Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Multi Responses Optimization of Plastic Injection Moulding Through Simulation Using MOLDEX3D

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ABSTRACT

Process parameters in plastic injection moulding such as filling time, packing time, injection speed and cooling time are generally determined by a trial-and error method through the experiments. Trial and error method is cost and time consuming. Therefore, finding the optimal and best process parameter becomes the most crucial and important issue in injection moulding process. Thus, multi-response optimization of plastic injection moulding using MOLDEX3D simulation software is an alternative approach to determine the optimal process parameter. Three factors which are cooling time (10-20s), packing time (2-7s), and filling time (2-5ss) were controlled at 2 levels and the experiment were designed by using Full Factorial method of Design Expert that entail eight sets of process parameters. Subsequently, results obtained from the simulation works were thoroughly analysed by using Analysis of Variance (ANOVA). Result shows the cooling time is the most significant control factor which contributes to 83.7% and 100% on warpage and cycle time respectively. While for the filling time, the influence contribution is 92.56% on the volumetric shrinkage. Optimized process parameters were selected at packing time at 7 s, filling time at 5s and cooling time at 12.190s to achieve 25.690s of cycle time for producing a plastic card holder. For validation, the selected optimum process parameter was assigned to a plastic injection moulding machine and managed to produce a plastic card holder with better quality which suitable for small and medium scale production.

Keywords:
Injection Moulding; Optimization; Design Expert; ANOVA; MOLDEX3D

1. Introduction

The market demand for complex and intricate plastic components and parts for vast applications gradually increases annually as mentioned by Moayyedian [1]. Therefore, plastic manufacturing industries need to produce the required plastic product rapidly with minimum defects. During this manufacturing process Jaafar *et al.,* [2] says that, there are a lot of parameters such as injection temperature, mould temperature, injection time and many more that affiliate with the quality. This study focused on the multi optimization of a plastic injection moulding process to reduce cycle time

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https://doi.org/10.37934/araset.64.3.5968

in producing a plastic product with minimum warpage and volumetric shrinkage rate. In order to optimize the numerical result of plastic injection moulding, Samat *et al.,* [21] are among the researchers that have utilized several prediction models including Response Surface Methodology (RSM), and Artificial Neuron Network (ANN). RSM is a robust technique for optimizing responses by integrating multiple factors or inputs using both mathematical and statistical analysis. Apparently, Zhao *et al.,* [3] stated that a precise optimization algorithm is compulsory to fabricate any plastic product with the best quality. Thus, a conventional experimental approach involving a trial-and-error process to design the new plastic product and optimize its process parameters is not highly recommended as discussed by Radhwan *et al.,* [4] due to its time and cost consuming. There is also no assurance that the obtained optimum parameters are the best. Furthermore, Mukras [5] and Khan *et al.,* [6] assert that any unpredicted or uncontrolled circumstances may also lead to systematic error resulting in a higher probability of failure during the experimental work.

According to Khan *et al.,* [6], there are three main phases for plastic injection moulding which are packing, cooling, and parting. Ismail [7], Frizelle [8], Hashimoto *et al.,* [9] and Fu *et al.,* [10] extensively discussed that numerous variables and process parameters such as injection temperature, mould temperature, injection time are very influential on the quality and costing for any fabricated plastic product. According to Rajemi *et al.,* [11], machine parameters are the most significant element that affected the product quality and output capacity in injection moulding process. While Chiu *et al.,* [12] analyzed that the significant controlled parameters or variables for plastic injection moulding are the injection rate, the melt temperature, the injection pressure, the holding pressure, the holding time, and the mould temperature while the most crucial controlled parameters for plastic injection moulding was injection rate.

In this study, there are three controlled significant process parameters to reduce cycle time in producing a plastic product. The first process parameter is cooling time. According to Qiao [13] the cooling process holds for 80% or three-fourths of the cycle time in plastic injection moulding process. Kusić and Hančič [14] in their past research aim to optimize six moulding conditions (melt temperature, packing time, cooling time, injection speed, packing and injection pressures) on the specified test specimen through Taguchi Method stated that cooling time together with packing pressure are two significant process parameters that affect the post moulding shrinkage. Therefore, both statements prove that effective cooling process can reduce the cycle time for production of a plastic product with better quality.

