between the pursuit of quality and efficiency, striving to produce high-quality products while optimizing resource utilization. As stated by kapulin and Russkikh (2020), “The general goal of a manufacturing operation is to produce goods that satisfy consumer demands while making efficient use of resources”. In this context, the production of plastic cups serves as an illustrative example. These everyday used items seemingly simple are yet vital for human use. This study aims to investigate the interplay between production mold parameters and plastic cup quality, seeking to reveal insights that can lead to improved production efficiency, optimized mold settings, and ultimately, the delivery of high-quality plastic cups with optimized characteristics. While it’s undisputable that plastic cups are convenient, the production faces a critical challenge: achieving optimal quality while maintaining efficiency and sustainability. The cause however can be said to be the production molds. These apparently simple tools significantly impact the final cup’s strength, durability, aesthetics, and even environmental/ social footprint. Yet, current mold designs often fall short of optimal performance. Flawed mold designs lead to inconsistent shapes, and weak points, compromising cup quality. These flaws translate into leaks, cracks, and premature failure, over-weight frustrating consumers and increased waste. The consequences of sub-optimal mold configurations can be material waste, longer production cycles, and increased energy consumption. It adds to production cost and as well as generates unnecessary environmental burdens. Balancing the quality, efficiency, and cost becomes a balancing phenomenon. Investing in high-quality molds might be cost prohibitive, while cheaper options often introduce quality and sustainability deficiencies. And obtaining the sweet spot for each specific cup design and production context remains a challenge.

Injection mold parameters as seen hereafter can affect the production and the final plastic (cup) quality in several ways, namely: 1. Melt Temperature: Melt temperature refers to the temperature at which the plastic polymer is melted and injected into the mold cavity. Higher melt temperatures can improve flow and enable the polymer to fill thin-walled sections of the mold more easily. However, too high of a melt temperature can cause material degradation through thermal breakdown of polymer chains. Optimal melt temperature depends on factors like polymer type, mold design, presence of fillers, etc. Key cup qualities affected by melt temp include surface finish, impact strength, war-page, crystallinity, and cycle time. In summary, melt temperature is a critical injection molding process parameter as it influences polymer flow into the mold, thermal degradation, and final plastic cup properties. 2. Injection Speed: This refers to the velocity at which the molten polymer is injected into the mold cavity during the injection molding process. Faster injection speeds can promote better filling of the mold, ensuring all cavities and details are replicated. However, too fast of an injection speed can result in jetting - where polymer partially solidifies and doesn't fill the mold properly. Slower injection speeds allow gases to vent and let the material front flow advance uniformly, minimizing defects. But slow speeds could lead to premature freezing. Optimal injection speed depends on factors like part geometry, gate design, polymer viscosity, mold temperature, etc.

For plastic cups, injection speed impacts properties such as surface finish, war-page, shear thinning, and weld line strength. In summary, the injection speed of an injection mold affects mold filling behavior and final cup mechanical properties and appearance and it's interaction with other mold parameters may also have its influence on the output quality hence be strongly considered for optimization. 3. Injection Pressure: This refers to the amount of force applied to inject the molten polymer into the mold cavity during injection molding. Higher injection pressures enable the polymer to better fill thin sections and complex geometries of a mold. However, excessively high pressure can cause flash (leakage from the mold), war-page, and increased part stress. Lower injection pressures may result in incomplete mold filling, especially in detailed areas. Optimal injection pressure ensures complete cavity filling while minimizing flash and other defects. For plastic cups, injection pressure impacts replication of cup details like logos, handle strength, war-page control, and cycle time. In summary, injection pressure is important for plastic cup production to ensure high mold replication while preventing defects. 4. Cooling Time: This refers to the duration the molded plastic part remains in the mold to solidify and cool to an ejectable temperature. Longer cooling times allow more time for the molten polymer to solidify and stabilize dimensionally once it fills the mold. However, excessively long cooling reduces the cycle time and productivity. Short cycles are important for high volume products like cups. Insufficient cooling time can lead to war-page, distorted features, and poor ejection. The part needs to adequately solidify before de-molding.

Cooling time requirements depend on plastic thickness, thermal properties, mold design, and other factors. For plastic cups, cooling time impacts cycle efficiency, dimensional stability, war-page control, crystallinity, and brittleness. In summary, cooling time is a crucial injection molding process factor for plastic cups to ensure good dimensional and thermal stability. 5. Mold Temperature: This refers to the operating temperature of the steel mold during the injection molding process. Higher mold temperatures keep the polymer molten longer, improving flow into thin sections, but can increase cycle time. Colder mold temperatures promote faster cooling and solidification, but may lead to premature freezing and short shots. Optimal mold temperature balances flow with efficient cooling and dimensional stability. For amorphous plastics like polystyrene (PS) and polyethylene terephthalate (PET), higher mold temperatures are used to reduce brittleness and improve flow. For semi-crystalline plastics like polypropylene (PP), lower mold temperatures are preferred to increase crystallinity. In plastic cups, mold temperature impacts properties like surface finish, shrinkage, war-page control, and de-molding. In summary, identifying the ideal mold temperature is crucial for plastic cup manufacturing to balance polymer flow with proper solidification and de-molding. 6. Mold Design and Geometry: The mold design must precisely mirror the intended shape of the final product, and the geometry of the mold is especially critical for intricate or complex components.

