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Mass Production Tools and Process Readiness for Uniform Parts—Injection Molding Application

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Abstract

A mass production always aims to produce uniform performing products. Production tools such as pressing dies, casting dies and injection moulds, play a significant role by producing uniform parts for achieving final products. Tool complexity increases when multiple cavities are present. These tools pass through several stages of quality maturation, before starting production, where the tool capability for part uniformity can be assessed, corrected and aligned to mass production variables. This research article describes the process of systematic understanding of the impact of variables and of finding opportunities to counter them. Application is assessed over a hypothetical plastic injection mould and found feasible. Proposed process could evaluate the tool capability for producing uniform parts, at its digital design verification and its physical validation.

Keywords: *Product consistency, injection molding, uniform parts, cavity to cavity variation*

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INTRODUCTION

Original equipment manufacturers have always aimed at producing uniformly performing products, the production of which contributes significantly to brand identity [1, 2]. Individual parts contribute to unit-to-unit variation, and parts vary due to the impact of process variables [3]. This cascading situation demands that mass production tools like pressing dies for sheet metal parts, pattern equipment for metal casting, and injection molds for the plastic part be produced with the aim of reducing sensitivity to the process. Figure 1 shows the variation flow to production tools causing unit-to-unit variation in generic mass production. Three different tools with four cavities in each can produce four product units at each shot.

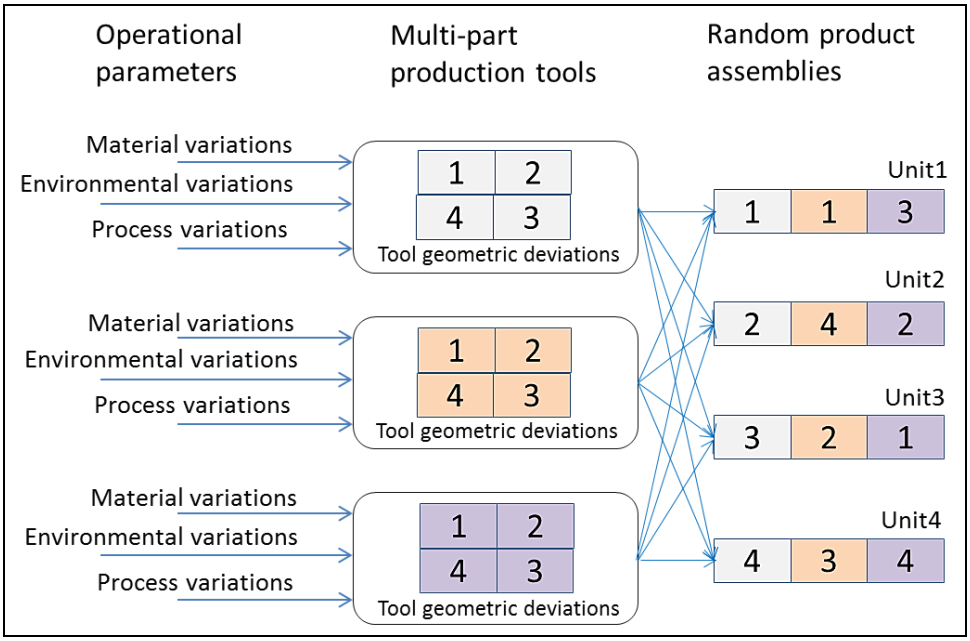


Fig. 1: *Variation Flow to Product Units in Mass Production Scenario.*

Parts from each tool can go to any product unit randomly in mass production. Being all four parts from the tool are with different characteristics, product units also perform differently; accurate performance estimation of units is not possible. That results need of producing uniform parts from each tool. Here, uniformity is defined as:

Uniformity: Parts with identical characteristics in all aspects of geometrical, mechanical, chemical properties are said to be uniform.

The aim of the tooling is to produce uniform parts. The raw material variations like modules, density, composition etc, contribute to the final part performances. However, the raw material processing environment influences the material conditions and response to the processes; for example, relative humidity changes the moisture content in the raw material. Similarly, the environment also influences the process performance; for example, ambient temperature changes influence the cooling/heating pattern in the process. Along with these dynamics, actual process settings vary due to machine accuracies, for instance, stroke speed changes due to voltage fluctuations, pressure variations due to change in hydraulic oil viscosity, temperature loss due to sensor reading error and so on, changing the tool performance in producing uniform parts.

