PRECISION PROCESS CONTROL OF INJECTION MOLDING

David Kazmer
Associate Professor
Department of Mechanical and Industrial Engineering
University of Massachusetts Lowell

1 INTRODUCTION

The technical requirements of precision injection molded components demand a heightened level of process performance, and with corresponding process monitoring and control technologies. To obtain the desired **critical to quality attributes** (**CTQ**s) of the molded products, the injection molding process must be consciously designed such that the **key process variables** (**KPV**s) are observable and controllable. Failure to understand and control the linkage between KPVs and CTQs may result in undesirable levels of defects during production, unattainable levels of demanded precision, and technical and/or economic infeasibility of the molding application.

A fundamental difficulty in control of injection molding is that few of the final molded part properties can be ascertained within the molding cycle. Instrumentation does not yet exist, and may never exist, to yield information about aesthetics, structural integrity, and other part properties prior to opening of the mold and inspection of the part. For instance, a pressure sensor may be placed at the end of flow to detect the arrival of the melt and pressure decay during cooling. Yet such use of the sensor may or may not be able to consistently predict the formation of flash during filling or sufficient part packing so that the molded component(s) meet the desired level of precision. As such, precision injection molded parts generally require integrated product and process design, in which the product development process provides not only the design of the precision component (geometry, material, specifications), but also the validated design of the precision molding process (process parameters, sensors, allowances).

This chapter is divided into three sections. First, fundamental principles of process control and performance measures for precision injection molding are reviewed. Second, current process control approaches are discussed with deference to process control of precision injection molding. Third, an application development methodology is presented for precision process control as exemplified with two industry applications.

2 FUNDAMENTALS

2.1 Injection Molding Fundamentals

Overview: Injection molding consists of several stages: plastication, injection, packing, cooling, and ejection. It is more complex than extrusion or thermoforming, but also more capable of producing very complex components to tight specifications. For instance, injection molding embodies the extrusion process for generation of polymer melt yet has faster time dynamics than thermoforming over a greater temperature and pressure range. In injection molding and its variants (coinjection, injection compression, gas assist molding, etc.), thermoplastic pellets are fed into a rotating screw and melted. With a homogeneous melt collected in front of the screw, the screw is moved axially at a controlled, time-dependent velocity to drive the melt into an evacuated cavity. Once the melt is solidified and the molded component is sufficiently rigid to be removed, the mold is opened and the part is ejected while the next cycle's thermoplastic melt is plasticized by the screw. Cycle times range from less than four seconds for compact discs to more than three minutes for automotive instrument panels.

Control of injection molding is significantly challenged by the nonlinear behavior of the polymeric materials, dynamic and coupled process physics, and convoluted interactions between the mold geometry and final product quality attributes. A system's view of a conventional injection molding process is presented in Figure 1. The machine parameters are indicated on the left side of the figure, and some common measures of molded part quality are listed on the right. In this figure, the process is decomposed into five distinct but coupled stages. The output of each stage not only directly determines the initial conditions of the next stage, but also influences some of the final qualities of the molded part.