The mold design and geometry encompass several critical elements, including: (i) Mold Cavity Dimensions: The design of the mold cavity must precisely mirror the intended shape of the final product. This includes the size, minimum gap (minimum wall thickness of the part), and core size. The number of cavities in the mold impacts cycle time and productivity. More cavities improve efficiency but require robust runners and cooling. (ii) Runners and Gates: These are included in the mold design to direct the flow of the molten material into the mold cavity. They are essential for the proper filling of the mold and the quality of the final product. (iii) Cooling Channels: An effective cooling system is essential during the molding process to ensure proper temperature control. Mold designers must strategically place channels and cooling lines to maintain uniform temperatures and facilitate the solidification of the molten material. (iv) Venting and Ejection: Adequate venting is crucial to allow gases to escape during the molding process. Additionally, the mold design must allow for the ejection of the final product, which may require special designs for complex components or undercuts. (v) Mold Material: The choice of mold material is crucial and depends on various factors such as the type of material, production volume, and desired product characteristics. Common mold materials include tool steel, aluminum, and pre-hardened steel, each with its own set of advantages and limitations. (vi) Geometry and Complexity: The geometry of the mold is especially critical for intricate or complex components. Computer-Aided Design (CAD) tools are extensively used to create detailed and accurate mold designs, ensuring that every contour and detail of the final product is captured. In summary, a well-designed mold with optimized runners, cooling layout, texturing, and components is crucial for plastic cup manufacturing to enable high quality, high efficiency production. These elements are essential for achieving consistent and high-quality manufacturing results in plastic injection molding.

Thermal performance refers to the cup's ability to maintain the temperature of hot or cold liquids inside. Thermal performance can be a significant indicator of a plastic cup's quality, particularly influencing its ability to insulate and retain desired temperatures. The benefits of good thermal performance include: (i) Improved temperature maintenance: High-performance cups effectively insulate hot drinks from the environment, keeping them warmer for longer. Conversely, they insulate cold drinks, preventing them from warming up quickly. (ii) Enhanced user experience: Maintaining desired temperatures ensures a pleasurable drinking experience, preventing lukewarm coffee or scalding hot beverages. (iii) Reduced condensation: Good insulation minimizes condensation on the cup's exterior, improving grip and comfort while preventing water rings on surfaces. Desired thermal performance specs will usually depend on intended use - cups for hot drinks need to retain heat longer while cold drink cups must avoid condensation and keep contents cold. Testing thermal performance should involve fill tests with hot and cold water to measure heat loss/gain rates over time compared to desired targets. Balance is needed between thermal performance, cost and other factors like durability and ease of use when setting specs. But insulation is a key purchasing driver. Consistent thermal performance testing ensures plastic cups maintain the desired temperature retention and insulation properties for their intended application.

The significance of this study is of great importance to both the manufacturers and the consumers. In the case of the manufacturers, it would bring a better understanding of injection mold parameter influences on cup quality; Identification of optimized mold settings for maximum quality; Improved production process efficiency and yield; Potential defects and waste reduction; Increased profits resulting from: (i) Improved customer satisfaction due to higher quality cups, (ii) More efficient manufacturing process and higher yields, and finally, (iii) Reduced material waste from defects. On the side of the consumers, this study would enhance, (i) Improved cup quality and performance through optimized manufacturing, (ii) Increased customer satisfaction due to higher quality cups, and (iii) Enhanced environmental sustainability by reducing waste from poor quality cups. In summary, optimizing the injection molding process through this study holds value for both consumers, in receiving higher quality, longer lasting cups, and manufacturers in gaining process insights to improve quality, productivity, and profitability. The history of plastic injection molds is interwoven with the evolution of various industries. It has enabled: (a) Mass production of complex and affordable products; (b) Lightweight and durable materials in diverse applications; (c) Technological advancements in various sectors, from automotive to healthcare. The future of plastic injection molding holds promise for: (1) Sustainable materials and processes to address environmental concerns; (2) Advanced functionalities like microfluidics and nano-composites; (3) Additive manufacturing integration for customized and on-demand production. The story of plastic injection molds is one of continuous innovation, propelled by the quest of efficiency, quality, and versatility. As technology continues to advance, this significant process will undoubtedly continue to shape our world in exciting new ways.

The experimental study of the impact of the production (injection) mold settings, namely: mold temperature, injection speed, injection pressure, and cooling time as input parameters on the final plastic cup's quality of thermal performance as the output parameter, using the response surface methodology design of experiment (DOE) for analysis is the gap this research study covered.

METHOD

This study began by identifying the key plastic cup qualities covering structural, durability and the user-experience aspects. Identifying the key injection mold parameters (factors) affecting the key cup qualities. Conducting experimental trials using varying mold settings to assess their performance, and then, evaluating the impact of the mold parameters on quality and efficiency. Optimizing and developing guidelines for mold settings to support plastic cup quality that will create a win-win situation for manufacturers and consumers. Study and observation of the interactions between the various mold parameters against the quality metrics as against the individual parameters. Thermal performance refers to the cup's ability to maintain the temperature of hot or cold liquids inside. Thermal performance can be a significant indicator of a plastic cup's quality, particularly influencing its ability to insulate and retain desired temperatures. Several key mold parameters were selected as factors for optimization based on their expected influence on the plastic cup quality attributes of interest. The factors chosen were: mold temperature, injection speed, injection pressure, and finally, cooling time. These parameters were identified based on general knowledge of injection molding dynamics and their importance in affecting the desired cup properties. Their selection considered the potential interactions between the settings of these variables as well. By focusing the experimental design and response modeling on these chosen factors, the aim was to efficiently map the process settings most critical to optimizing the specified cup quality parameters.

The software used for this study and analysis is Minitab Statistical Software (version 20.3.0). It is a powerful statistical software package used for data analysis, process improvement, and Six Sigma projects. It's known for its user-friendly interface, making it accessible to both statisticians and non-statisticians alike. Minitab is a valuable tool for anyone using RSM to optimize processes and products. It has comprehensive RSM features, and excellent data visualization capabilities make it a popular choice in various fields. It is widely used in fields such as engineering, manufacturing, and research to analyze and optimize processes, improve product quality, and reduce costs. Minitab offers various pre-defined experimental designs, like Box-Behnken, Central Composite, and Doehlert designs, suitable for different objectives and constraints. You can customize these designs by specifying factors, levels, and center points. Minitab automatically generates the experimental runs, saving you time and effort. Once you collect data from your experiments, Minitab helps you analyze it efficiently. It offers various regression analysis tools to fit models to your data, including square and cubic models commonly used in RSM. You can easily assess the model's fit using diagnostic plots and statistical tests.