How a sensitive part uniformity is to these production parameters is depends on the tool design philosophy. An intelligent approach to tool design aims to make the tool performance unchanged, even when the operational parameters are varying [4]. Digital simulation tools allow the impact of production variations to be identified and the uniformity of tool design quantified.

Steel tools are manufactured according to the given 3D geometry. However, machining and assembly processes of tool making can generate deviations. In general, tool quality is measured and maintained within a certain tolerance on the nominal 3D geometry; for example, an injection mould machining tolerance may be specified as ±0.015 mm, and a sheet metal forming might be ±0.05 mm. Often tool accuracy is a small portion of the overall part dimensional tolerance, and it is maintained irrespective of the part criticalities.

When the part is measured, and its characteristics are found deviate, the exact variables contributing to that deviation are less known. The present industry practice of tool maturation and readiness for production is by measuring the process capability [5]. Many variables generated at tool design and manufacturing are part of final part variations, and all are counted in process capability. Standard Process Capability Databases (PCDB) also do not indicate the variables causing the part variation [6, 7]. This current practiece is limiting the improvement cycle to achieve uniform parts. Knowledge of the variables' contributions and the linkages between them gives the opportunity to reduce/nullify their effect on parts.

This article focuses on identifying the approach for establishing the complex relationship between part achievement and production variables over the journey of tool design to Start of Production (SOP). Information about this relationship provides opportunities in mass production for compensating variations.

METHOD

Tool design starts from understanding the part performance requirements [8]. During the tool design process, the designer generates several variables that influence uniformity. Knowing the nature of variables helps to manage their effect on parts. Figure 2 shows the sequence of steps followed in the research for reducing the impact of variables and identifying the opportunities to nullify them.

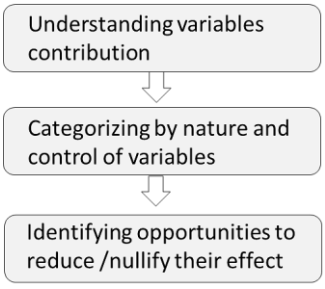


Fig. 2: *Research Method Followed to Understand Part Variations.*

UNDERSTANDING VARIABLES' CONTRIBUTION

How all the operational parameters (OP) (from Figure 1) together contribute to the part achievement in the tool is verified through simulation; for example, AutoForm used for sheet metal forming [9], Moldflow used for injection molding [10]. Through the cycle of improvements, the designer finalizes the nominal values of all operational variables to achieve the nominal characteristics of the parts [11]. Part characteristics influencing final product performance are identified and controlled as design parameters (DP) at the product design stage. A tool designer can tabulate the sensitivity of those DPs to each variable through virtual simulations. Part DPs may not always be physical dimensions, for example, stresses developed in a part may also be a targeted DP, linked to through-life deterioration.

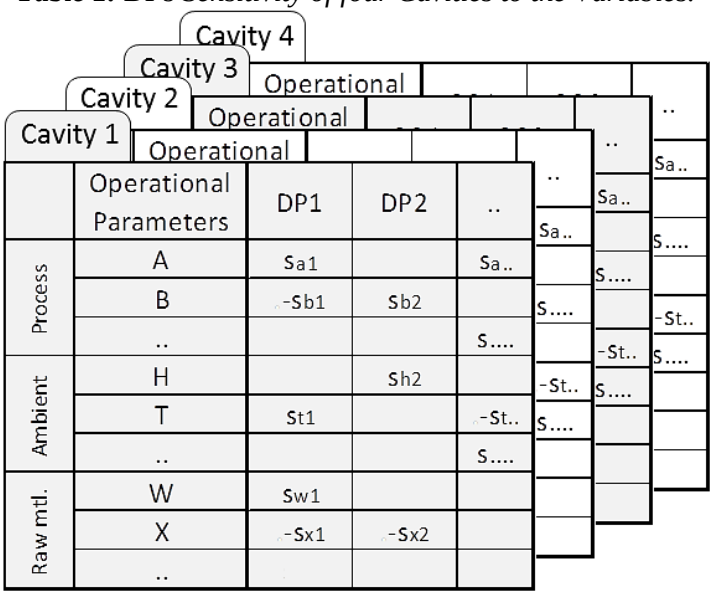
In the case of a multi-cavity system, this sensitivity table may differ for each cavity from the same production cycle/shot [12]. That difference describes how uniformly the process is carried out for all the parts, within one shot. A representative Table 1 shows the sensitivities of DPs for a four-cavity tool.