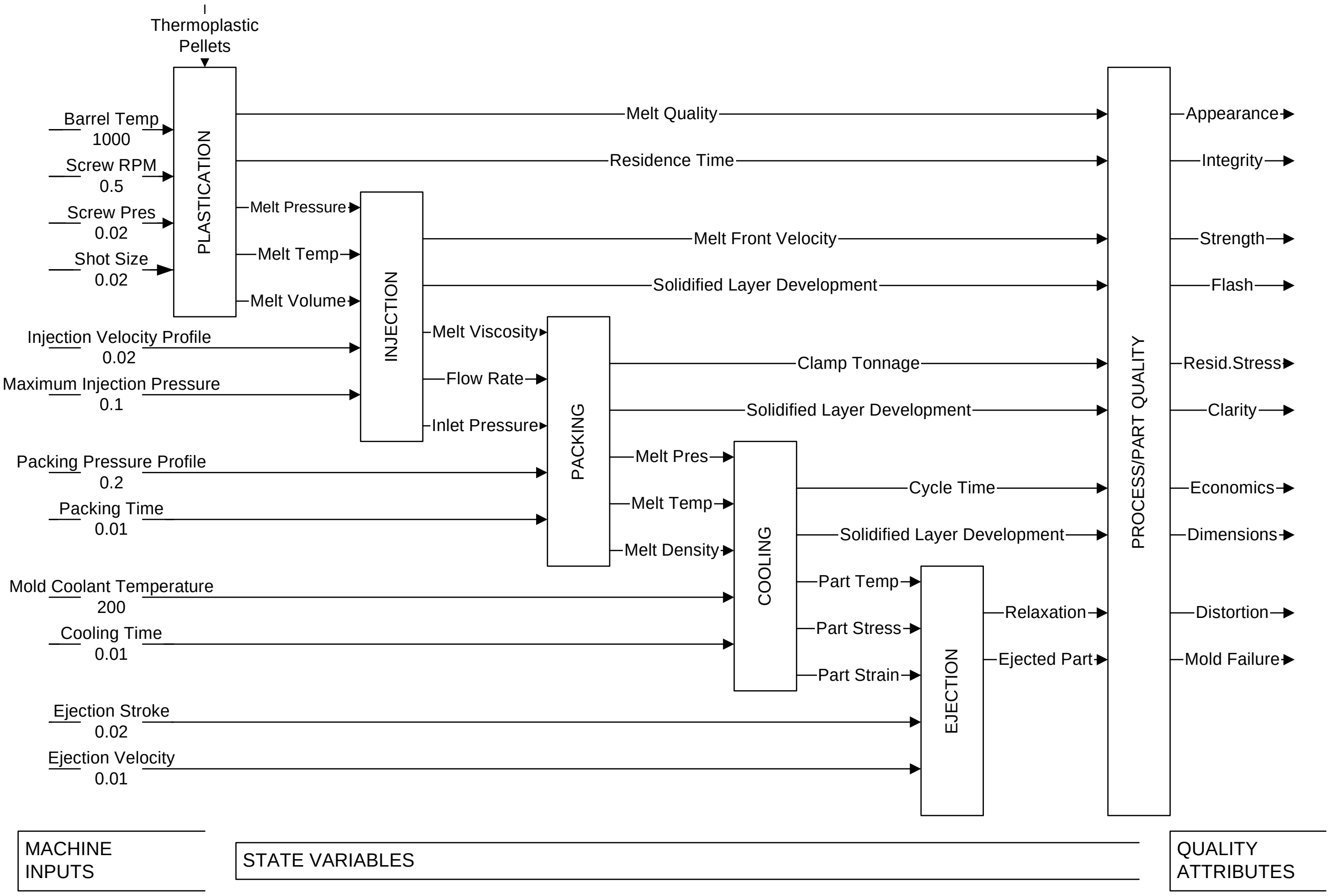


Figure 1: A system's view of the injection molding process

Every stage of the injection molding process is complex, and warrants detailed discussion regarding its behavior. Plastication of the polymer melt is accomplished through simultaneous shearing by rotation of an internal screw and heating by an externally heated barrel. As shown in Figure 1, the plastication inputs include barrel temperature, screw rotation rate, screw plastication pressure, and shot size. This list is simplified in that most inputs are vectors rather than scalar quantities. For instance, barrel temperature is specified at several locations, since multiple heater bands along the length of the injection unit influence the temperature of the plasticized melt. Each local segment of the barrel is typically equipped with a type J or K thermocouple embedded in the barrel steel, and the power to each heater band is individually controlled through a closed-loop programmable logic controller utilizing PID control [1]. The resulting melt quality and residence time can directly affect the quality of the molded part as unplasticized pellets and/or degraded material can reduce the structural integrity and aesthetics of the molded component.