The Pareto chart provides a quick visual overview of the most significant factors and interactions affecting the response. The Pareto chart allows rapid identification of the vital few factors with the greatest impact on the response being analyzed. Bars are ordered from most significant to least. The Pareto Chart allows assessing the relative importance and statistical significance of effects. The Pareto chart also is used to identify the vital few factors to focus on for the response.

Table 1: Input and Output Parameters under Study

PLASTIC CUPS QUALITIES UNDER STUDY	MOLD PARAMETERS UNDER STUDY
Tensile Strength (MPa)	Mold Temperature (^{0}C)
Thermal Performance (W/mK)	Injection Speed (mm/s)
Weight (g)	Injection Pressure (MPa)
	Cooling Time (sec)

Table 1 is the table of the plastic cup qualities under study against the mold parameters under investigation.

Table 2: Central Composite Design (CCD) Matrix Showing Experimental Results and Data

INPUT PARAMETERS				OUTPUT PARAMETER
Mold Temp. (^{0}C)	**Injection Speed (mm/s)**	**Injection Pressure (MPa)**	**Cooling Time (sec)**	**Thermal Performance (W/mK)**
60	70	80	16	0.21
80	50	90	25	0.33
50	80	70	15	0.2
70	50	50	20	0.15
60	60	70	15	0.23
50	70	60	18	0.2
80	110	90	30	0.3
50	70	60	15	0.22
80	80	75	25	0.27

70	50	60	23	0.24
60	80	90	17	0.26
50	55	95	15	0.35
50	70	80	18	0.27
60	50	70	20	0.22
50	60	50	16	0.2
70	80	60	19	0.24
80	60	90	30	0.3
50	70	90	17	0.28
60	60	50	19	0.22
60	100	70	21	0.25
50	70	70	23	0.23
90	90	80	30	0.35
60	50	80	16	0.27
70	70	90	27	0.36

RESULT AND DISCUSSION

For the response surface methodology data analysis employed in this research study, the software used the full quadratic model as suggested by the software to be the best model to fit the data and the analysis. The central composite design (CCD) was used in this research study for the experimental design. To find the significance and impact of the input parameters against the output parameters, Response Surface compares the input parameters (mold settings) against each quality response. The coded coefficient table helps to tell if the impacts are positive or inverse using the "coeff." column. A positive coefficient value indicates that the factor is directly proportional to the response (an increase in the factor leads to an increase on the response) while a negative coefficient value indicates an inverse relationship or impact from the factor to the response (an increase on the factor leads to a decrease on the response). The response surface regression analysis of the response variable, thermal performance (W/mK) versus the input parameters, namely: mold temperature (^{0}C), injection speed (mm/s), injection pressure (MPa), and cooling time (sec), produced the following analytical results:

Table 3: Coded Coefficient Table for Thermal Performance Response Variable

Term	Coeff.	SE Coeff.	T-Value	P-Value	VIF
Constant	0.2842	0.0225	12.63	0.0000	
Mold Temperature (°C)	-0.0274	0.0488	-0.56	0.589	26.86
Injection Speed (mm/s)	-0.0057	0.0269	-0.21	0.838	6.14
Injection Pressure (MPa)	0.0021	0.0300	0.07	0.946	10.80
Cooling Time (s)	0.0905	0.0595	1.52	0.163	47.88
Mold Temperature (°C)*Mold Temperature (°C)	-0.0699	0.0589	-1.19	0.266	17.64
Injection Speed (mm/s)*Injection Speed (mm/s)	-0.0420	0.0409	-1.03	0.331	7.70
Injection Pressure (MPa)*Injection Pressure (MPa)	0.0272	0.0201	1.35	0.209	1.55
Cooling Time (s)*Cooling Time (s)	-0.0606	0.0481	-1.26	0.239	10.33
Mold Temperature (°C)*Injection Speed (mm/s)	-0.0112	0.0815	-0.14	0.894	20.33
Mold Temperature (°C)*Injection	-0.0024	0.0412		0.955	

Pressure (MPa)			**-0.06**		**9.36**
Mold Temperature (°C)*Cooling Time (s)	**0.1111**	**0.0909**	**1.22**	**0.249**	**25.35**
Injection Speed (mm/s)*Injection Pressure (MPa)	**-0.0373**	**0.0298**	**-2.93**	**0.017**	**5.38**
Injection Speed (mm/s)*Cooling Time (s)	**0.0307**	**0.0810**	**1.00**	**0.345**	**29.86**
Injection Pressure (MPa)*Cooling Time (s)	**-0.0118**	**0.0511**	**-0.23**	**0.823**	**15.94**

The Summary of Table 3 above suggests that all the independent factors have no significance on the thermal performance response variable while cooling time is the most significant among the factors having a P-value at 0.163. The square terms also show no significant influence on the thermal performance response variable. Additionally, the 2-way interactive term - Injection Speed * Injection pressure show huge significant impact on the thermal performance response variable with a P-value of 0.017 but the impact is inverse to the response.