The second process parameter is filling time. In recent studies, researchers such as Zhao *et al.,* [3] have stated that three main stages for plastic injection moulding consists of filling, packing/holding, and cooling. Moayyedian [1] revealed during the filling stage in plastic injection moulding, the cavity is started to fill by selected material through the screw that facilitates the velocity with predetermined velocity profile. This shows that filling time is one of significant process parameters that can influence the required injection pressure in filling stage for plastic injection moulding.

The last process parameter chosen is packing time. According to Kusić and Hančič [14], warpage and shrinkage behavior of a standardize test specimen for plastic injection moulding process can be controlled through six process parameters which are melt temperature, injection speed, injection pressure, packing pressure, packing time, and cooling time. At the end of the study, Ghazali *et al.,* [15] calculated the SN ratios for each process parameter and found out that packing time can contribute on post-moulding shrinkage. This research highlighted that packing time can be considered as an influential process parameter that affects the quality of the test specimen. Researchers such as Ghazali *et al.,* [15] also agreed that packing time can play a significant role in the formation of warpage on a plastic product. Lastly, the findings of this study will significantly grant

enhancement of knowledge and progress in this field, hence redistributing the advantages to society. As a result, the findings of this study might be precious and advantageous consequently to manufacturing industries, students, academic institutes, and researchers.

This study addresses the gap in optimizing plastic injection moulding by focusing on the simultaneous optimization of cooling time, filling time, and packing time to reduce cycle time while improving product quality. Unlike conventional trial-and-error methods, it integrates advanced tools like MOLDEX3D with DOE and ANOVA for efficient parameter optimization. The research bridges the gap between simulation and practical application through experimental validation of results. Ultimately, the findings contribute to improving manufacturing efficiency and product quality while offering valuable insights for academic and industrial advancements.

2. Methodology

2.1 Identify the Significant Parameters, Responses, and Design of Experiment

For this study, the filling time, packing time, and cooling time were identified as three significant process parameters through intensive literature studies and past research in the plastic injection moulding process. Table 1 shows the controlled factors and their control ranges, as well as the responses to be measured. While for the responses, the main aims are to minimize cycle times for plastic injection moulding processes with minimum warpages and volumetric shrinkage rates. By using the Full Factorial method, 8 sets of experiments were entailed using Design Expert V10.0.3. This software can generate a set of thorough experiments with a variety of factors according to the desired range. These parameters will be simulated in MOLDEX3D.

Table 1
Process parameters and their levels

Process Parameters (unit)	Level of Controlled Parameters	
	Low	High
Filling Time (s)	2	5
Packing Time (s)	3	7
Cooling Time (s)	10	20

2.2 Analysis Setup for Simulation Using MOLDEX3D

For simulation of the plastic injection moulding process, a 3D model of a plastic card holder was assigned to MOLDEX3D. Then the assigned 3D model of the plastic part was constructed into the corresponding solid geometry mesh, the analysis setup for simulation in MOLDEX3D R14 is then executed. In MOLDEX3D R14, New Project Wizard must be launched and initiated to indicate a new run analysis for simulation of a plastic injection moulding process. All three significant process parameters, filling time, packing time, and cooling time were defined as the input variables for computational parameters to run for simulation. Figure 1 shows shaded model of the 3D plastic product with its runner and gate that has been appointed for simulation. Process condition assigned for simulation according to the first set of experiment provided by Design Expert with 2 s for filling time, 7 s for packing time and 10 s for cooling time. Material selection for this simulation also was appointed to Polypropylene Thermoplastic with trade name PP P-20TC – 1156 manufactured by ASAHI from the MOLDEX3D user bank materials. Since this study required three process parameters as input parameter, eight sets of parameters generated by the Full Factorial method were simulated using MOLDEX3D R14.

