THE UNIVERSAL PROCESS: A NOVEL APPROACH TO ENABLE INJECTION MOLDED PART(S) TO GENERATE A SINGULAR PROCESS ACROSS MULTIPLE MACHINES AND MATERIALS

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Abstract

The macro-issues the plastics industry is trying to resolve today pertain to sustainability, supply chain shortages, and the lack of skilled labor. Within the injection molding sector, manufacturers typically perform a full validation when a mold is moved to a different injection molding machine (IMM) or there is a material change. These full validations are labor-intensive, expensive, and not sustainable. Moreover, these methods may or may not utilize scientific molding principles. There has been a demand for a standard "part process" development method to transfer a mold between IMMs that is more efficient and can embrace variation in resins. iMFLUX's Auto-Viscosity Adjust (AVA) technology has made doing so easier with its low, constant pressure injection molding process. This adaptive technology enables the molding process to automatically adjust parameters in real-time around parts' response. This research focuses on developing a regenerative part process with low, constant pressure that is independent of resin and machine. Using AVA and cavity pressure sensors, two molds' processes were transferred to another capable press with the original process, no user adjustments, and parts were studied for visual and dimensional integrity. It was determined that iMFLUX can automatically regenerate optimized part processes in different IMMs deemed capable with negligible part variation as seen from the visual and dimensional results. This is the first time an intelligent controller can autonomously redevelop and validate a part process to mold parts within spec despite varying IMMs and resins.

Introduction

Conventional Processing

Conventionally, injection molding is a two-phase process that is controlled by injection velocity and screw position setpoints. IMM parameters such as shot size, transfer, and volumetric flow rate are derived from machine-specific proxies based on barrel size and injection speed. Process development entails filling a part(s) in an injection phase to 95% before transitioning to a hold phase at approximately half of the highest pressure recorded from the injection phase. For the injection phase, an acceptable velocity is determined through a rheology study to see where the shear of the material no longer affects a material's viscosity. In the hold phase, hold time is decided by a gate seal study. Gate seal occurs when the gate that runs molten plastic into a part has solidified and no material can flow back out.

Part Process Validation: History of Industry Attempts

In 2015, a consortium of leading global medical device OEMs began collaborating on a new validation strategy that had the capability to reshape industry standards for mold transfer validation requirements. This group's mission was to execute a proof-of-concept study inspired by a whitepaper written in 2000 by Rod J. Groleau, founder of the RJG Association and RJG Technologies, titled *Location Independent PPAP Streamlined for Global Manufacturing*. Groleau, who constructed and defined the term systematic molding in the late 70's[2], suggested the use of a lean systematic "part process" model as an alternative to machine validation. Groleau's whitepaper defines a part process validation as one that shifts the focus from the response of the machine to the part(s) in the mold and whether parts are being produced consistently.

In other words, this method optimizes in response of the "plastic's point of view."[1] Since the scientific molding process parameters are derived from plastic variables, not IMM variables, a mold has the capability to be moved between different IMMs despite them having different tonnages, intensification ratios, screw sizes, etc.[3] This idea was and is difficult for molders who use traditional, nonscientific methods to comprehend. The fact that a tool can move in-between such different IMMs, even hydraulic to electric, without a lengthy and careful requalification is difficult to accept. It appears too easy. It should be more complicated to be more credible.

The integrity of scientific, or systematic, molding is carried most predominantly by RJG, General Polymers, John Bozzelli, and other molding experts. Each of these ambassadors *strongly* recommends the use of cavity pressure sensors when molding because these transducers truly know the condition of the melt, and therefore assume part consistency in molds.[2]

For the consortium to develop this suggested part process validation model, a machine-independent variables (MIV) method was created where actual plastic conditions and parameters that characterize a part are recorded from one IMM to then be converted to have matching specified outputs

or results on a different IMM. Examples of these recorded parameters were fill time, actual melt temperature, volumetric shot size, and hold pressure. Since these variables were part-specific and not machine-specific, like the traditional validation approach, they were independent of the four distinctly different IMMs in this study. It was determined that this system could replicate optimized plastic parts data in different IMMs that were deemed capable with negligible part variation as seen from its dimensional results. This study satisfied visual and dimensional Ppk requirements of 1.5 or higher on the other three IMMs.[1]