Sensitivity value indicates the change of the DP per one unit change of variable. Table 1 gives an understanding that DP1 will vary by "sa1" with one unit change in variable A. Similarly, DP2 will vary by "sb2" when one unit change occurs in variable B. Negative sensitivity indicates that DP variation and variable change are inversely proportional when variable B increases by one unit DP1 is decreasing in its value by "sb1".

Once each cavity response to the process is fixed in the steel tool, the set of relationships continues until the end of the tool life. Means variation between cavities is unchanged due to OPs changes. This understanding gives two segments of variation; one is due to tool architecture (difference of the parts within one cycle/shot), second is due to change in OPs. Figure 3(a&b) shows the part DP behavior in the multi-cavity system over operational parameters variations, considering a part nominal DP of 10 mm.

Figure 3(a) shows that parts from one production shot varying from 9.9 mm to 10.18 mm from the tool, is due to the non-uniform processing created in the tool layout/architecture. This difference (10.18-9.9 = 0.28) is unchangeable via controlling Ops (e.g., better raw material, controlled climate, new machinery, etc.), and can be eliminated only by correcting the tool. This variation in DP is the Tool Contribution (TC). Figure 3(b) shows that variation leads to shifting the cavities to a negative side by 0,15mm (9,9–9,75), and positive side by 0.07mm (10.25–10.18), which is due to OPs variations.

Table 1: *DPs Sensitivity of four Cavities to the Variables.*



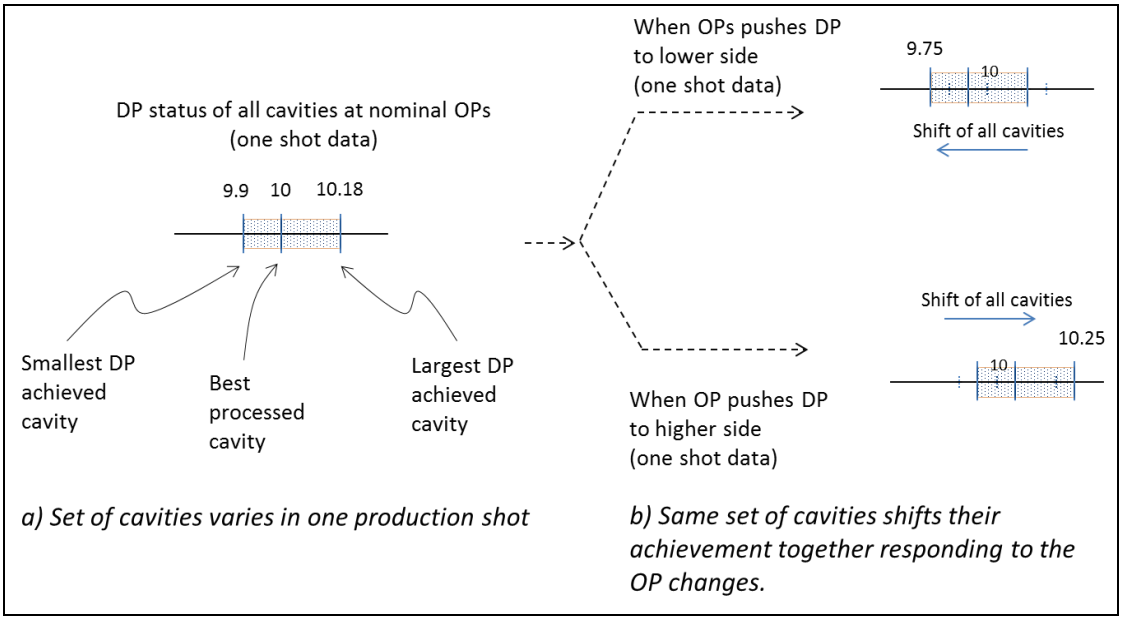


Fig. 3(a&b): *A Multi-Cavity Tool Behavior at Nominal and Extreme OPs for DP Achievement.*

Eliminating this DP variation may be achieved by keeping consistent OPs or by compensating one OP effect for another OP [13]. This variation in DP is the Process Contribution (PC). Understanding these two segments of variation and aligning the tool maturation leads to the production of uniform parts.