2.3 Post Processing

Post processing in MOLDEX3D can generate an in-depth moulding analysis and interpretation results on the constructed geometrical mesh model during filling, cooling, and packing time to complete one plastic injection moulding cycle. Defects such as warpage, volumetric shrinkage, short shot, air trap and weld line were also identified and observed visually with accurate animation detail during the simulation for plastic injection moulding process [16]. For this study, three responses which are cycle time, volumetric shrinkage and warpage were observed whether the assigned process parameters can effectively reduce the cycle time with minimum volumetric shrinkage and warpage on the plastic product. Therefore, post processing analysis is very crucial for this study. For example, MODEX3D can generate a comprehensive report result on warpage. Figure 1 shows the total displacement of the warpage at x-axis after the plastic product is ejected and cooled down to room temperature with orthographic view in 3D.

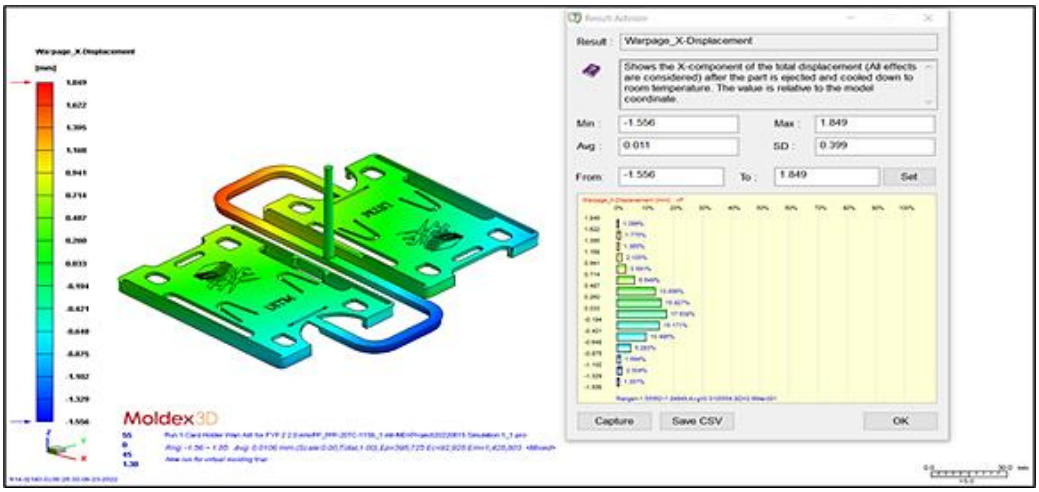

Fig. 1. Warpage on the plastic product simulated in MOLDEX3D

2.4 Analysis of Variance (ANOVA)

St and Wold [17] mentioned that analysis of Variance (ANOVA) is a statistical analysis method that differentiates observed aggregate variability within a data set into two parts which are systematic components and random factors. It also can be considered one of the most widely implemented approaches for statistical methods utilized in hypothesis testing. For this study, analysis of Variance (ANOVA) was applied to distinguish the relationship between the process parameters that can affect the cycle time to produce the card holder with minimum warpage and volumetric shrinkage.

2.5 Optimization

According to Staněk *et al.,* [18], the optimization procedure can guide users to run Design of Experiments (DOE) to determine the best values required to compensate for normal process variation to ensure the acceptable desired plastic part. In this study, the best optimum parameter was extracted by the Analysis of Variance (ANOVA). In Design Expert V10.0.3, criteria on the process parameters were assigned within the controlled ranges. In contrast, the responses were assigned to be minimum to facilitate the Analysis of Variance (ANOVA) in extracting the optimum parameter. Lastly, the selected optimum parameters with the best cycle time and minimum volumetric shrinkage

and warpage were validated using JINWHA GLOTECH VDCII 140 to run at least one complete cycle to produce the desired plastic part. Then, comparisons in terms of cycle time and appearances were made between the results generated from the simulation of the plastic injection moulding process in MOLDEX3D and the experimental work with the actual plastic product.

3. Result

Table 2 shows the results from post-processing generated in MOLDEX3D. These results were obtained from eight experiments with different filling time, packing time and cooling time. From the simulation, the shortest cycle time took to produce a plastic part was 24s and the longest cycle time was 37s, respectively, both obtained at run number 3 and run number 8.