The result of this lean systematic method research was a well-documented case study to introduce the medical device industry to the "Part Process Development/Validation" strategy as a robust alternate methodology to traditional validation concepts.[4] The ultimate paradigm shift this team faced after was to convince the average molder to focus on the plastic part process outputs rather than machine set points. It is important to note that the initial full IQ, OQ, and PQ part validations are still required. In addition, this method requires complex calculations, manual iterations, and is not applicable in the case of material changes.

iMFLUX Processing

The key difference between these two processes is that iMFLUX's technology controls with low, constant pressure using a closed-loop software integration. There are three main variables in this process. Melt Pressure and time, referred to as Step Time, are the first two and can be seen in **Figure 2**.

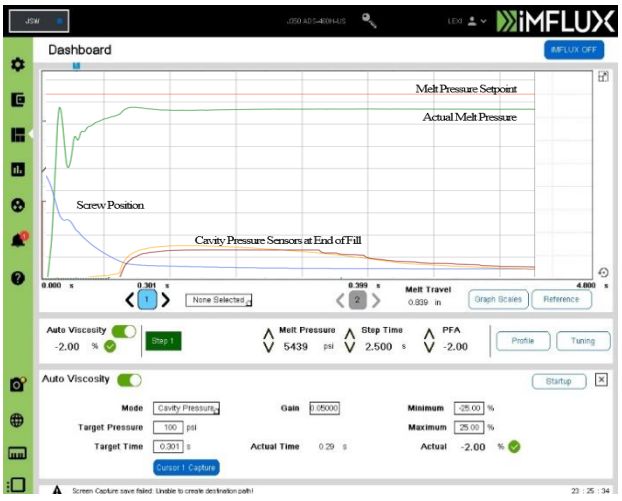

Figure 1: iMFLUX interface curve analysis.

In conventional molding terms, Step Time is equivalent to total fill and hold times combined. PFA is the third variable that is used to control the process at the end of fill and is best explained in the following equation.

Melt Pressure Setpoint (MPa) = Peak Pressure (MPa) - (PFA * Cavity Pressure (MPa))

Typically ranging from -2 to 0, PFA reacts to a cavity pressure sensor attached to the mold. It is a pressure change factor that can be used to increase or decrease the melt pressure in response to cavity pressure values. A PFA value of -1.0 will result in a melt pressure reduction that is equal to the increase in the mold cavity pressure. For instance, for every 1 psi increase in cavity pressure, there will be a 1 psi decrease in Melt Pressure.

Process development is done through a high-low range finding method referred to as Largest Empty Corner Rectangle (LECR). The LECR window populates as it appears in **Figure 2** where three acceptable process windows are calculated for a processor.

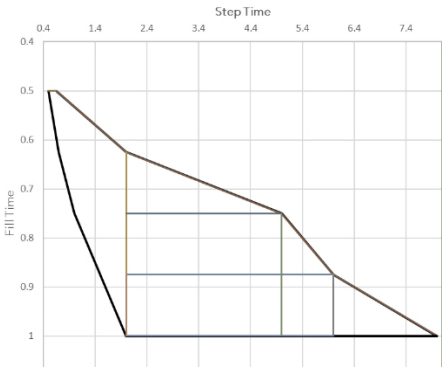

Figure 2: LECR process window with fill time versus step time.

Using a melt pressure transducer (MPT), as seen in **Figure 3**, attached to the nozzle of the injection unit, this technology measures actual plastic pressure rather than a proxy or calculated plastic pressure value seen on traditional IMMs.