CATEGORIZING NATURE OF VARIABLES

Variations in TC and PC lead to considering the nature of each variable. Understanding them more deeply allows for planning to reduce their effect.

Tool Contribution

Different achievement between cavities is due to the difference in the process applied to each cavity. When designing the tool for higher volume production, multi cavity tools are most cost effective [14]. Due to different manufacturing and space constraints, a process in each cavity differs; for example, cooling water temperature displays low at first cavity and high at last cavity within its circuit in the injection mold. These process input differences get fixed along with tool layout, and cannot be changed throughout the tool life. Even if all the cavities are the same in a virtual environment, geometrical differences present due to the machining and assembling deviations, which cause part variation from cavity to cavity. However, cavities can be intentionally made geometrically different to compensate for variations, as a one-time tool corrective action.

Process Contribution

During the process, the variation contribution starts from raw material which is controlled within the range given by its property specifications. The material report along with every batch gives the property status. Manufacturing process parameters, optimized through design of experiments (DOE), are controlled by operators through machine settings. It is generally possible to change these at any time during production.

After a detailed study of TC and PC, the variables are categorized by two of their criteria, position and applicability.

Position

Tool development and use process have been laid in sequential steps and each step/position identified with a number. Variables are studied and assigned the number at which position it is enetring into the part. This task helps to plan the remedial action after this position in the process. Variables contributing at earlier positions will have more opportunities to counter in the later stages. Figure 4 shows the generic tool development and mass production process with positions numbered.

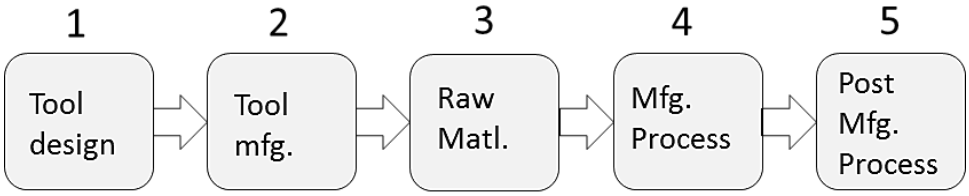


Fig. 4: *Positions Numbered Over Generic Tool Development and Use Process.*

Table 2: *Variables Applicability and Their Interpretation for Action Alignment.*

	Applicability	Interpretation
1	Throughout Production	A tool and process design followed at multiple locations, carries the same non-uniformities those are induced by the tool design philosophy.
2	Throughout tool life	Deviations generated in tool manufacturing are specific to tool, even their design is common. These are applicable only to that tool till its life.
3	Environmental check interval	Ambience measurement and data feed frequency may be depends on product and process sensitivity to those parameters. Applicability may be seasonal, monthly, weekly, day and night, or even hourly etc.
4	Throughout the material batch	Variables influence through raw material are consistent to batch in use. Status of those variables to be applied same for all the parts of that batch according to the report received from supplier.
5	Shift / stop over	Variables come into influence due to operator skills, machine shutdown, etc. are to be understood, act in the same frequency
6	Every shot-All cavities	Differences between shot to shot may occur due to some machine variables like lag in stroke, temperature raise, etc. to be verified and acted at every shot for uniformity.
7	Every shot-Specific cavities	Some times specific cavity shows variation due to layout orientation, gravity, etc. Actions may required at every shot for that specific cavity to bring uniformity.

Applicability

The timing of counter actions must also be aligned with the timing of variable changes. For example, a deviation in a batch of raw material may effect all of the parts produced from that batch of material. Any counter action is required to be active until that batch is completed, but not after. Table 2 shows the interpretation of different temporal applicability applied to a generic production system.

The effects of variables may not always be independent; their interaction with other variables may be significant and also may contribute differently to different part DPs. This information allows for balancing the counter-action influence across the part and process. Sometimes the measurement may be done indirectly, which adds more variables and sensitivities into the system. For example, concentricity of a solution is estimated by its color measurement, a linkage to be established between color variations to concentricity variation. Here color is a new variable.

IDENTIFYING OPPORTUNITIES

Production control on all variables is not the same. Their degree of control is classified into three groups [4].

Uncontrolled

Many of the production floors work in an uncontrolled climate. In those cases, environmental changes are just given, like temperature, humidity, air quality, dust content, etc. Even in climate controlled production plants, some processes may have uncontrolled variables, such as seismic vibrations.