Table 4: Model Summary Statistics for the Thermal Performance Response Variable

S	R-Sqr.	R-Sqr. (Adj.)	R-Sqr. (Pred.)
0.0278362	**89.68%**	**73.62%**	**0.00%**

From the model summary statistics table above, the standard error of regression (S) at 0.0278 is relatively low, indicating a good fit between the model predictions and the actual data points. The R-sqr. value of 89.68% indicates that the model explains 89.68% of the variance in the response variable. This is a relatively high value, suggesting that the model fits the data to a very good extent and can be used to predict and model the thermal performance response variable. The adjusted R-sqr. value of 73.62% is lower than the R-sq value. This suggests that the model is not over-fitting the data, as the adjusted R-sq takes into account the number of independent variables in the model. The predicted R-sqr. value of 0.00% is surprisingly low and suggests that the model is too poor at predicting future values of the response variable. Overall the model appears to be statistically significant and explains a large portion of the variance in the response variable.

Table 5: Analysis of Variance Table for the Thermal Performance Response Variable

Source	df	Seq. SS	Contribution	Adj. SS	Adj. MS	F-value	P-value
Model	**14**	**0.060589**	**89.68%**	**0.060589**	**0.004328**	**5.59**	**0.007**
Linear	**4**	**0.049270**	**72.92%**	**0.023840**	**0.005960**	**7.69**	**0.006**
Mold Temperature (°C)	**1**	**0.013867**	**20.52%**	**0.000243**	**0.000243**	**0.31**	**0.589**
Injection Speed (mm/s)	**1**	**0.000585**	**0.87%**	**0.000034**	**0.000034**	**0.04**	**0.838**
Injection Pressure (MPa)	**1**	**0.033409**	**49.45%**	**0.000004**	**0.000004**	**0.00**	**0.946**
Cooling Time (s)	**1**	**0.001409**	**2.09%**	**0.001792**	**0.001792**	**2.31**	**0.163**
Square	**4**	**0.002781**	**4.12%**	**0.000943**	**0.000943**	**1.22**	**0.369**
Mold Temperature (°C) * Mold	**1**	**0.001694**	**2.51%**	**0.001090**	**0.001090**	**1.41**	**0.266**

Temperature (°C)							
Injection Speed (mm/s) * Injection Speed (mm/s)	**1**	**0.000034**	**0.05%**	**0.000818**	**0.000818**	**1.06**	**0.331**
Injection Pressure (MPa) * Injection Pressure (MPa)	**1**	**0.000880**	**1.30%**	**0.001417**	**0.001417**	**1.83**	**0.209**
Cooling Time (s) * Cooling Time (s)	**1**	**0.000173**	**0.26%**	**0.001231**	**0.001231**	**1.59**	**0.239**
2-Way Interaction	**6**	**0.008538**	**12.64%**	**0.001423**	**0.001423**	**1.84**	**0.198**
Mold Temperature (°C) * Injection Speed (mm/s)	**1**	**0.001221**	**1.81%**	**0.000015**	**0.000015**	**0.02**	**0.894**
Mold Temperature (°C) * Injection Pressure (MPa)	**1**	**0.000025**	**0.04%**	**0.000003**	**0.000003**	**0.00**	**0.955**
Mold Temperature (°C) * Cooling Time (s)	**1**	**0.000637**	**0.94%**	**0.001461**	**0.001461**	**1.89**	**0.203**
Injection Speed (mm/s) * Injection Pressure (MPa)	**1**	**0.005883**	**8.71%**	**0.006648**	**0.006648**	**8.58**	**0.017**
Injection Speed (mm/s) * Cooling Time (s)	**1**	**0.000732**	**1.08%**	**0.000769**	**0.000769**	**0.99**	**0.345**
Injection Pressure (MPa) * Cooling Time (s)	**1**	**0.000041**	**0.06%**	**0.000041**	**0.000041**	**0.05**	**0.823**
Error	**9**	**0.006974**	**10.32%**	**0.000775**	**0.000775**		
Total	**23**	**0.067562**	**100.00%**				

The ANOVA table above shows that from the model source, the P-value of the model is 0.007, which is less than 0.05 and the contribution of 89.68% of the model (quadratic source) expresses the percentage of the total variation in the model that can be explained (R-sqr. value). This is a very high value, suggesting that the model is a good fit for the data and can be used to predict and model the response variable. The linear source shows total contribution to the model with 72.92% and total P-value of 0.006. This means that each of these factors has a statistically significant linear relationship with the model. The cooling time factor is the most significant to thermal performance with P-value of 0.163. The square source shows low contribution to the model with 4.12% and a P-value of 0.369. The interaction between the Injection Speed and Injection pressure show huge significant impact with P-value of 0.017 with a contribution of 8.71% to the overall model. The error or unexplained variations in the overall model is 10.32%. Overall, this table suggests that the RSM model is a good fit for the data and can be used to predict the response variable. The most important factors affecting the thermal performance response variable are the interaction term between injection speed and injection pressure.

Thermal Performance Regression Model

The Regression Model of the thermal performance response variable is shown below:

Thermal Performance (W/mK) = -0.483 + 0.0083 Mold Temperature (°C)
+ 0.00989 Injection Speed (mm/s)
+ 0.00457 Injection Pressure (MPa)
- 0.0150 Cooling Time (s)
- 0.000175 Mold Temperature (°C)*Mold Temperature (°C)
- 0.0000047 Injection Speed (mm/s)*Injection Speed (mm/s)
+ 0.000054 Injection Pressure (MPa)*Injection Pressure (MPa)
- 0.001077 Cooling Time (s)*Cooling Time (s)
- 0.0000019 Mold Temperature (°C)*Injection Speed (mm/s)
- 0.0000005 Mold Temperature (°C)*Injection Pressure (MPa)
+ 0.0000741 Mold Temperature (°C)*Cooling Time (s)
- 0.0000129 Injection Speed (mm/s)*Injection Pressure (MPa)
+ 0.0000359 Injection Speed (mm/s)*Cooling Time (s)
- 0.0000070 Injection Pressure (MPa)*Cooling Time (s)

The Pareto chart shows that injection speed/ injection pressure interaction and the cooling time are the predominant influences and the length of their bars confirms their statistical significance on the thermal performance response.

