Injection molding control parameter assessment by nested Taguchi design of simulation experiments: a case study

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Abstract. Injection molding of a polypropylene (PP) food packaging container is studied using a dedicated simulation program. Three successive Taguchi designs of experiments (DoE) are performed to identify the influence of control factors and to adjust their levels for optimal result. These are nested, each one narrowing down the decision space of its predecessor. In the first design (L27), seven control factors were considered: polymer material in terms of MFI, melt and mold temperature, maximum injection pressure, filling time, maximum packing pressure and packing time. Part weight, clamping force and a fictitious factor related to premature solidification of the material during packing were quality factors. In the next DoE (L27 again), for fixed material, the four most important process factors determined before are examined in more detail, adding cycle time as an extra quality factor. Dependence of results on melt temperature proved to be strong, so a third DoE (L9), examined a narrower temperature range. Calculation of S/N ratios and analysis of variance (ANOVA) led to optimization of control parameters through a weighted objective function.

Introduction

Injection molding is the best-established manufacturing processes for producing thermoplastic parts [1]. The process starts with the plasticizing phase where the material is heated above glass transition temperature T_g and is pushed towards the injection nozzles by a ram or transfer screw. The filling phase involves feeding of the material through sprue, runners and gates to fill the cavity. The filling time and injection pressure have to ensure complete filling of the mold and avoidance of premature solidification. As the material starts solidifying it shrinks, thus additional pressure needs to be applied at a switch-off point of the nozzle and the injection pressure signifying the beginning of the packing phase. Packing pressure should cease when its influence becomes negligible in order to reduce residual stresses in the part. The cooling phase ensures that no material flows towards the nozzles and that temperature falls below T_g to obtain rigid parts without distortions as fast as possible. During filling, packing and cooling the mold is kept closed by a clamping force. This is released only to allow ejection of the part from the mold. [2]

Material behavior during molding, mold design, as well as process parameters have been studied extensively through simulation [3]. Simulation software of the injection molding cycle is probably the most advanced compared with other manufacturing process platforms [4]. Yet, due to inherent complexity, optimization of mold design and process planning is quite difficult. A particular requirement is prediction of a variety of defects associated with feeding system design and process control parameters, e.g. short shots, sink marks (especially at thick sections), weld lines (where flow fronts meet), warpage (associated with residual stresses), flow marks (associated with in-homogenous flow), jetting (associated with turbulence near gates), air traps (where vents are inadequate), burn marks and flash (e.g. due to inadequate clamping) [5].

In fact, there are numerous research articles studying various aspects of part, mold and process design which continue to emerge at a constant rate [1], examples of the most pertinent to this work being briefly presented next. The importance of the Melt Flow Index (MFI) for the selection of a suitable polymer material is highlighted in [6], and its correlation with other processing parameters was studied. In [7] the filling, compression and cooling phases were studied by simulation software, in order to establish general guidelines for machine operators. Part weight was used as a quality factor to study a polypropylene product observing that melt temperature had the largest influence followed by filling pressure and speed [8]. Part weight was also used in [9] combined with flash forming to define optimum parameters in micro-injection molding. Three polypropylene materials with different viscosities were tested with respect to part weight to find the appropriate switch-off point and optimum clamping force [10].

Injection molding of a thin-walled part was studied using simulation and the Taguchi method, combined with real-time experiments, concluding that melt temperature and packing pressure had the greatest effect on part distortion [11]. Further Taguchi-based optimization work is reported on, with assessment of alternatives by numerical simulation, e.g. for PC/ABS part molding [12], or in combination with neural networks targeting avoidance of defects of weighted significance [13]. In Taguchi-based optimization, real experiments have also been used for assessment of alternative process parameters targeting improvement of mechanical properties of recycled polypropylene [14], minimization of weld-line width and sink-mark depth [15] etc. A comprehensive review of optimization approaches for injection molding is provided in [16].

This work aims at demonstrating a sequential Design of Experiments (DoE)-based simulation methodology for studying the influence of injection molding control parameters under ideal cooling conditions on part quality. The setup of simulation on Moldex3D platform is briefly presented next, followed by extensive presentation of three DoE experiments and their results as well as the optimization that was based on them, closing with some concluding remarks.

Process simulation setup

The part that was studied is a food container with 450 ml capacity made of Polypropylene by a mold design and manufacturing company, see Figure 1(a). Section thickness is 0.5 mm. Possible defects include air traps, flow lines associated with inadequate packing time and distortion at the rim. The part is made in a mold with 4 cavities on a machine with 350 ton maximum clamping force. An initial estimate [2] corresponding to 147 mm flow length yields 110 MPa injection pressure, i.e., after multiplication with cavity projected area, a total clamping force of 320 tn.