Semi-Controlled
The variables may not all be produced in-house. Those are controlled with some acceptable range of variation and maintained through supplier quality control methods. For example, raw material characteristics, out-sourced parts, standard parts.

Fully Controlled
The set of process parameters for mass production is in the full control of the production operator. For example, machine stroke length and speed in a die pressing process, coolant temperature and injection speed in the plastic molding process. These parameters are fixed at their best suitable values during tool maturation. The changing of these parameters is in the production operator's control.

Mapping all the variables and understanding their nature (position and applicability) allows finding opportunities to compensate the effect of semi and uncontrolled variables, through fully controlled (FC) variables. For example, the layout of the tool causes certain deviation in each cavity on either the positive or the negative side. Knowing the exact contribution of TC, each cavity geometry can be made to compensate to have all cavities for the same output. However, the tool designer should think through and plan a tool maturation strategy.

Some deviations are periodical. The raw material may change its characteristics batch to batch, with consequent different impact on part achievement. For example, a less ductile sheet metal batch can be formed with a slower press speed setting. This action is limited to only that batch. Similarly, higher relative humidity may need larger pre-heating time in the molding process. This action is only for the specific times when humidity is high. Utilizing these opportunities needs to be pre-thought and accurate sensitivity values established for all variables through virtual and physical DOE.

RESULTS
Table 3 shows the identified opportunities and enablers over the process positions. Focusing on utilizing every FC parameter to compensate all previously contributed deviations is required to determine the possibilities for any product and process. For achieving uniform parts, the calculated effect of opportunities needs to be equal or more than the effect of other variables. It is not possible to remove the effect of variables contributing after the last opportunity in the sequence. When opportunities are capable of compensating larger variation effects, semi-controlled variables can be relaxed. This process of developing a table of variable effects and opportunities is required to be part of a manufacturing strategy starting from tool design to SOP. Application effectiveness depends on accurate sensitivities and interactions identified by the tool verification process (virtually and physically).

Measurement uncertainty, machine accuracy and some of the human skill variation may still impact the part. These are established by calibration, but not measured in day to day production. Aiming for less uncertainty and higher calibration frequency helps in reducing their contribution.

CASE STUDY—AN INJECTION MOULDING PROCESS
A plastic part production process has been chosen from the injection molding industry to demonstrate the discussed process. Part and tool are simplified for the purpose of demonstration, as shown in Figure 5, with a critical DP, for the study.

Nullifying TC
After digital and physical simulations, a possible shrinkage results at each cavity, as shown in Figure 6. These simulations are, with nominal process settings, finalized after optimization. Also, the raw material for physical trails is at nominal specs.