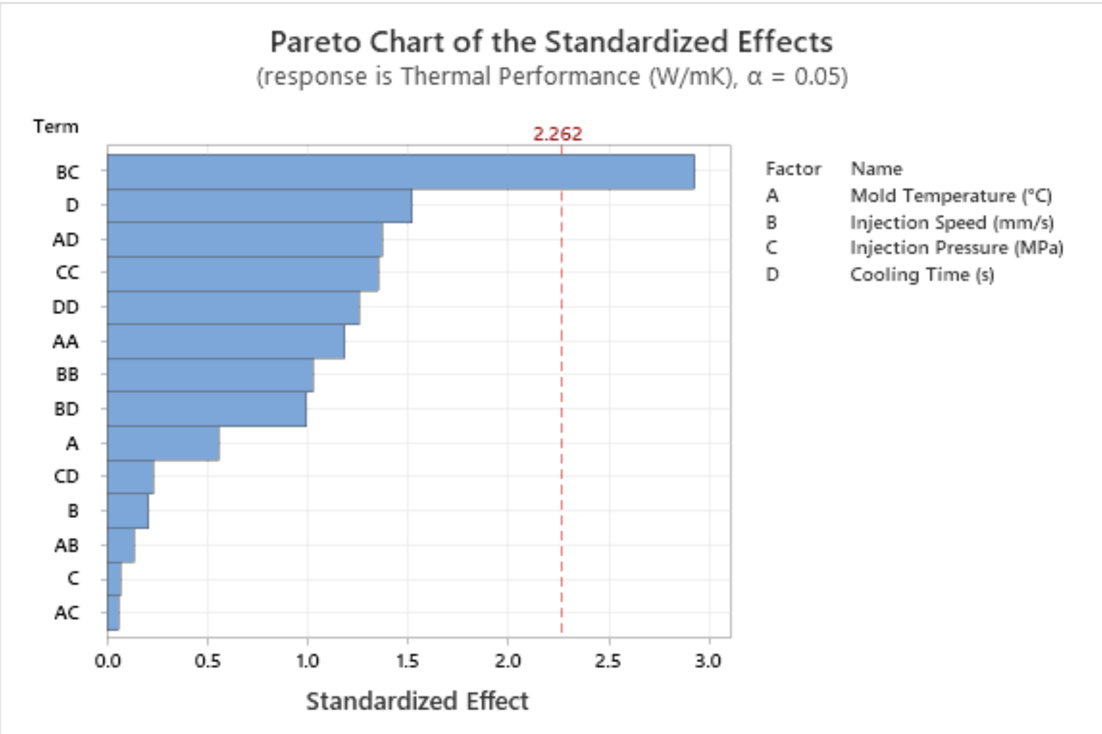

Figure 1: Pareto chart for thermal performance response variable.