Figure 3: MPT from Kistler.[5]

Where the consortium effort left off in 2017 is a notable case study. However, manufacturers are still tied to their material suppliers and machine-specific process setups. This is where iMFLUX has found opportunity. The flowchart in **Figure 4** displays the difference between conventional and iMFLUX's universal process validation procedures for two

resins on two IMMs

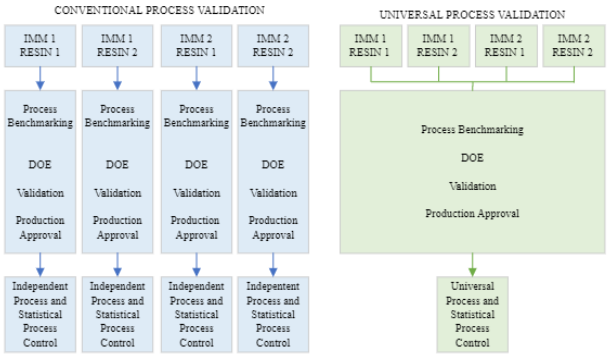

Figure 4: MIV transfer verification process – conceptual test plan for the VMP.

Unlike conventional processing, iMFLUX does not rely on machine proxies for success. Therefore, this technology does not require machine-specific process setups. The technology naturally determines velocity based on part geometry. Since the technology is utilizing actual plastic pressure, the process is always operating from the "plastic's point of view".

AVA Technology

iMFLUX allows for highly variable materials to be processed utilizing AVA technology which adapts in real-time. Post-consumer recycle (PCR), post-industrial recycle (PIR), ocean bottle grade plastics, and bio-filled plastics are examples of sustainable resins that have a history of being challenging to process. These resins have varying pellet sizes and molecular weights making them difficult to process conventionally. However, these materials are competitive alternatives to virgin resin being they are desired by consumers.

AVA is the component that potentially allows for resin to be independent of mold qualification when using cavity pressure sensors. The technology allows the IMM to behave like a giant rheometer to regulate and maintain stable flow rates into the mold. If the material viscosity varies, and the IMM does not vary then parts will vary. AVA automatically adjusts driving pressure to accommodate material viscosity variation thus providing a consistent, quality part. This allows for the IMM to vary, but the parts to maintain their integrity. Essentially, the variation seen in the resin isn't impacting the part quality.

The Medical Device OEMs' independent variables mentioned before were fill time, actual melt temperature, volumetric shot size, and hold pressure. iMFLUX's independent variables are fill time, PFA, and PFA time. AVA solves for plastic pressure as an output. **Figure 5** is how this feature appears on the technology's user interface.

Figure 5: AVA on iMFLUX's user interface in standard units. – Retrieved from iMFLUX.

Mode, set to Cavity Pressure, allows processors to connect physical cavity sensors to the interface to study the plastic's response. The input for fill time is referred to as Target Time. Cavity pressure is referred to as Target Pressure. In real-time, this feature analyzes the delta between the Target Time and Actual Time and alters melt pressure to match these times and to accommodate for resin variation. A stable process is achieved when Target Time is equivalent to Actual Time. The Gain value determines how aggressive the screw velocity should be to achieve the Target Pressure in the set Target Time. The standard Gain value is 0.05. The higher this value the more aggressive the drive to setpoint and vice versa. The Minimum and Maximum ranges from -100% to 200%, respectively. This range regulates AVA's pressure changes.

When experimenting with several resins, by enabling this feature and inputting the same Target Time for each resin, AVA communicates with the cavity pressure sensors to solve for the plastic pressure it needs to keep making parts with acceptable Cpks. For the first time, processors are seeing IMMs solve for the parameters it needs to make the same part regardless of the material or IMM type.

Materials & Methods

Materials

Three polypropylene (PP) post-consumer resins (PCRs), a PP post-industrial regrind (PIR), and a virgin PP were used for this study due to their wide melt flow index (MFI) range. The following table describes each resin's name and type as well as its reported MFI.

Table 1. Material descriptions and characterization.

Resin Name	Resin Type	Reported MFI
Braskem FT200WV (Virgin)	Homopolymer	20
KAL Polymers KP-PPH10M20N	PCR	10
KAL Polymers KP-PPH20M20N	PCR	20
KAL Polymers KP-PPH40M20N	PCR	35
NEWKO	PIR	varies

These resins will be referred to as virgin, KAL10, KAL20, KAL40, and PIR for the remainder of this paper.