Simulation of the process was set up on Moldex3D^{TM}, an advanced dedicated software platform for injection molding. Many of the simulation setup parameters as well as molding physics parameters have been left to defaults recommended by the software according to experience accumulated over the years, since the main aim of this work was not the detailed design of the mold or the feeding system but the comparative study of process control parameters. Thus, the part geometry was imported, see Figure 1(b), a hot ingate of pin type was set to the center of the container bottom, see Figure 1(c), and the cooling circuit was selected from standard shapes available in the software, its sizing being also recommended by the system, see Figure 1(d). As a final step, the dimensions of the mold block are defined, see Figure 1(e). These settings were accomplished with help by the company's experts.

The mesh employed was of medium accuracy level (3 in a scale of 5). A finer mesh (2 out of 5) resulted in doubling execution time, whilst results remained very close to those attained by the coarser mesh. Polypropylene (supplier Borealis) was selected from the software's database, starting at MFI45. Maximum allowable injection pressure and packing pressure were set at 200 MPa and 60 MPa following Demag^{TM} Systec 350 machine capabilities.

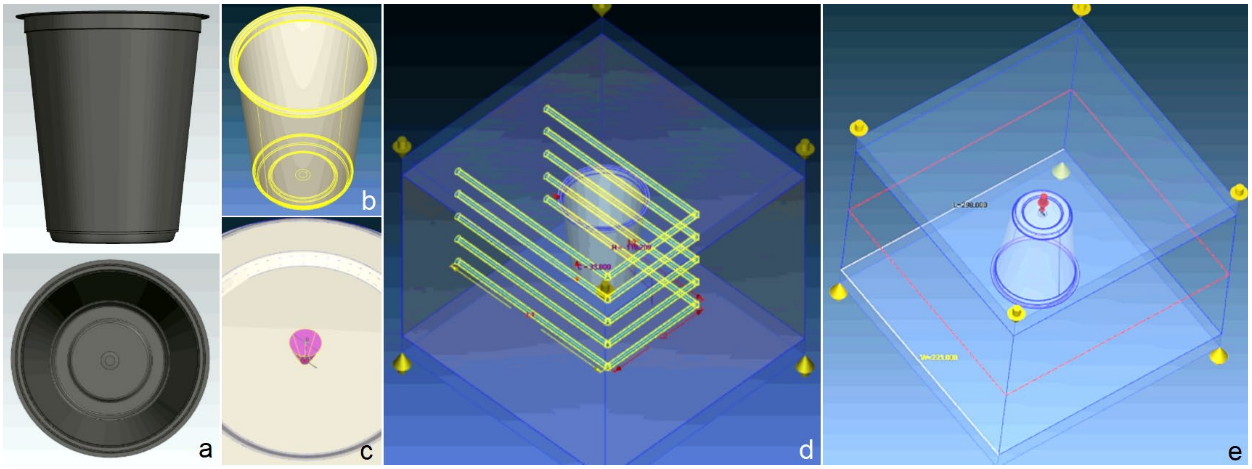

Figure 1 Simulation setup (a) part design (b) part geometry in Moldex3D (c) gate definition (d) simplified cooling system definition (e) Mold with feeding system represented by the gate alone.

Process parameters are set according to the scenario to investigate. Standard pressure profiles over time for the filling and packing phases are followed as defined in the software. Typically, packing pressure starts at 75% of the pressure at the end of the filling phase further dropping in three stages, i.e. from 100% to 62% at 45% of the packing time and further to 50% at 75% of the packing time. Furthermore, the switch-off point from filling to packing is chosen at filling ratio of 98%, as for larger ratios material velocity and pressure in the cavity may exceed machine capacity. Similarly, system defaults have been adopted for the cooling parameters. Cooling is considered ideal i.e. heat is dissipated to the full, thus, distortion calculation is only indicative. Cooling time was set to 1.6 sec, mold open time to 3.48 sec and ejection temperature to 90 ºC according to the company's engineers.

The type of analysis was set to 'Filling and Packing', except for familiarization and for optimum control parameter verification where 'Injection Analysis' was set. The 'Enhanced P' solver was opted for as it is recommended for thin-walled parts with a high ratio of flow length to wall thickness. This takes into account viscous heating, non-isothermal and non-newtonian flow.