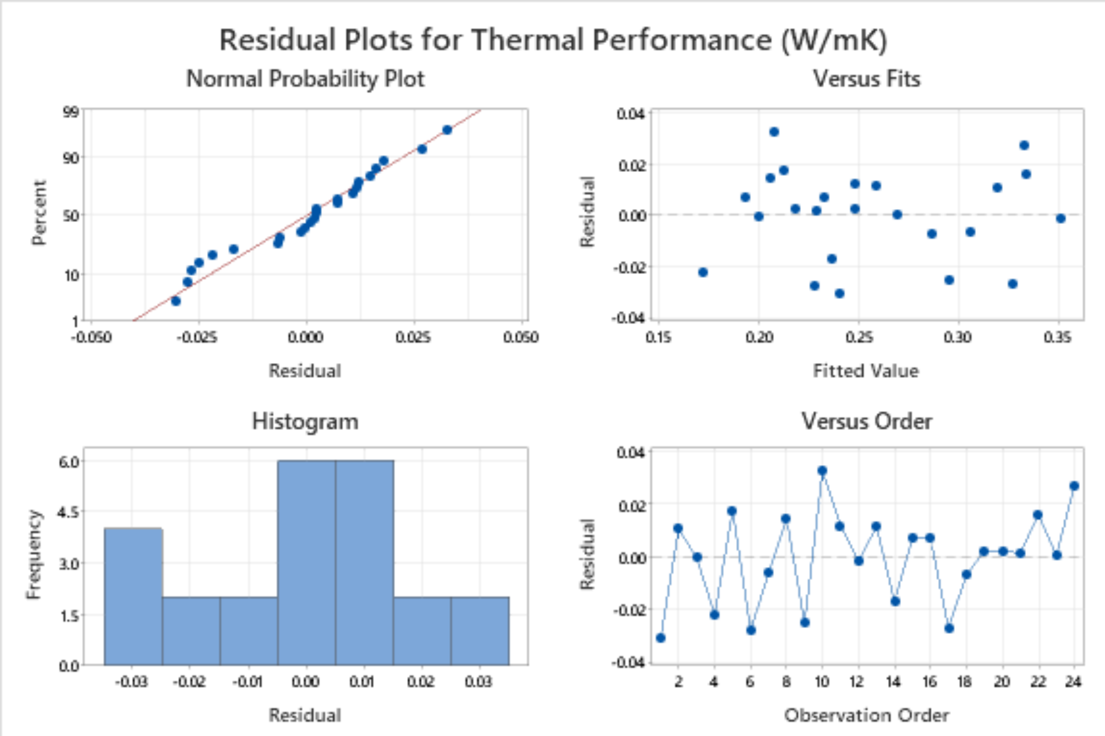

Figure 2: Residual plots for thermal performance response variable

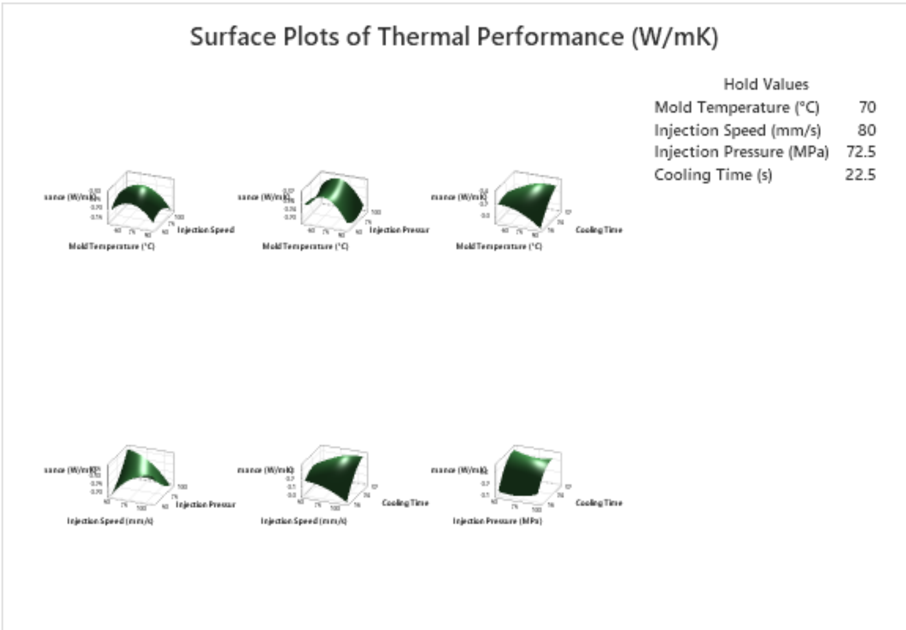

Figure 3: Surface plots for thermal performance response variable

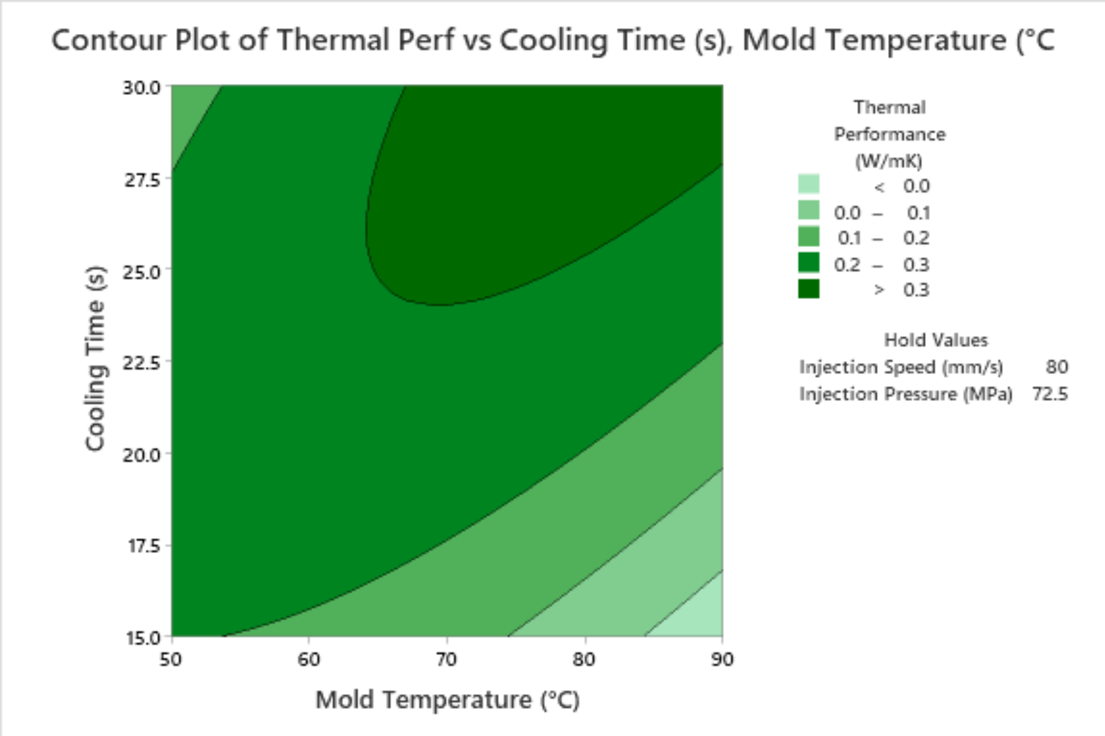

Figure 4: Contour plot of thermal performance vs cooling time and mold temperature

3.1 Response Surface Optimization

Optimization of the response surface models indicated that simultaneously maximizing tensile strength and thermal performance while minimizing weight could be achieved at a mold temperature of 57°C, injection speed of 50 mm/s, injection pressure of 95 MPa, and cooling time of 15 seconds. The highest desirability that could be reached using these mold settings are Tensile strength – 31.43Mpa, Thermal performance – 0.36W/mk and Weight – 32g.

Table 6: Response surface optimization

Solution	1
Mold Temperature (°C)	57.2727
Injection Speed (mm/s)	50
Injection Pressure (MPa)	95
Cooling Time (s)	15
Tensile Strength (MPa)	31.44
Thermal Performance (W/mK)	0.360
Weight (g)	32.06
Composite Desirability	1

3.2 Predictive Analysis

By inputting settings for the four mold factors, the response surface regression equations can predict the corresponding tensile strength, weight, and thermal performance of the molded plastic cups as guided by the experimental data trends. To test the ability of the response models, we entered a mold temperature of 90°C, injection speed of 105 mm/s, injection pressure of 130 MPa, and cooling time of 35 seconds into the response models, we got a projected/ predicted tensile strength of 45 MPa, weight of 45 grams, and a thermal performance of 0.36 W/m-K for the resulting plastic cups.