Injection Molding Process: IMMs and Molds

A 3600 kN Haitian Zhafir and a 3440 kN JSW, seen in **Figure 6**, were the IMMs that were used to process the PP materials in two different molds.

Figure 6: Haitian Zhafir and JSW IMM.[6,7]

Each mold was designed to produce parts for the assembly of a deodorant container. The parts are referred to as Inner Barrels and Outer Barrels. The cavitation for each mold was four, and both had two end-of-fill cavity pressure sensors to record the response of each leg of the Design of Experiments (DOEs) and validations to ensure part consistency.

Process Window Development Method: LECR

This study begins with the development of a LECR. The process range is determined by the fastest and slowest fill times at the shortest and longest Step Times. The high and low PFA value is then determined at the shortest Step Time and longest fill time.

DOE Method

Minitab® was the statistical software used to generate a response surface DOE. A DOE is a standard, statistical method used to study and justify variation within plastic parts under conditions that are assumed to be the source of that variation. This method outputs a combination of parameters to test in several trials and measure how this affects plastic parts' dimensions. Through a DOE matrix, continuous factors and categorical factors can be isolated.

Continuous factors are derived IMM inputs which can also be considered machine-learned inputs. Examples are PFA Time, PFA, and Target Time. PFA Time is Step Time minus Fill Time. Categorical factors have a countable number of categories or distinct groups. The categorical factors in this study were the IMMs and resins.

Each mold's DOE had 65 randomized trials, referred to as legs, on each IMM with all the PPs. For each leg, five kilograms of material was used, and a resin sample was collected for MFI analysis. A shot was collected at the beginning, middle, and end of each DOE leg to be dimensionally measured. The dimensional data was then analyzed in Minitab's response optimizer to determine the most ideal settings across both IMMs and tested resins. The output is a single set of validation inputs to be tested for all IMM and material combinations.

Dimensional Measurement Method

A coordinate-measuring machine (CMM) is a device that measures the geometry of physical samples by sensing discrete points on the surface of the parts with a probe. As seen in **Figure 7**, a Mitutoyo Crysta-Apex S 500 series CMM was used to measure the dimensions for the inner and outer barrel parts.

Figure 7: Mitutoyo Crysta-Apex S 500 series CMM.[7]

A Gage R&R is developed to ensure that any variation in dimensional measurements comes from the parts and not the process and measurement method.

For the inner and outer barrels, the height and perimeter were the dimensions measured and studied for Cpk results.

MFI Method

A melt indexer measures a polymer's resistance to flow, also known as viscosity, at a set temperature, under a force, for a duration of time. To determine the MFI of the resin for each leg, Dynisco's LMI5500 melt indexer was used.

Figure 8: Dynisco LMI5500 melt indexer.[8]

As seen in **Figure 9,** a schematic of the MFI process is provided.

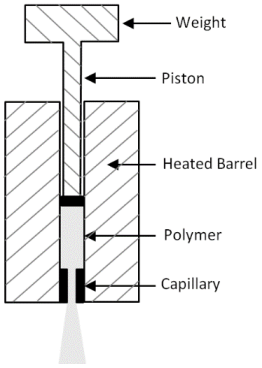

Figure 9: Melt indexer sample collection schematic.[9]

A stopper was placed at the bottom capillary to ensure no pellets escaped the heated barrel. Approximately six grams of resin were maneuvered into the heated barrel. A piston was used to pack the pellets down. A 2.06-kg weight was placed on top of the piston and left to set for seven minutes. The stopper was then removed, and excess resin was trimmed before the sample collection. A sample is then extruded for a set amount of time before being trimmed and weighed in grams on a scale. The weight was input into the melt indexer to generate an MFI value in g/10min. This test was done 260 times for all the DOE leg samples.