Simulation experiments

Taguchi DoE emphasizes robustness to variations and seeks to improve quality while reducing costs by considering both mean and variability simultaneously. It involves a series of well-designed experiments to understand how different control factors influence process or product quality and to determine the optimal settings of those factors with respect to quality criteria. Responses regarding signal to noise ratio (S/N) and analysis of variance (ANOVA) are commonly used to this direction. The former is defined as $S/N=-10*\log_{10}(MSD)$ where MSD stands for mean squared deviation and depending on the quality definition is given alternatively as: $MSD=(y_1^2+y_2^2+y_3^2+\ldots.y_n^2)/n$ (smaller is better - SB), $MSD=((y^1-m)^2+(y^2-m)^2+\ldots(y^n-m)^2)/n$ (nominal is best - NB), $MSD=(1/y_1^2+1/y_2^2+\ldots+1/y_n^2)/n$ (larger is better - LB) where $y_1,y_2,\ldots$ are results of experiments, m is the target value and n is the number of experiment repetitions [17].

First DoE. As we focus on the filling and compression phases, factors related to the cooling phase are excluded, ideal heat dissipation being assumed. The quality factors are selected based on customer specifications. Thus, 7 control factors are selected, each examined at three levels, see Table 1, according to experienced company engineers, yielding an L27 Orthogonal Array (OA). Similarly, quality factors in Table 1 are chosen by the engineers for the machine at hand. In addition, since at this stage the sensitivity of the system is examined and material flow cutoff at the packing phase is expected to be intense, the molten core as a fictitious quality factor is defined, which reflects lack of solidification in the part's centre at the end of the packing phase (=1/.2, if it is present / absent). Note that according to the company expert engineers cooling time was set to 1.6 sec, mold open time was set to 3.48 sec and room temperature was set to 25 ºC.

Table 1 Control factors (incl. abbreviated names) and Quality factors for the first DoE.

Control factor	*Abbr*	*Level1*	*Level2*	*Level3*	*Quality factor*	*Loss*	*Nominal*
Material [MFI g/10 min]	MFI	45	70	100	Clamp force [tn]	SB	87.5
Melt temperature [°C]	MET	220	240	260	Part weight [gr]	NB	15.5 ±3%
Mold temperature [°C]	MOT	10	20	30	Molten core	SB	0.2
Max injection press. [MPa]	MIP	160	180	220			
Filling time [s]	FIT	0.17	0.22	0.28			
Max packing press. [MPa]	MPP	40	60	80			
Packing time [s]	PAT	0.45	0.50	0.80			

The results obtained are summarized in Table 2 concerning mean response of S/N ratio and % ANOVA Contribution of the 7 control factors for each one of the 3 quality factors. Indicative results from run no. 2 are shown in Figure 2. In addition, Figure 3 displays S/N diagrams.

It is noteworthy that 19 of the 27 runs exhibit a molten core, which is desirable. The material seems to play the main role (33% contribution) followed by packing time (25%), see Table 2. The rest of the control factors play a small role. Furthermore, runs where flow cut-off is observed are associated with extreme filling and packing times. When filling takes place at slower rates or when the material does not have enough time to solidify during packing, uneven pressure distribution is reduced, see Figure 3, where even medium time values result in a higher S/N ratio.

Table 2 S/M Delta analysis and ANOVA % Contribution of control factors in the first DoE.

	Clamping force		*Part weight*		*Molten core*	
Control factor	*S/N Δ*	*% Contr*	*S/N Δ*	*% Contr*	*S/N Δ*	*% Contr*
Material [MFI g/10 min]	1.42	53.34	12.75	95.20	9.44	32.90
Melt temperature [°C]	0.99	26.99	5.38	2.10	3.78	5.26
Mold temperature [°C]	0.12	0.70	1.07	0.02	1.89	1.32
Max injection pressure [MPa]	0.54	9.12	6.69	1.65	1.89	1.32
Filling time [s]	0.45	4.72	3.22	0.24	5.60	9.21
Max packing pressure [MPa]	0.21	1.77	2.92	0.05	9.44	9.21
Packing time [s]	0.27	2.19	2.80	0.19	5.66	25.00