Table 7: Mold Settings Values to be Predicted

Variables	Settings
Mold Temperature (°C)	90
Injection Speed (mm/s)	105
Injection Pressure (MPa)	130
Cooling Time (s)	35

Table 8: Tensile Strength Prediction

Fit	SE Fit	95% CI	95% PI
45.0158	5.65981	(32.2124, 57.8192)	(32.0155, 58.0162) XX

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

Table 9: Thermal Performance Prediction

Fit	SE Fit	95% CI	95% PI
0.364645	0.158083	(0.0070354, 0.722254)	(0.00153, 0.7278) XX

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

Table 10: Weight Prediction

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

This study successfully showed how optimizing injection mold settings can improve plastic cup manufacturing. However, there were some limitations in the research scope. They include: (i) only polypropylene plastic was tested. Other plastics may have different optimal settings; (ii) only a few mold factors and cup properties were included. Expanding these could give more comprehensive models; (iii) The number of experimental trials was small due to practical limits. Some interactions may have been missed; (iv) The lab-scale process may not capture all real-world production considerations.

While this research was an effective demonstration, more work can be built on it to: (i) Test other plastics like polystyrene to find their ideal parameters; (ii) Include more mold factors and cup properties in the optimization; (iii) Run larger experimental designs to catch more interactions between variables; (iv) Scale up experiments to simulate commercial production conditions. By addressing these limitations, future research can advance injection mold optimization across more materials and production scales. This will help plastic manufacturers improve quality and efficiency.

CONCLUSION

This study aimed to find the best settings for making high-quality polypropylene plastic cups using an injection molding machine. We used "Response Surface Methodology (RSM)" to test different combinations of four important mold settings: (i) How hot the mold itself is (mold temperature), (ii) How fast the melted plastic is injected (injection speed), (iii) The force applied to the melted plastic during injection (injection pressure), (iv) How long the plastic cools in the mold (cooling time). We did many experiments to explore all possible combinations of these settings. We measured different qualities of the cups we made, like: (i) How strong they were (tensile strength), (ii) How well they retained temperature of the liquid inside (thermal performance), (iii) How much the cup weighed (weight). Here's a summary of the results which are also the findings from this research study: (a) Injection pressure among the mold factors has the most significance on tensile strength and the impact is direct. (b) Injection pressure square term also shows a good significance on the tensile strength. (c) The interaction between Injection speed and Injection pressure was found to have most significance on the thermal performance. (d) The square term for cooling time and the interaction between Injection pressure and Cooling time has most impact on the weight response. Only the square term for cooling time shows an inverse impact or relationship with the weight. (e) Optimization of the response surface models indicated that simultaneously maximizing tensile strength and thermal performance while minimizing weight could be achieved at a mold temperature of 57°C, injection speed of 50mm/s, injection pressure of 95MPa, and cooling time of 15 seconds. (f) The quality response that could be reached using these optimized mold settings are Tensile strength – 31.43Mpa, Thermal performance – 0.36 W/m-K and Weight – 32g. We also created charts and plots showing how changing the settings affect the cup quality. These pictures helped us find the best setting or range of settings to meet various quality criteria. This method could be used to make better quality cups from other plastics too, like polystyrene and polyethylene terephthalate. We also need to test these settings in real factories to make sure they're practicable and work. Overall, this study showed that using science, technology and careful testing we can make much better plastic cups and other plastic products that make comfort maximized in our world.

5.0 Recommendation

Based on the findings of this study, the following recommendations are made for optimizing production mold settings and improving plastic cup quality:

For Manufacturers:

(i) Implement the identified optimal settings: mold temperature - 57°C, injection speed - 50mm/s, injection pressure - 95MPa and cooling time - 15s. Adjust mold settings to the values found to achieve desired quality characteristics like tensile strength, weight, and thermal insulation.

(ii) The optimized parameter settings should be implemented over longer production runs to assess their impact on reducing variability and increasing process capability over time.

(iii) Consider utilizing the design of experiments, response surface methodology, or other similar methods to further fine-tune settings for specific materials, cup designs, and other products and quality targets.

(iv) More mold process parameters beyond just mold temperature, injection speed, injection pressure and cooling time should be investigated and included in future optimized RSM models.

(v) Additional plastic cup quality metrics beyond tensile strength, thermal insulation, and weight could be evaluated as responses. Properties like optical clarity, thermal stability, surface finish and dimensional consistency would provide further insights.

(vi) The process models should be validated at full industrial manufacturing rates and scales. High volume production may introduce additional dynamics between parameters not observable on laboratory-scale molding.

(vii) Should invest in mold modifications. Explore incorporating design features like ribs or double walls to enhance strength and insulation without significantly increasing weight.

(viii) Regularly assess cup quality and production efficiency, making adjustments to the mold settings as needed to maintain optimal performance.

(ix) Alternative and hybrid modeling techniques like artificial neural networks could be explored and compared to the response surface models in terms of accuracy and predictive capability.

For consumers:

(i) Choose brands and products that prioritize quality whether by investing in mold optimization techniques, use of environment-friendly materials or making use of sustainable processes and practices.

(ii) Share their experiences with cup quality and express their preference for products made with optimized settings and sustainably sourced materials. This will also help the manufacturers to be informed and to improve their processes.

Additional recommendations:
(i) Further research is needed to explore the optimization of settings for different plastic materials and cup designs.
(ii) Investigating the economic feasibility of implementing optimized settings and balancing quality with cost and environmental impact is crucial for widespread adoption.
(iii) Developing standardized quality measures and guidelines for plastic cups could benefit both manufacturers and consumers.
By implementing these recommendations, manufacturers can produce higher-quality plastic cups that are more durable, efficient, and environmental friendly, while consumers can make informed choices that contribute to a sustainable future.