Validation Method

The collection and evaluation of DOE data should be able to justify validation settings. A validation can ensure a process is capable of consistently delivering quality parts with a set of the inputs that were studied. Minitab® is the statistical software used to generate all validations in this study. A single validation was selected to meet the dimensional Cpk targets of 1.33 or higher on the height and perimeter of the inner and outer barrel parts. 25 shots of each material were collected at the validation settings output by Minitab®. The validation metrology results were analyzed for their mean and standard deviation on the different IMMs and resins. An overall capability analysis is drawn as well.

Results

DOE Results: Response Optimizer

The response optimizer determined that the following setpoints for fill time, PFA time and PFA were the best for the inner barrel mold to achieve desired critical target dimensions on both IMMs.

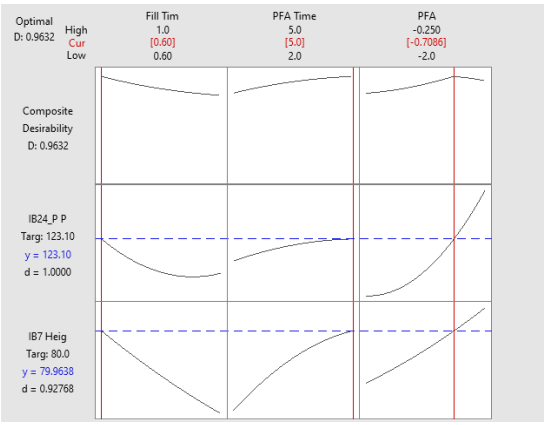

Figure 10: Response optimizer results for the inner barrel mold.

The following is the response optimizer results for the outer barrel mold to achieve desired critical target dimensions on both IMMs.

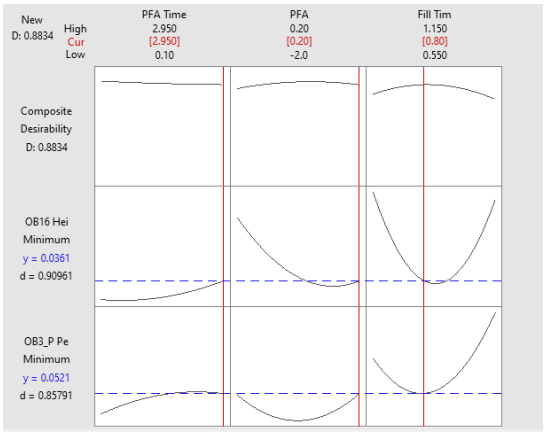

Figure 11: Response optimizer results for the outer barrel mold.

In the top left corner, the corresponding D values, also known as composite desirability, are 0.9632 and 0.8834 respectively. Desirability ranges from 0 to 1. The most optimal results for processing parts at their critical dimensions targets are when D equals 1.

MFI Results

The following are MFI mean and standard deviation results.

Table 2: MFI Results for all DOE legs.

	Virgin	KAL10	KAL20	KAL40	PIR
Mean MFI g/10min	21.2	10.9	16.6	44.5	15.0
Standard Deviation	3.6	7.1	3.7	5.8	4.5

Fifty-two MFI samples were collected of each material at different locations in their corresponding gaylords. **Figures 12 and 13** display interval plots for the inner barrels' and outer barrels' heights across all resins.

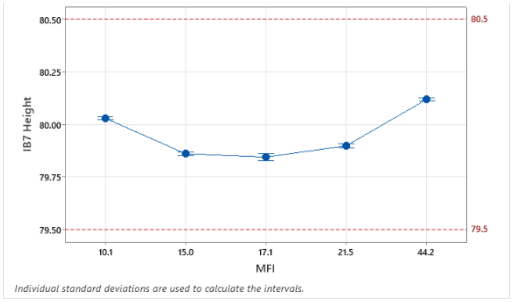

Figure 12: Inner barrel interval plot for height versus MFI.

For both figures, a direct relation between actual MFI and the dimensions are not seen.

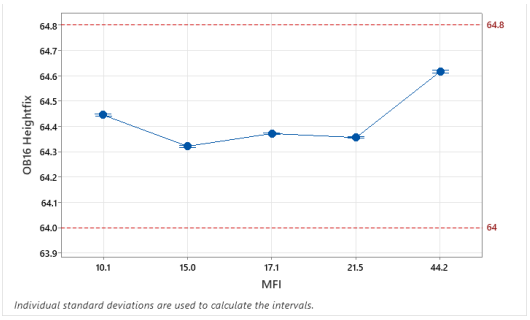

Figure 13: Outer barrel interval plot for height versus MFI.