The purpose of the injection stage is to completely fill the mold cavity with the polymer melt. This goal is achieved by driving forward the screw used for plastication at velocities of the order of 100 cm/sec according to a selected time-velocity profile. The velocity profile is selected such that the melt travels at relatively uniform velocity while converging and diverging in the mold cavity. During polymer injection, contact of the hot polymer melt with the cold mold wall results in the immediate formation of a frozen skin. Thermal conduction to the mold is then balanced against thermal convection of the melt. This thermal equilibrium stabilizes the growth of the frozen layer, which reduces the flow conductance of the melt. If too low a velocity is selected, the melt front will prematurely solidify. If too high a velocity is selected, the resin may degrade or cause excessive mold deflection and flash. The relationship between the screw velocity profile and melt front velocity is convoluted by the compressibility and acceleration dynamics of the melt. The specification of time-velocity profile is so difficult, in fact, that most molders utilize the same profile (slow at start, fast in the middle, and slow at the end) for all molding applications. The distributed nature of the melt flow changing with both time and position also precludes simultaneous control of the melt flow at different positions. Considering that the injection stage provides the initial conditions for the packing stage, the absence of complete controllability of the melt flow does result in uncontrolled (open loop) melt viscosity, solidified layer distribution, and temperature/pressure contours (see Figure 2).

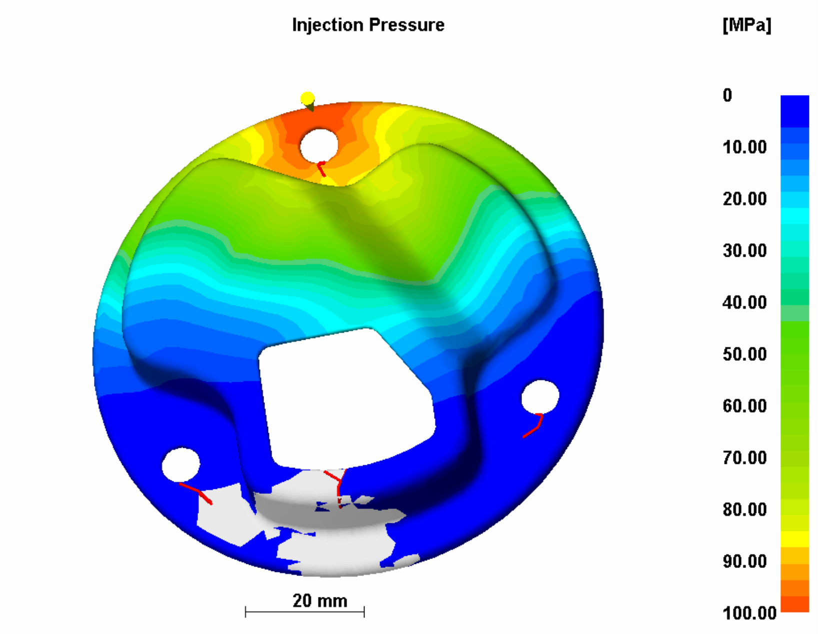


Figure 2: Pressure distribution of a typical molding at the end of the injection stage

Due to volumetric shrinkage during cooling of the melt, additional material must be forced into the mold cavity during the packing stage to obtain satisfactory parts. For pack pressure control, the hydraulic pressure behind the screw is adjusted through a high-speed servovalve to decrease or increase the melt pressure at the inlet to the mold. The pressure feedback for control may be provided by a pressure transducer mounted at the mold inlet, or it may be calculated by multiplying the hydraulic pressure by a screw intensification ratio. Pressure is maintained and additional material is forced into the mold cavity until the part has solidified. However, part solidification is an internal state variable to the molding process that cannot be measured directly. To determine the correct packing time, multiple molding trials with various packing times must be performed and the molded parts weighed. It should be noted that part weight is also dependent on melt temperature and pressure, so a change in machine inputs may result in inaccurate packing times.