5.1 Contribution to Knowledge

We discovered some additional capabilities of Response Surface Methodology (RSM) for optimization in this research study. They include:
(a) It can target not just maximizing or minimizing a response, but also achieving a desired target range for the response quality. This provides more control over the optimization.
(b) Constraints can be placed on factors during optimization. For example, a factor can be held at a specific value or within a specified range or limit. So RSM can optimize quality while respecting real-world equipment constraints on the factor settings.
In summary, RSM offers flexible optimization abilities beyond just maximizing or minimizing a response. Quality target ranges and factor constraints can be incorporated to better match real-world process limitations. This demonstrates RSM's versatility for practical process optimization applications.

REFERENCES

Bahreini, A., Taghiyari, S. M., Ayatollahi, M. R. (2013). Investigation on the Effects of Injection Molding Parameters on the Compressive Strength of Polystyrene Cups using Response Surface Methodology. *Journal of Applied Polymer Science,* 129(3), 1803-1810. DOI: 10.1002/app.39222

Changsheng, Q. (2025). Analysis of the Application of Injection Molding Technology in the Manufacturing Industry. *International Journal of Applied Sciences,* 8 (3), p.30, DOI: https://doi.org/10.30560/ijas.v8n3p30

Cunha, A. G., Melo, J., Marques, T., Pontes, A. (2025). A Review on Injection Molding: Conformal Cooling Channels, Modelling, Surrogate Models and Multi-Objective Optimization. *Polymers: MDPI,* 17 (7), 919; https://doi.org/10.3390/polym17070919

Czepiel, M., Bankosz, M., Sobczak-Kupiec, A. (2023). Advanced Injection Molding Methods: Review. *Materials,* 16 (17), 5802; https://doi.org/10.3390/ma16175802

Dung, N. D. (2025). Numerical Results for Gauss-Seidel Iterative Algorithm Based on Newton Methods for Unconstrained Optimization Problems. *European Journal of Mathematical Analysis,* 5 (9), https://doi.org/10.28924/ada/ma.5.9

Dabhi, D. (2025). Advancing Manufacturing Efficiency: Multi-Cavity Tool Implementation for High-Volume Production in Plastic Injection Molding. *International Scientific Journal of Engineering and Management,* 3 (6), 1-7; DOI: 10.55041/ISJEM02084

He, C., Cheng, R., Li, L., Tan, K. C., Jin, Y. (2024). Large-Scale Multi- Objective Optimization Via Reformulated Decision Variable Analysis. *Journals and Magazine:*

IEEE Transactions on Evolutionary Computtion, 28 (1), 47-61; DOI: 10.1109/TEVC.2022.3213006

Hossain, M. A., Rohed, T. A., Uddin, M. F. (2025). Design and Optimization of an Injection Mold for Automotive Air Duct Head Using Advanced CAE Tools. *Scientia. Technology, Science and Society,* 2 (5), 75-99; DOI: 10.59324/stss.2025.2(5).07

Kanbur, B. B., Zhou, Y., Shen, S., Wong, K. H., Chen, C., Shocket, A., Duan, F. (2022). Metal Additive Manufacturing of Plastic Injection Molds with Conformal Cooling Channels. *Polymers: MDPI,* 14, 424; https://doi.org/10.3390polym14030424

Kapulin, D. V. and Russkikh, P. A. (2020). Analysis and Improvement of Production Planning within Small-Batch Make-To-Order Production. *Journal of Physics: Conference Series*, 1515 (2), 022072; DOI: 10.1088/1742-6596/1515/2/022072

Karaağaç, Y., Özcelik, B., & Erzurumlu, T. (2013). Optimization of Injection Molding Process Parameters for a Plastic Dustpan using Taguchi Method. *Journal of Polytechnic*, 16(2), 149-158.

Khan, M. A., Alam, M. I., Khan, M. P. (2015). Effect of Injection Molding Parameters on Quality of Polypropylene Plastic Cups Using Design of Experiments. *International Journal of Polymer Science,* 2015, 1-10. DOI: 10.1155/2015/937812

Kim, J., Kim, D., Ryu, K. H. (2025). Piecewise Response Surface Methodology for Enhanced Modeling and Optimization of Complex Systems. *Korean Journal of Chemical Engineering,* Volume 42, 537-545

Masato, D., Piccolo, L., Lucchetta, G., Sorgato, M. (2022). Texturing Technologies for Plastic Injection Molding: A Review. *Micromachines: MDPI,* 13 (1211), 1-33; https://doi.org/10.3390/mi13081211

Minh, P. S., Dang, H., Ha, N. C. (2023). Optimization of 3D Cooling Channels in Plastic Injection Molds by Taguchi-Integrated Principal Component Analysis (PCA). *Polymers: MDPI*, 15 (5), 1080; https://doi.org/10.3390/polym15051080

Titu, A. M and Pop, A. B. (2024). Implementation of CAD/ CAM/ CAE Systems for Improved Design and Manufacturing Processes in Industrial Organizations. Proceedings of the International Conference on Business Excellence, 18 (1), 3069-3078; https://doi.org/10.2478/picbe-2024-0253

Wang, Y. and Lee, C. (2023). Design and Optimization of Conformal Cooling Channels for Increasing Cooling Efficiency in Injection Molding. *Applied Sciences,* 13 (13), 7437; https://doi.org/10.3390/app13137437

Wang, K. K. and Wang, V. W. (2017). Computer–Aided Mold Design and Manufacturing. *Injection and Compression Molding Fundamentals, 1st Edition,* 607 – 669, 2017.

Yang, B. and Lin, C. (2025). Optimal Runner Design for Balanced Filling in a Multi-Cavity Mold using a Two-Stage Analytical Approach. *Polymer Engineering & Science,* 64 (11), 5688-5701, DOI: 10.1002/pen.26945