The confidence intervals were expected to be tighter and more precise for each resin due to there being 52 samples each.

Validation Results: Process Capability Analysis by Material

The following validation process capability reports are for the overall height and perimeter of the inner barrel parts by material based on both IMMs.

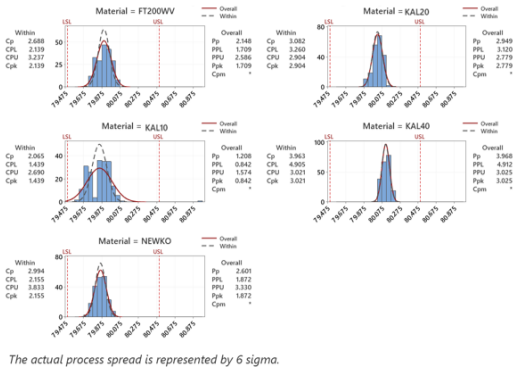

Figure 14: Process capability report for inner barrel part height by material.

This report shows the capability of each resin with the data from both IMMs. There is a bi-modal distribution in KAL10.

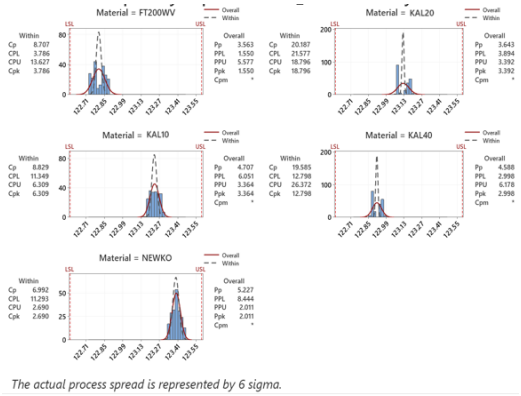

Figure 15: Process capability report for inner barrel part perimeter by material.

The report in **Figure 15** shows the capability of each resin with the data from both IMMs. There is a bi-modal distribution in FT200WV, KAL20, and KAL40.

The following validation capability reports are for the overall height and perimeter of the outer barrel parts by material based on both IMMs.

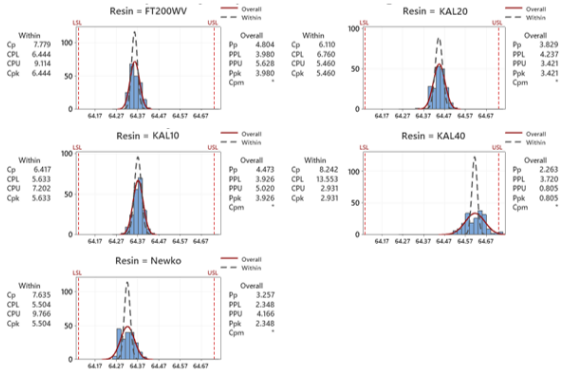

Figure 16: Process capability report for outer barrel part height by material.

The figure above shows the capability of each resin with the data from both IMMs. There is a bi-modal distribution in KAL40. All other materials have tight distributions within the spec limits.

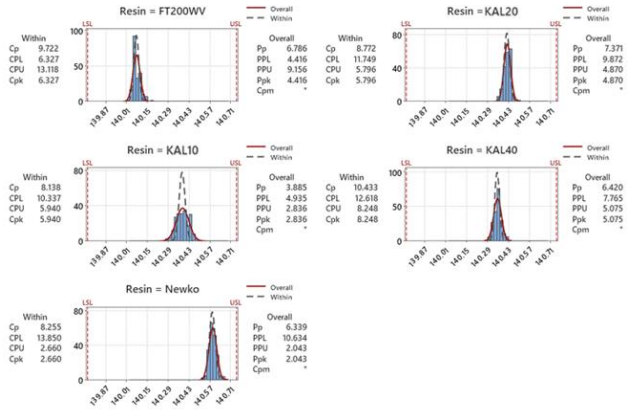

Figure 17: Process capability report for outer barrel part perimeter by material.