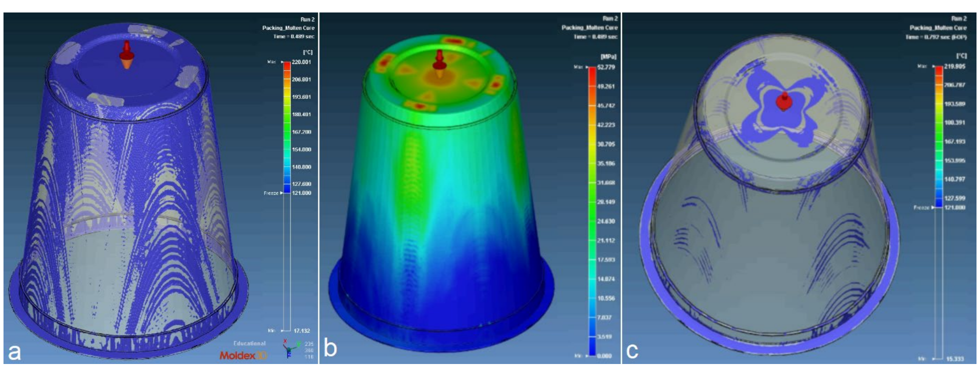

Figure 2 Indicative results for first DoE at the end of packing phase corresponding to MFI 45, MET=220ºC, MOT=10ºC, MIP=160 MPa, FIT=0.22 sec, MPP=60 MPa, PAT=0.5 sec (a) Temperature at the molten core (b) Pressure in cavity (c) Remaining molten sections.

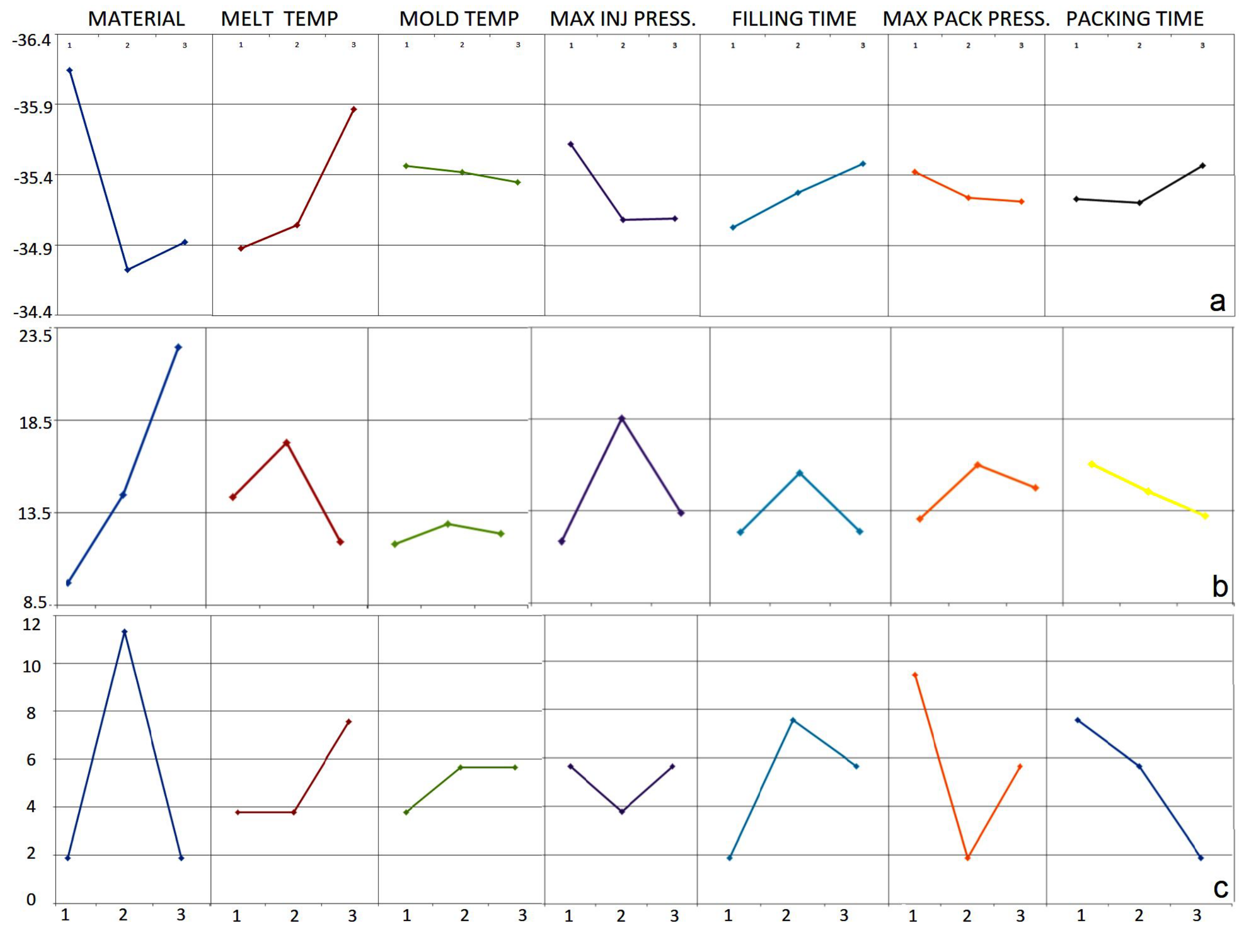

Figure 3 S/N diagrams for first DoE (a) Clamping force (b) Part weight (c) Molten core.