Lam *et al.,* [19] revealed that a volumetric shrinkage analysis generated during post processing shows the percentage of part volume change due to Pressure-Specific Volume-Temperature (PVT) change as the part is cooled from high temperature and pressure conditions at current instant to room temperature and ambient pressure conditions. From the simulation, plastic product with shortest cycle time obtained the highest percentage of volumetric shrinkage with 16.407% while plastic product with longest cycle time obtained the lowest percentage of volumetric shrinkage with 14.835%.

As for warpage, MOLDEX3D generated the length of the total displacement vector right after the part is ejected and cooled down to room temperature. The value is relative to the model coordinate [15]. From the simulation, plastic product with shortest cycle time obtained the highest total displacement of warpage with 4.056mm while plastic product with longest cycle time obtained the lowest total displacement of warpage with 1.192mm.

Table 2
Responses obtained from the simulations

Run	Process Parameters (unit)			Responses (unit)		
	Filling Time (s)	Packing Time (s)	Cooling Time (s)	Cycle Time (s)	Volumetric Shrinkage (%)	Warpage (mm)
1	2	7	10	24	16.407	3.156
2	2	3	20	30	16.366	1.273
3	2	3	10	20	16.47	4.026
4	5	3	20	33	15.543	1.272
5	5	7	10	27	14.866	2.377
6	5	3	10	23	15.193	4.248
7	2	7	20	34	16.366	1.181
8	5	7	20	37	14.835	1.192

3.1 Analysis of Variance (ANOVA) for the Responses

Table 3 shows the results of ANOVA for warpage. From the analysis, the Model p-value for the response was less than 0.05 indicates that the models were significant. There was only a 0.14% chance that an F-value as large can occur due to noise.

Table 3
Analysis of Variance (ANOVA) for warpage

Source	Sum of Squares	df	Mean Square	F-Value	p-Value prob > F	Contribution
Model	11.76	3	3.92	47.8	0.0014	
A-Packing Time	1.06	1	1.06	12.93	0.0228	9.017%
C-Cooling Time	9.88	1	9.88	120.40	0.0004	83.97%
AC	0.82	1	0.82	10.06	0.0338	7.015%
Residual	0.33	4	0.082			
Cor total	12.09	7				

The most dominant factor that influences warpage is the cooling time that comes out with the highest contribution of 83.9% in which p-Value is 0.0004. Researchers such as Kitayama and Natsume [20] and St and Wold [17] also found that cooling time with other significant process parameters such as melt temperatures and cooling conditions can influence the formation of the warpage.

Table 4 shows the fit statistics of the model for warpage. The Predicted R2 of 0.8914 is in reasonable agreement with the Adjusted R2 of 0.9525, as the difference is less than 0.2. An adequate precision of 14.5687 indicates an adequate signal that this model is desirable and can be used to navigate the design space.

Table 4
Fit statistics model for warpage

Std. Dev.	0.29	R-Squared	0.9729
Mean	2.34	Adjusted R-Squared	0.9525
C.V. %	12.24	Pred R-Squared	0.8914
Adequate Precision	14.5687		

Table 5 shows the results of Analysis of Variance (ANOVA) for volumetric shrinkage. For the analysis, the Model p-value for this response was 70.86 implied that the model was significant. The value of “Prob > F” for the model was smaller than 0.05 indicated that the model terms were significant. However, there was only a 0.06% chance that an F-value would become this large due to noise.

Table 5
Analysis of Variance (ANOVA) for volumetric shrinkage

Source	Sum of Squares	df	Mean Square	F-Value	p-Value prob > F	Contribution
Model	3.61	3	1.20	70.86	0.0006	
A-Packing Time	0.15	1	0.15	8.87	0.0408	4.17%
B-Filling Time	3.35	1	3.34	196.75	0.0001	92.56%
AB	0.12	1	0.12	6.95	0.0578	3.27%
Residual	0.068	4	0.017			
Cor total	3.68	7				