The report in **Figure 17** shows the capability of each resin with the data from both IMMs. All resins display tight distributions within spec.

Validation Results: Study of Curvature

The iMFLUX interface was studied for the main curves labeled in **Figure 1**. For instance, the following graphs show the inner barrel mold with KAL40 resin being used in the Haitian Zhafir and JSW respectively. The peak melt pressures are compared in Tables 3 and 4.

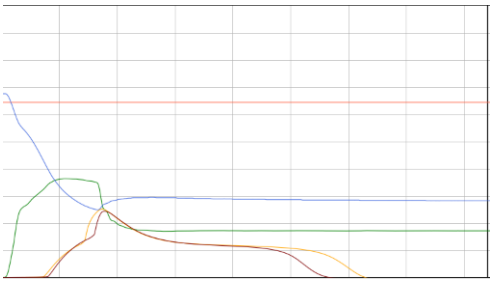

Figure 18: Inner barrel, KAL40, and JSW IMM process.

For this example, it can be seen that the JSW required more pressure to produce the same part process as the Haitian Zhafir.

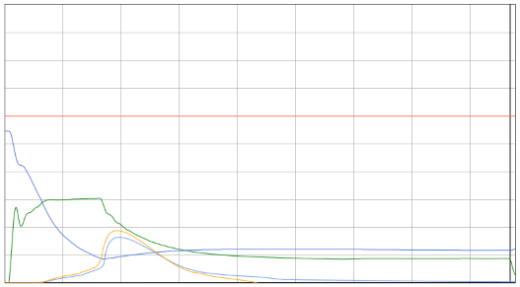

Figure 19: Inner barrel, KAL40, and Haitian Zhafir IMM Process.

From the four validations, the average peak plastic pressures of each material are provided below for the inner and outer barrel parts. The data has been organized in ascending MFI results, because lower MFI resins are expected to see higher pressures needed to fill out parts.

Table 3. Inner Barrel's AVA melt pressure results for resins on each IMM's validation.

	Actual MFI Results	JSW Pressures (MPa, psi)	Zhafir Pressures (MPa, psi)
KAL10	10.1	88, 12763	75, 10878
NEWKO	15	65, 9428	64, 9282
KAL20	17.1	62, 8920	60, 8702
VIRGIN	21.5	60, 8746	59, 8557
KAL40	44.2	53, 7687	52, 7542

The following is a graphical representation of the inner barrel data presented above.

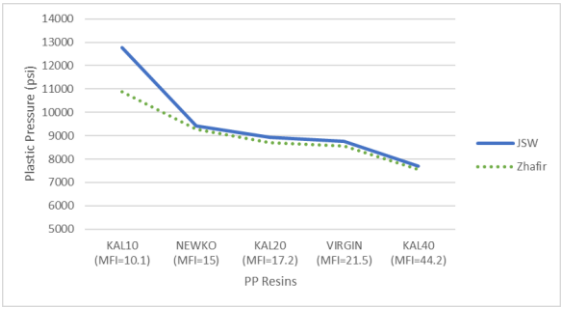

Figure 20: Inner barrel validation's average peak pressures of each material to make the same part process.

It is important to note that there were no operator adjustments between resins due to AVA independently altering the melt pressure to make consistent parts.

Table 4. Outer Barrel's AVA melt pressure results for resins on each IMM's validation.

	Actual MFI Results	JSW Pressures (MPa, psi)	Zhafir Pressures (MPa, psi)
KAL10	10.1	108, 15664	130, 18782
NEWKO	15	90, 13053	93, 13489
KAL20	17.1	87, 12546	92, 13344
VIRGIN	21.5	85, 12256	90, 13053
KAL40	44.2	76, 11023	88, 12691

The following is a graphical representation of the outer barrel data presented above.