At a second level, it becomes clear that choice of material is crucial for all three quality factors examined. Especially with regard to part weight, it holds the exclusivity, see Table 2. A higher MFI facilitates ease of fill as is also confirmed by increase in part weight. Regarding clamping force, the results are somewhat misleading. Materials with a higher MFI, precisely because they achieve easier filling, also show a lower pressure drop at the nozzle and at the inlet gate. Therefore, higher pressures prevail within the cavity, so higher clamping forces are needed. Since all clamping force results are within machine safety margins, at this first stage of investigation no particular attention will be devoted to the respective quality factor. Regarding melt temperature, the value of 240ºC tends to give the best results considering all quality factors together. The higher the temperature of the melt, the lower its viscosity becomes, thus better filling of the cavity is achieved. However, high melting temperatures also require longer cooling times, which adversely affects sustainability and productivity.

Second DoE. The aim is to further investigate the most important control factors as a follow up to the first DoE. Given that all three materials investigated there ensure the mechanical strength and thermal properties of the part and knowing that materials with a higher MFI are also more expensive, it is decided to fix the material to ISPLEN™ PB300 A3M with MFI: 80 gr/10min, Density: 905 kg/m^3, Flexural modulus: 1250 MPa, Charpy impact strength: 5kJ/m^2, heat deflection temperature (0.45 MPa): 90 ºC and Shore hardness: 62 (D Scale) (see www.b2bpolymers.com). In addition, less influential control factors according to the first DoE are also fixed, in addition to those that were fixed in the first place in the first DoE, as follows: Max injection pressure: 200 MPa, Mold temperature: 20 ºC. As far as control factors are concerned, in order to reduce the emergence of material flow cut-off inside the cavity, the range of filling time and packing time is reconsidered, since medium values exhibited better results in the first DoE. Thus, control factors are summarized in Table 3. An L27 OA is again adopted. Regarding quality factors, see Table 3, in addition to those investigated in the first DoE, the cycle time is added, its variable component consisting of filling plus packing time, whereas the sum of its fixed components, namely cooling and mold open time amount to 5.08 sec. Similarly to the first DoE, the results obtained are summarized in Table 4.

Table 3 Control factors for the second DoE.

Control factor	*Level 1*	*Level 2*	*Level 3*	*Quality factor*	*Loss function*	*Nominal*	*Weight (%)*
Melt temperature [°C]	220	240	260	Clamping force [tn]	SB	87.5	35
Max pack press [MPa]	40	60	80	Part weight [gr]	NB	15.5 ±3%	35
Filling time [s]	0.19	0.22	0.25	Molten core	SB	0.2	10
Packing time [s]	0.45	0.50	0.65	Cycle time [s]	SB	4.5	20

Table 4 S/N Delta analysis and ANOVA % Contribution of control factors in the second DoE.

	Clamping force		*Part weight*		*Molten core*		*Cycle time*	
Control factor	*S/N Δ*	*% Contr*	*S/N Δ*	*% Contr*	*S/N Δ*	*% Contr*	*S/N Δ(X10^{-6})*	*% Contr*
Melt temperature [°C]	1.69	78.98	2.49	74.99	7.551	36.00	13895	0.20
Max pack press. [MPa]	0.343	3.4	1.60	9.86	3.775	10.00	14548	0.95
Filling time [s]	0.632	11.92	0.12	2.97	3.775	10.00	33740	6.00
Packing time [s]	0.377	4.99	0.18	5.94	7.551	36.00	41509	89.82

Indicative results from run no. 3, which is one of the two runs leading to uneven pressure distribution, are shown in Figure 4. In addition, Figure 5 displays all pertinent S/N diagrams.

The second DoE can be deemed successful, since only 2 out of 27 experiment runs showed a cut-off of material flow inside the cavity, in contrast to 18 out of 27 in the first DoE. The two runs involve lower material temperature and longer packing time, thus an increase in the former and/or a decrease in the latter should be alleviate this problem, as is also confirmed in Table 4 regarding quality factor 'part weight'. In the simulation run example shown in Figure 4(a)-(b), at the end of the packing phase, the pressure and temperature distribution in the part is generally acceptable. At the same time, the area around the ingate remains molten and is cut off from the rest of the already solidified block. This has already started 0.10 sec earlier, see Figure 4(c).