After packing, the polymer melt is solidified but it is too soft for part ejection. As such, coolant is recirculated at controlled temperature through the mold to remove heat. The cooling stage dominates the molding cycle time, requiring approximately half of the cycle to complete. Production economics dictate shorter cycle times, but shorter cooling times may lead to excessive part shrinkage and warpage.

From this prior discussion, it should be understood that injection molding possesses the characteristics of both continuous and discrete processes as well as distributed and dynamic processes. Moreover, there are frequently conflicts between multiple critical to quality attributes. In precision injection molding, as in many constrained manufacturing processes, the tendency may be to sacrifice production efficiency for the sake of quality. However, repeated use of such an approach may not guarantee heightened levels of quality but will likely ensure a lack of competitiveness. As such, knowledge of the fundamentals coupled with a rational process control approach is needed.

2.2 Process Control Fundamentals

Open & Closed Loop Control: The injection molding process consists of multiple coupled stages, in which the dynamics of each stage are determined through control of different but related machine elements such as motors, heaters, servovalves, etc. These machine elements are typically controlled via a closed feedback loop as shown in Figure 3, in which the control signal is determined by real time comparison of the desired machine set-points with their corresponding observed state, such that the difference (or error) is used to correct the process.

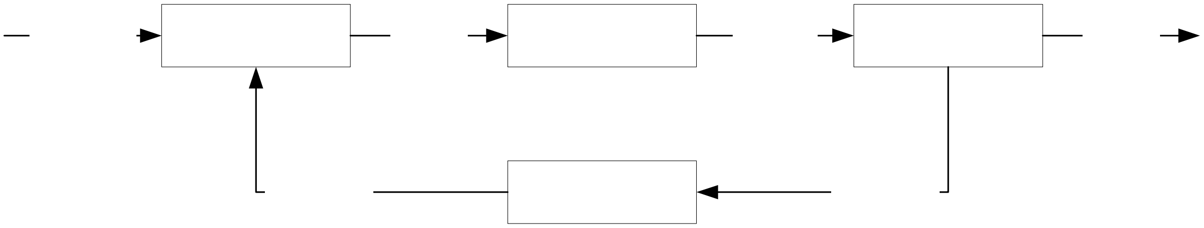


Figure 3: Block Diagram of a closed control loop

The performance of a closed loop controlled machine element is dependent upon a number of system properties, such as the inertia or dynamic behavior of the machine element, availability and amount of control energy applied to the machine element, the time response and resolution of the sensors providing feedback, and the validity of the control laws which convert perceived errors into corrective actions. It should be realized that sustained advances in hardware devices and software algorithms have led to substantial gains in process control performance, such that precision process control is no longer limited by the response time or algorithmic complexity of the controller. In fact, while there remains significant variation between control system suppliers, a control system response time (from input of feedback signal to output of control signal) of 2 mSec is quite common, with sub 10 μSec response times widely available.

There are two fundamental concepts that should be stressed regarding closed loop control. First, it is important to realize that process control of precision injection molding is not so dependent upon the response time of the controller, but the response time of the system. As a simple example, consider the task of increasing the temperature of a 100 kg steel barrel (heat capacity of 473 J/kgC) by 10 C, which theoretically requires 473,000 J. If four 1000 Watt heaters are utilized, then the minimum theoretical response time is about 120 seconds, or two minutes. Realistically, however, the response time will be three to ten times longer than the theoretical minimum, depending upon whether the system is over or under damped, and how much error is tolerable. As such, a reduction in the control system response time is likely less important than an improvement in the control law, controller tuning, heater design, barrel design with respect to improving the performance of the precision molding process.