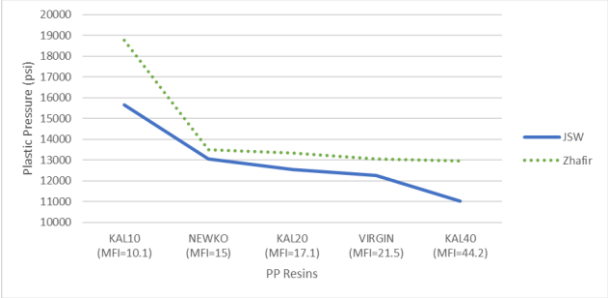

Figure 21: Outer barrel validation's average peak pressures of each material to make the same part process.

Discussions

iMFLUX's continuous factors, or derived inputs, were fill time, PFA, and PFA time. The derived inputs expand the capability of artificial intelligence for developing learning models. There was confidence in the response optimizer outputs for both inner and outer barrel molds' DOE results. Being that the desirability values exceeded 0.85, it was presumed the parts could achieve spec requirements. This is affirmed by the validation's dimensional results. Aside from the bi-modal trends seen, the data between the IMMs were indistinguishable.

The inner and outer barrels' height and perimeter Cpks on all materials exceeded the 6-sigma standard of 1.33. This means that there would be no defects with these validated parameters. An extensive process development was not necessary like it has been traditionally. There was a slight mean shift between resins that iMFLUX plans to address with 2nd-level intelligence in future work.

The key takeaway is that, despite all the variation this technology sees from the resins and IMMs, iMFLUX is able to automatically regenerate the part process to match validated parts on different IMM deemed capable. Conventionally, this validation processed is manual and iterative.

Conclusions

In the molding industry where tools move so readily from machine to machine and the demand to process regrind continues to escalate, the ability to quickly establish a process that produces good-quality parts is vital from a material expense, sustainability, and labor efficiency standpoint. iMFLUX's Universal Process allows for the IMM and resin type to be independent of the mold qualification process when using the following three independent factors: fill time, PFA time, and PFA. This case study has demonstrated that iMFLUX's part process capability is robust when using these continuous factors.

The economics of adopting this approach could potentially not only save tens to hundreds of thousands of dollars for each mold moved, but the speed-to-market advantages and operations flexibility would be simply invaluable. iMFLUX-validated molds can transfer in and out of facilities without redoing a validation qualification. This technology can control the variation seen from IMMs and resins and regenerate a part process that ensures the integrity of validated parts.

References

1. Lusardi, G., et al. (2017) "Part Process" Transferability Using a Machine Independent Variable (MIV) Methodology for Multiple Machines
2. Scientific Molding Part 1: Portability Retrieved November 21, 2022, from https://www.plasticstoday.com/print/19124
3. Scientific Molding Part 1: Filling Retrieved November 21, 2022, from https://www.plasticstoday.com/print/7859
4. "Part Process" Development and Validation for Multiple Machines. (n.d.). Medical Product Outsourcing. Retrieved November 21, 2022, from https://www.mpo-mag.com/issues/2017-07-01/view_features/part-process-development-and-validation-for-multiple-machines/
5. Curran, P. (2009, October 22). *Melt Pressure Sensor from Kistler*. Design World. https://www.designworldonline.com/melt-pressure-sensor-from-kistler/
6. Absolute Haitian to run Zeres electric injection molding machine at PLAST-EX. (2019, May 22). Plasticstoday.com. https://www.plasticstoday.com/injection-molding/absolute-haitian-run-zeres-electric-injection-molding-machine-plast-ex
7. News – Contur 2000. (n.d.). Retrieved November 21, 2022, from https://contur2000.pl/en/news/
8. Dynisco-LMI5500Series.(n.d.).Www.dynisco.com. Retrieved November 21, 2022, from https://www.dynisco.com/polymer-evaluation/laboratory-quality-control-testing/melt-flow-indexers-plastometers/LMI5500
9. One Way Solutions | Page 3 of 10 | Plastic Pallets Sales & Expertise. (n.d.). One Way Solutions. Retrieved November 21, 2022, from https://oneway-solutions.com/blog/page/3