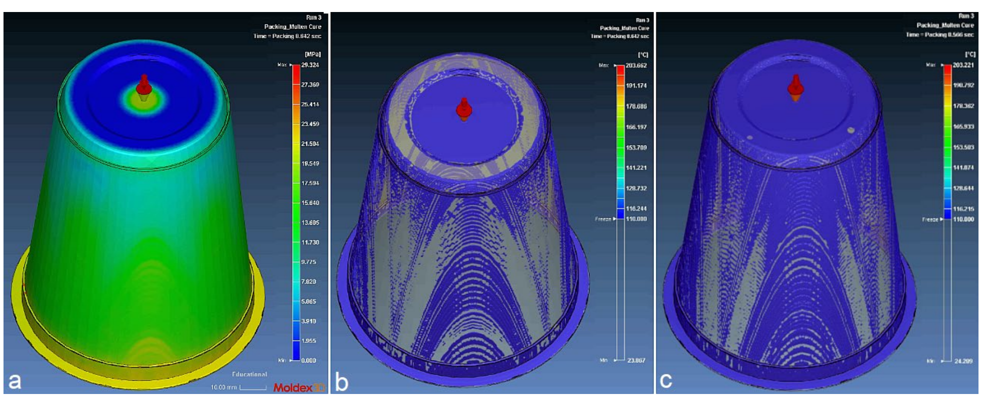

Figure 4 Indicative results for second DoE with MET=220°C, MPP=40 MPa, FIT=0.25 sec, PAT=0.65 sec (a) Pressure at the end of packing phase (0.65 sec) (b) Temperature at the core at the end of packing phase (0.65 sec) (c) Molten core temperature at 0.55 sec into packing phase

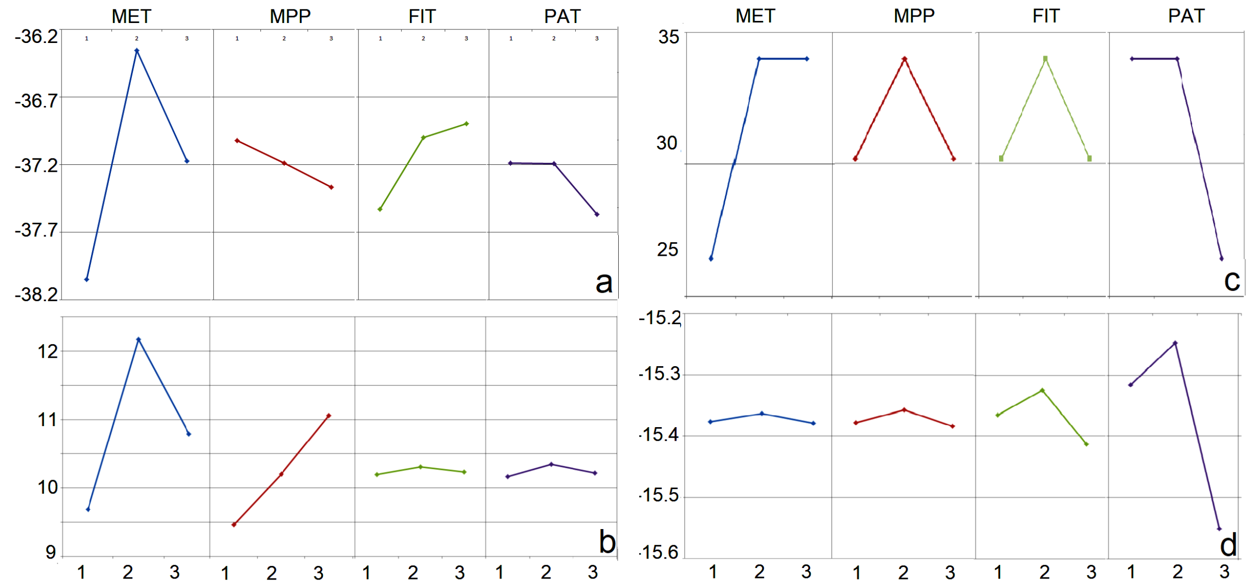

Figure 5 S/N diagrams for second DoE (a) Clamping pressure (b) Part weight (c) Molten core (d) Cycle time

In general, results are strongly dependent on melt temperature, the latter being the most influential factor for three out of four quality factors examined. As a matter of fact, melt temperature range considered is quite wide, so its further investigation is necessary. Actually, the highest S/N ratios correspond to a temperature of 240ºC.

With regard to the quality factor 'cycle time', the most significant control variables are : filling time and packing time, the latter having by far the greatest effect, see Table 4. This seems reasonable, in view of the very short cycle time, meaning that the phase with the longest duration (and also coarser variation step of the order of 0.1 sec) should also have the overwhelming influence. Finally, regarding part weight, the second most important factor is maximum packing pressure, whereas regarding clamping force, it is the filling time.