Table 3: Generic TC nd PC Variables Arranged by their Position and Identified the Opportunities for Compensating their Effect

		Variable	Nature: Position	Nature: Applicability	Opportunity at Mfg.	Nature of Opportunity	Aim	Enabler
TC		***Tool Design***						
	SC	Cavity to cavity pressure difference	1	Throughout production	Nil	Nil	Pass the calculated deviation	1.Establishing sensitivity values of each process parameter while virtual simulations and confirm them in physically. 2.Establish reference cavity for each DP and identify each cavity deviation at nominal PPs. 3.Induce maturation scope for DPs at tool design stage.
	SC	Cavity to cavity temperature difference	1	Throughout production				
	SC	Assumptions - specific heat, friction, etc.	1	Throughout production				
	SC	Virtual simulation accuracy, Etc.	1	Throughout production				
		Tool Manufacturing					⇩	
	FC	Cavity to Cavity geometry difference	2	Throughout tool life	Compensating in tool geometry	Every tool and every cavity specific. One time task	To compensate all theoretical errors and design imperfections	Tool maturation process aiming to compensate all possible variations, instead of aiming to be with in specific limits.
	FC	Tool alignment, .Etc.	2	Throughout tool life				
		Stage 1 - All the variation so far from position 1 and 2 are compensated						
PC		***Raw Material***						
	SC	Density	3	Throughout tool life	Nil	Nil	Pass the calculated deviation	Measure all variables linked to DP achievement pass feed the data proactively to production.
	SC	Young's modules, Etc.	3	Throughout tool life				
		Environmental					⇩	
	UC	Relative humidity	4	Checking interval	Nil	Nil	Pass the calculated deviation	Ensure the measuring frequency is matched to quickest action possible at production.
	UC	Temperature, Etc.	4	Checking interval				
		Mfg. Process					⇩	
	FC	Process setting - Pressure	4	Every shot- All cavities	Adjustability is process parameter setting	Every production location and batch specific	To compensate all the raw material and environmental impact	Ensuring dynamic process setting linked to all deviation inputs. A production monitoring system proactively accept previous stages information and suggest setting changes to nullify the effect on parts.
	FC	Process setting - Temperature	4	Every shot- All cavities				
	FC	Process setting - Stroke length, Etc.	4	Every shot- All cavities				
	FC	Lubricant spray non-uniformity	4	Every shot- Specific cavity	Compensating action for every shot	Specific effected cavities only	To compensate issues identified over maturation, not anticipated while design	Design specific actions depends on the nature and variation contribution of specific variable for specific cavity effected
	FC	Gravity effect due on cavity layout, Etc.	4	Every shot- Specific cavity				
		Stage 2 - All the variation so far from position 3 and 4 are compensated						
	UC	Machine accuracy	4	Throughout the machine life	Nil	Nil	Estimate the uncertainties and quantify the effect on DPs	Establish sensitivity values while designing the process
	UC	Process adjustment interval effect	4	Shots between the adjustment				
	UC	Operator skill difference/efficiency, Etc.	4	Throughout the shift				
		Post Processing					⇩	
	SC	Cleaning / degreasing	5	Throughout production	Nil	Nil	Calculate possible effect	Establish sensitivity values while designing the process
	SC	Forced Cooling	5	Throughout production				
	SC	Post shrinkage control, Etc.	5	Throughout production				
							⇩	