Moreover, process parameters A-Packing Time, B-Filling Time and the interaction between both process parameters AB are significant model terms. For this study, the most dominant factor that influences volumetric shrinkage was the filling time that came out with the highest contribution of 92.56% in which p-Value is 0. 0001. This is contradicted to a study conducted by Kitayama and

Natsume [20] that found out injection pressure and packing pressure were the significant process parameters in controlling the formation of volumetric shrinkage via sequential approximate optimization method. However, defects such as volumetric shrinkage are heavily influenced by many process parameters such as the filling time, the injection pressure, packing pressure and many more. Meanwhile, Table 6 shows the fit statistics of the model. The Predicted R^2 of 0.9084 is in reasonable agreement with the Adjusted R^2 of 0.8373, as the difference is less than 0.2. An adequate precision of 10.9152 indicates an adequate signal that this model is desirable and can be used to navigate the design space

Table 6
Fit statistics model for volumetric shrinkage

Std. Dev.	0.2369	R-Squared	0.9084
Mean	15.7557	Adjusted R-Squared	0.8932
C.V. %	1.5036	Pred R-Squared	0.8373
Adequate Precision	10.9152		

The Model p-value as in Table 7 was 24.0 implied that the model was significant. There was only a 0.27% chance that an F-value would become this large due to noise. According to Table 8, process parameters which was C-Cooling Time is the significant model terms. For this study, the most dominant factor that influences cycle time was the filling time that comes out with the highest contribution of 100% in which p-Value is 0. 0027. Researchers such as Kusić and Hančič [14] and Ghazali *et al.,* [15] were agreed that cooling time together with packing pressure are two significant process parameters that affect the post moulding shrinkage and cycle time depending on the cooling time and the geometry of the moulded part. Simpler design for the moulded part would lead to shorter cooling time and cycle time

Table 7
Analysis of Variance (ANOVA) for cycle time

Source	Sum of Squares	df	Mean Square	F-Value	p-Value prob > F	Contribution
Model	200.00	1	200.00	24.00	0.0027	
C-Cooling Time	200.00	1	200.00	24.00	0.0027	100%
Residual	50.00	6	8.33			
Cor total	250.00	7				

Table 8
Fit statistics model for cycle time

Std. Dev.	2.8867	R-Squared	0.8
Mean	28.5	Adjusted R-Squared	0.7666
C.V. %	10.1289	Pred R-Squared	0.6444
Adequate Precision	6.9282		

The Predicted R2 of 0.8 in Table 8 is in reasonable agreement with the Adjusted R2 of 0.7666, as the difference is less than 0.2. An adequate precision of 6.9282 indicates an adequate signal that this model is desirable and can be used to navigate the design space.

3.2 Development of Mathematical Equations

A second-order statistical equation model was developed by multiple regression generated by the Analysis of Variance (ANOVA). The Eq. (1), Eq. (2) and Eq. (3) can be used to make predictions

about the responses for the given levels of each factor because the determination coefficient (R^2) of the model for warpage, volumetric shrinkage and warpage was 0.9729, 0.9815 and 0.8 respectively. This indicates that all three models were significant enough to predict the value of Fr, within the limited range of the investigated parameters.

$$Warpage = +8.992750 - 0.66375 \times Packing\ Time - 0.3827875 \times Cooling\ Time + 0.0321125 \times Packing\ Time \times Cooling\ Time \quad (1)$$

$$Volumetric\ shrinkage = +16.898625 + 0.073125 \times Packing\ time - 0.2285 \times Filling\ time - 0.0405 \times Packing\ time \times Filling\ time \quad (2)$$

$$Cycle\ time = +13.5 + 1.0 \times Cooling\ time \quad (3)$$

For validation, the identified optimum parameter was executed through experimental work using a real-life plastic injection moulding machine. The validation results show that when the process parameters, which are packing time = 7 s, filling time = 5 s and cooling time = 12.070 s, were assigned to the plastic injection moulding machine, the time taken to complete one cycle time was 39.2 s. Other than that, the cycle time that was predicted from the Analysis of Variance (ANOVA), which was 25.557 s, was much shorter for about 39.58% compared to experimental work. As for the simulation, the time taken to complete one cycle time was 29.704 s, much shorter than experimental work. This is due to the material selection during the experimental work that is different from the simulation. The material that was assigned to the plastic injection moulding machine was polypropylene with the composition of 70% pure propylene and 30% recycled propylene, while the material that was assigned in the simulation was polypropylene with 100% of pure polypropylene. Furthermore, the process conditions and machine specifications assigned in the simulation were slightly different from the actual injection moulding machine. The plastic injection moulding machine also was assigned with packing time + filling time + 3 s and cooling time = 12 s to produce the plastic card holder. The drawback of these process parameters was their appearance.