Third DoE. According to the second DoE melt temperature proved the most significant control factor, thus a further DoE yet restricted in scope was deemed important focusing on a narrower melt temperature range examination around the 240ºC value recommended by the manufacturer, i.e. 235, 240 and 245 ºC. The rest control factors and their levels remained as in Table 3. Of the quality factors examined in the second DoE, see Table 3, the molten core was exempted because material feed cut-oof is not expected given the much narrower melt temperature range. Weights for the three factors of clamping force, part weight and cycle time have been set to 40, 40 and 20% respectively. The OA employed is L9. Note that degrees of freedom are zero, thus error factor is not relevant. Similarly to the previous DoEs, the results obtained are summarized in Table 5. In addition, Figure 6 displays the pertinent S/N diagrams.

Table 5 S/N Delta analysis and ANOVA % Contribution of control factors in the third DoE.

	Clamping force		*Part weight*		*Cycle time*	
Control factor	*S/N Δ*	*% Contr*	*S/N Δ*	*% Contr*	*S/N Δ (X10^{-6})*	*% Contr*
Melt temperature [°C]	0.398	27.64	3.630	32.85	0.263	0.9
Max packing pressure [MPa]	0.570	49.92	1.838	11.76	0.672	8.2
Filling time [s]	0.283	13.68	3.127	28.06	0.400	1.9
Packing time [s]	0.087	9.00	3.117	27.33	2.168	90.0

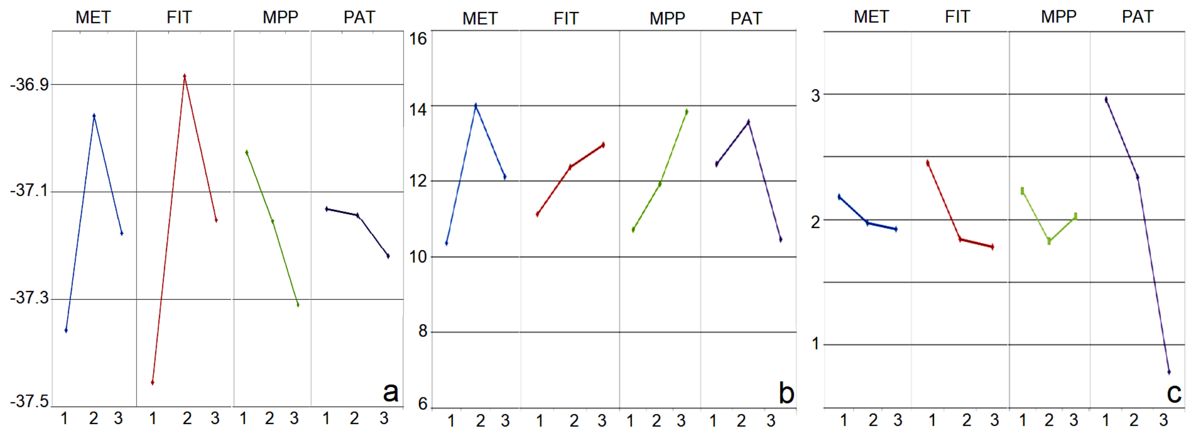

Figure 6 S/N diagrams for third DoE (a) Clamping pressure (b) Part weight (c) Cycle time.

It is to be noted that no cut-off of material flow was observed in any simulation run, hence temperature increase is beneficial. In addition, dependence of the quality factors on the temperature of the polymer material is significantly reduced. Melt temperature remains as the first of the two factors with the greatest influence on part weight and clamping force, however it now has a much smaller share. More specifically, the picture concerning cycle time remained approximately the same as in the second DoE. As for part weight, all control parameters contribute to the result. As regards clamping force, the factor with the most significant effect is now filling time, with a percentage contribution of around 50%. It should also be noted that levels 1 and 2 of packing time perform very close to each other. In general, the optimal value for melt temperature is 240 ºC, which is also recommended by the material supplier. Regarding filling and packing times, it can be stated that the middle values considered, i.e. 0.22 s and 0.5 s respectively, are preferable. As for the maximum injection pressure its preferable level differs for each quality factor considered. In any case, the optimal values for the control factors will be determined in the next section.

Optimisation. In order to determine the optimum values of the control factors a weighted objective function was created, whose minimization was sought, involving the normalized quality factors, where denominators represent the maximum values encountered and multiplicators denote the % weight of each factor:

$$40\frac{Clamping\ Force(Tn)}{75.1}+40\frac{Abs.Deviation\ from\ Target\ Weight(gr)}{0.339}+20\frac{Cycle\ Time(s)}{0.923} \quad (1)$$

The resulting optimum values were as follows: Material MFI=80, Melt temperature: 240 ºC, Mold temperature: 20 ºC, Max injection pressure: 200 MPa, Filling time: 0.22 sec, Max packing pressure: 60 MPa, Packing time: 0.50 sec.