TC- tool contribution; **PC**- process contribution; **UC**- uncontrolled; **SC**- semi-controlled; **FC**- fully controlled

Part DP

The difference in shrinkage between cavities reflects how uniform the cavities are processed in the given arrangement. The smaller the difference between the highest and lowest shrinkage is a measure of mould design achievement, for its cavity layout and cooling circuit. Differences between digital and physical simulation results show the errors in assumed values for digital simulation, such as surface friction coefficient, mould steel conductivity, and also the accuracy of the simulation software. This data helps in deciding the exact size of the cavity required to get the drawing specified part DP from each cavity as in Table 4, calculated through the basic shrinkage relationship Eq. 1.

$$Size\ of\ the\ Cavity = \frac{Size\ of\ the\ part}{(1 - Shrinkage)} \quad (1)$$

These size differences in cavities counter the TC and bring all eight parts from each shot to the 22 mm DP at nominal OPs.

Compensating PC

Influencing OPs with their variations are defined/ estimated as shown in Table 5. Semi-controlled parameters come from a supplier and are from the raw material batch report. DP sensitivity to their variation is captured through experiments. Specific material is not sensitive to semi-controlled environmental parameters. Fully controlled process parameters are established with DP sensitivity to their changes.

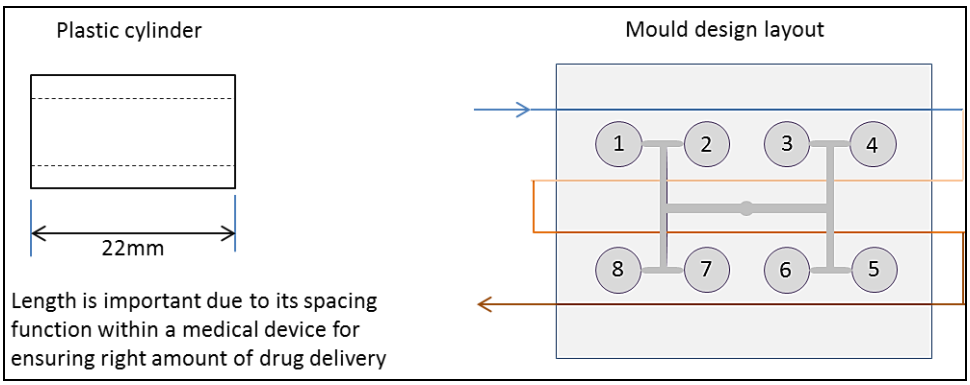


Fig. 5: *A Plastic Part and Its Representative Mould Diagram.*

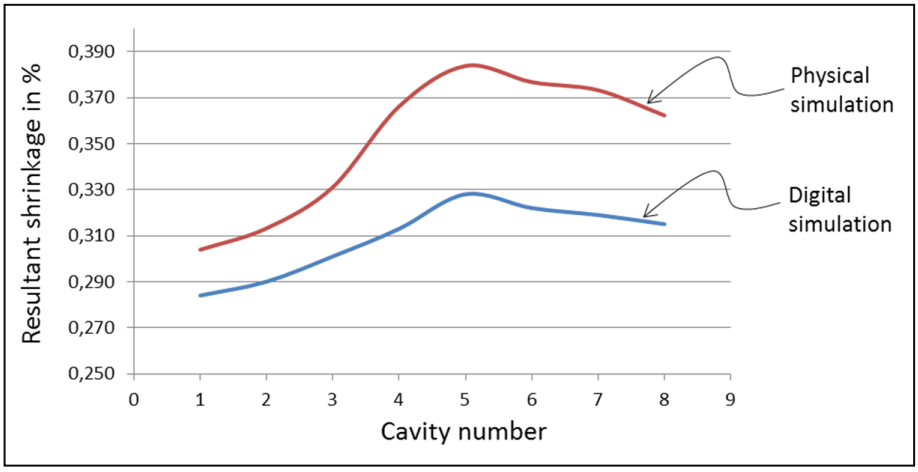


Fig. 6: *Resultant Shrinkage Variation Over Each Cavity.*

Table 4: *Cavity Size Required for Uniform Parts, Meeting the Specification.*

		Cavity number							
		1	2	3	4	5	6	7	8
Srinkage	Digital simulation	0,284	0,290	0,301	0,313	0,328	0,322	0,319	0,315
	Physical simulation	0,304	0,313	0,331	0,366	0,384	0,377	0,373	0,362
Cavity size required		**22,067**	**22,069**	**22,073**	**22,081**	**22,085**	**22,083**	**22,082**	**22,080**

The aim at the digital simulation stage is to fix the parameter's nominal value to a point where the DP is at its least sensitive point. The same is to be reestablished with physical experiments. The overall mold development process is expected to improve continuously to match the results of both simulations for accurate estimation. Figure 7 shows possible linkages of DP with all variables identified based on published research [15–20]. Process parameter interactions are neglected for case simplification.

Table 5: *DP Sensitivity to Operational Parameters.*

Operational Paramters					DP Sensitivity	
	Parameter	Nominal	Tol	Unit	Digital	Physical
SC	Melt flow index	10	±1,5	g/10min	0,075	0,097
	Glass fiber content	30	±2,5	%	0,056	-0,095
UC/SC	Room temp	23	±4	degree	NA	NA
	Humidity	50	±5	%	NA	NA
FC	Holding pressure	40	±5	Mpa	0,028	0,021
	Holding time	8	±3	sec	0,025	0,025
	Melt temperature	270	±10	˚C	-0,04	-0,05
	Mould temperature	60	±5	˚C	-0,013	-0,035