Figure 2 and Figure 3 show the physical appearance of both plastic products fabricated at different cycle time. Plastic products with 39.2 seconds cycle time have better surface finish in which the splay and flashing were less visible compared to plastic product with 3.9 seconds cycle time. As for volumetric shrinkage and warpage, the defects were too small to measure and considered to be neglected. In terms of profit, the shorter cycle time in producing the plastic product will be more favorable compared to the longer cycle time because it is more economical as the production productivity is higher.

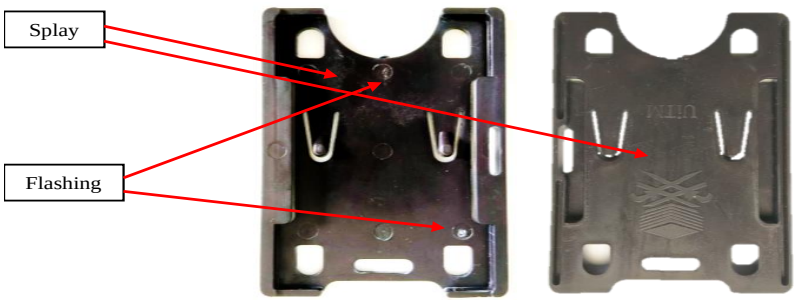

Fig. 2. Fabricated plastic product with 39.2 seconds cycle time

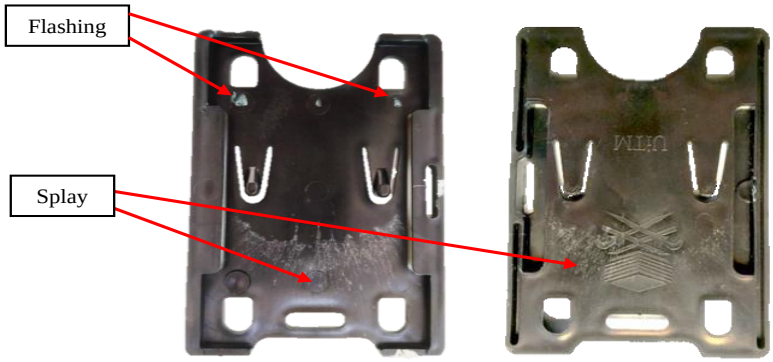

Fig. 3. Fabricated plastic product with 3.9 seconds cycle time

4. Conclusions

This paper focuses on the multi response optimization of the plastic injection moulding process of the plastic card holder. Based on the obtained results, cooling time with the contribution of 83.71% and 100% influenced the warpage and cycle time, respectively. In comparison, the filling time with the contribution of 92.56% influenced the volumetric shrinkage during the production of the plastic card holder. Then, the optimum parameter was found on solution 1 out of 55 solutions. It suggested that the packing time for 7 s, filling time for 5 s, and cooling time for 12.070 s was preferred to produce the plastic card holder with the best cycle time for 25.570 s with a minimum volumetric shrinkage rate at 15.109 % with 2.439 mm. This optimum parameter was also validated through experimental work and produced a better-quality plastic card holder with no significant defects such as volumetric shrinkage and warpage. Nonetheless, there was a 24.22% error for cycle time between the simulation and the experimental work due to the process condition and machine specification between simulation and experimental work. Therefore, this optimum parameter was not suitable for mass production due to the longer cycle time to produce the plastic card holder.

Acknowledgement
This research was funded by a grant from Ministry of Higher Education of Malaysia (FRGS/1/2019/TK03/UiTM/03/5).

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