A simulation was run for these inputs and characteristic results are depicted in Figure 7. The corresponding quality factor values were as follows: Max clamping force: 70.1 tn, Part weight: 15.365 gr, Cycle time (filling and packing only): 0.73 sec. At the end of packing phase more than 80% of the material has solidified, yet the core remains fully molten, see Figure 7(e). Note that some air bubbles seem to be trapped where flow direction changes, see Figure 7(h). Also note that some volumetric shrinkages has been predicted (1.69, 1.71, 1.58 % in the X,Y,Z direction respectively) but deflection at the rim is negligible, see Figure 7(i).

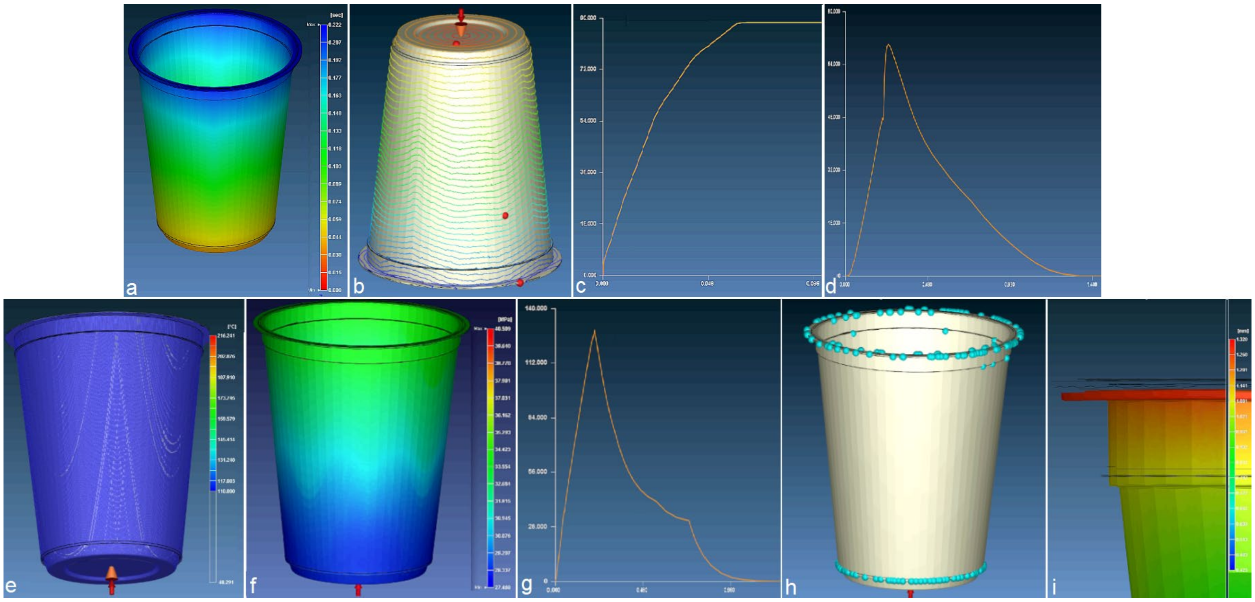

Figure 7: Indicative simulation results for the optimum case (a) Filling melt front time (b) iso-parametric pressure curves in filling phase (c) filling flow rate vs time curve (d) clamping force vs time curve (e) molten core at the end of packing (f) pressure distribution after packing (g) pressure vs time in sprue during packing (h) air bubbles accumulation (i) final part distortion

Concluding remarks

In the present work, injection molding parameters for a polypropylene food packaging container were studied using a dedicated, well-established in industry simulation program. The latter enabled understanding of the process via visualization of the filling pattern of the cavity as well as prediction of any defects.

The Taguchi DoE method proved to be time-efficient for examining different process parameter combination scenarios, given the manageable number of experiments it requires. In this work, it was proven that cavity filling is facilitated by using materials with a higher MFI, as opposed to increasing melt temperature which is economically unacceptable. The influence of filling time and packing time was also confirmed, while the temperature of the mold did not play a special role in the two phases examined. The appropriate order of significance of process control parameters was calculated leading to optimize the overall result in terms of part weight, clamping force and cycle time.

In the future, investigation should be completed by embedding cooling stage in the simulation, since cooling time accounts for the largest part of the injection cycle. In addition, with appropriate channel design, part shrinkage and distortion should be realistically predicted.

Finally, it would be useful to validate simulation results. The software employed enables simulations in ‘Machine Mode’, which requires data from the controller of the injection molding machine. This will ultimately lead to a digital twin.

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