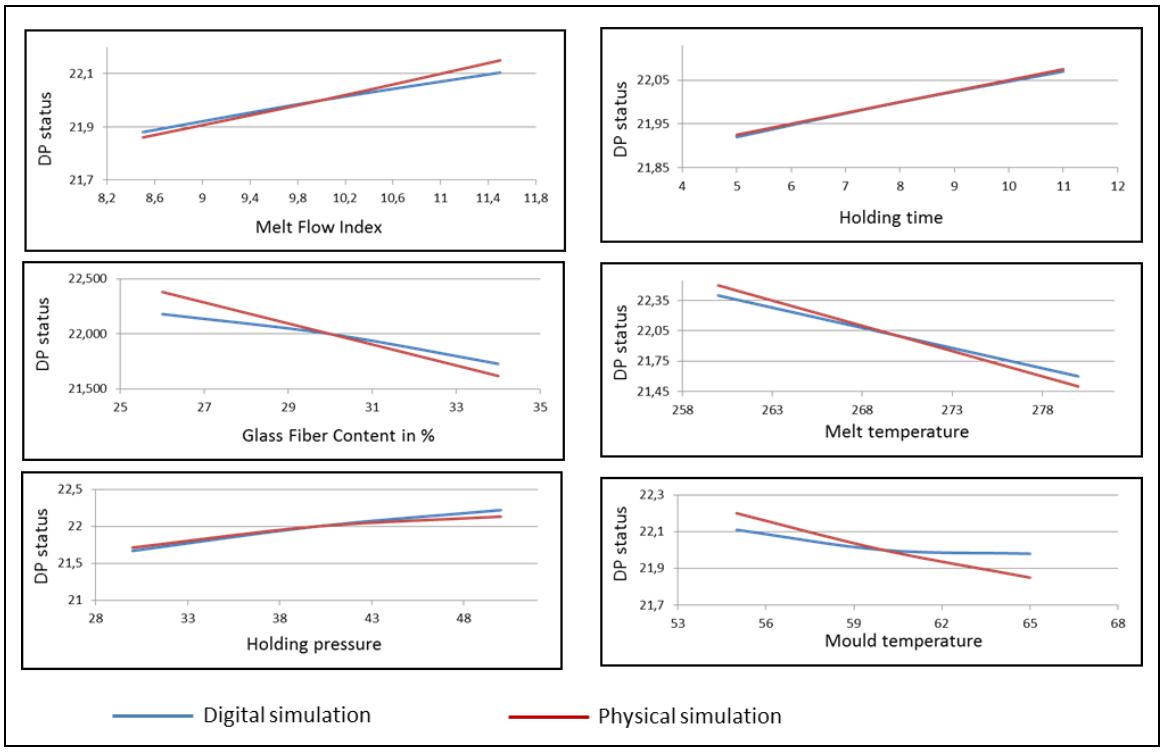


Fig. 7: *DP Relationship Established with all OPs Trough Digital and Physical Simulations. DP is always scaled on the Y axis in mm and variables on the X axis with their corresponding units.*

Table 6: *Example Production Situation of PC Compensation.*

SC Parameter	Measured	Effect (mm)	Total effect		FC parameter	Setting	Effect(mm)	Total effect
					Holding pressure	37	-0,063	
Melt flow index	10,5g/10min	0,0485	**0,144mm**	⇨	Holding time	6	-0,05	**-0,143mm**
Glass fiber content	29%	0,095			Melt temperature	272	-0,1	
					Mould temperature	58	0,07	

Table 7: *Alternate Solution of Table 6.*

SC Parameter	Measured	Effect (mm)	Total effect
Melt flow index	10,5g/10min	0,0485	**0,144mm**
Glass fiber content	29%	0,095	

FC parameter	Setting	Effect(mm)	Total effect
Holding pressure	45	0,105	**-0,145mm**
Holding time	8	0	
Melt temperature	275	-0,25	
Mould temperature	60	0	

The action for compensating the raw material variation effect through fully controlled parameters is exemplified as in Table 6. The effect of melt flow index and glass fiber content change could compensate by changing the process setting within 1 micron. It is possible to derive multiple solutions to compensate the semi-controlled parameters change effect in different change combinations of the FC parameter. The possible alternate solution is shown in Table 7. However, the operator may choose the quick and easy one.

The accuracy of the sensitivity values is essential for the success of this model. Greater precision of FC parameters gives a higher opportunity to compensate for the exact deviation. For example, temperature setting is changeable for 0.5 degree steps instead of 1 degree which gives a higher opportunity.

SOP Readiness

A table of all variables with their accurate sensitivities is required to be a part of handover documentation from tool development team to production team. The ability to produce uniform parts can be understood by comparing the total incoming variables effect to the effect of opportunity. An algorithm, developed for the quickest and cheapest solutions, should be part of the tool maturation process, before handover to production.

DISCUSSION AND CONCLUSION

- Often project cost and time estimations do not have enough simulations, which limits establishing accurate relationships. This process includes extensive simulations, may become a bottleneck for implementation.
- In present industry practice, process parameter setting changes are only at the time of tool change, shift starting or restarting after shutdown. They are not aligned to the dynamics of incoming variables. The present quality assurance process may need to change.
- The agility of process adjustments also contributes to achieving uniform parts. For example, mold temperature setting change may take the time of three production shots to stabilize; parts produced by those shots may need to be scrapped.

The process proposal for tool design and maturation for uniform parts is suitable for any type of tool and production process. The case study demonstrated its application on an injection molding process. Targeting part uniformity as SOP readiness criteria and measuring uniformity at tool design and maturation stage are found to be feasible. This process of compensating incoming variation effects through process setting change needs to be equipped with integrated information flow from the data of various measurements. Recent developments through the industry 4.0 revolution have focused on proactive communications and adjustability [21, 22]. The proposed tool development process may become a requirement in the future for being compatible with Industry 4.0 manufacturing.

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