Secondly, it is important to realize that closed loop control of machine elements does not necessarily imply precision process control. In other words, there are many key process variables (KPVs) that are controlled in an open loop fashion, even though the machine elements are controlled closed loop, such as: 1) polymer melt temperature vs. barrel temperature, 2) mold temperature vs. mold coolant temperature, 3) cavity pressure vs. injection/pack pressure, and many others. As such, it is important to understand fundamentals regarding the observability and controllability of the precision injection molding process.

Observability & Controllability: As defined by control theory, a system is **observable** if its modes can be deduced by monitoring sensed outputs [2]. As just discussed, injection molding machines can only control machine elements with feedback from sensed process data. A fundamental difficulty in polymer processing is that few of the final part properties can be ascertained within the molding cycle. Instrumentation does not yet exist, and may never exist, to yield information about aesthetics, shrinkage, or structural integrity prior to removal of a plastic part from the mold. Therefore, **estimators** must be used to predict the part quality based on the sensed state of the machine inputs. Unfortunately, the prediction relations (between KPVs and CTQs available *a priori* from simulation or expert systems) are insufficient to reliably and accurately predict the part quality in-cycle. This limitation severely constrains the performance of general control strategies for precision injection molding. To develop a practical approach, an application development methodology will later be described for determining valid, observable estimators for use with process monitoring and control.

Franklin (1994) defines a system to be **controllable** if every output mode is connected to a control input. This definition is not met for most CTQs, and represents another fundamental difficulty in precision injection molding. Compare dimensional control in injection molding to that of machining. In machining, every part dimension is controlled by the specification of the cutting path and cutting tool geometry. Injection molding, however, is fundamentally different. The molded part dimensions are mostly dependent on the mold dimensions yet will vary significantly with the material properties, process conditions, and associated process dynamics. As such, the degrees of freedom do not exist to individually control multiple part dimensions. No process control technology currently enables direct control of the output part properties, nor can they ever if the CTQs are not observable. To develop a practical approach, an application development methodology will later be described for identifying the need for advanced process technologies to increase the system controllability.

2.3 Robust Design Fundamentals

Sources of Variation: Process variability in injection molding further complicates process control. The sources of variability are attributed to the thermoplastic resin, the injection molding machine, and environmental factors. Product inconsistencies among a batch of molded parts are most frequently blamed on lot-to-lot variations in material properties. Small changes in viscosity, density, or composition may occur when regrind is mixed with virgin material, a material is used after it has been stored over an extended period of time, or a switch is made between different batches of the same material grade [3]. Small changes in material properties can lead to inconsistencies in part weight, part dimensions, aesthetic, strength, etc.

The second source of variability is process machinery. Molding machines of different injection cylinder and clamp design will have very different machine dynamics, and provide different levels of molded part quality for the same process set points. Even identical machines from the same manufacturer can induce significant quality variation as a result of differences in their controller tuning and varying amounts of wear in the melt and hydraulic delivery systems. Finally, parts molded from the same press may vary due to internal controller variation relating to the shot size, injection velocity, switchover point, pack pressure, etc. Hunkar [4] has characterized and described a machine evaluation methodology that quantifies the process consistency of any molding machine, which categorizes machines into capability classes from 1 to 9 with pre-defined variances as shown in Table 1. In general, it is anticipated that a higher class machine with reduced ranges will produce more consistent, higher precision molded parts.

Table 1: Maximum allowable range by machine input and machine class

Control Quality	**Low (Class 9)**	**High (Class 1)**
Melt Temperature (C)	5	1
Mold Temperature (C)	8	2
Injection Time (sec)	0.17	0.04
Pack Pressure (Mpa)	0.5	0.1
Pack Time (sec)	0.02	0.009
Cooling Time (sec)	0.86	0.20

The third source of variability is human and environmental interaction with the process. For instance, process engineers have different definitions of 'optimal' [5] and can induce product inconsistency through the modification of standard process set points such as injection velocity, pack pressure, back pressure, cooling time, and ejection set-up. Press operators directly determine cycle time and part handling, and may influence some process settings. The physical environment will also introduce variation. For instance, outdoor temperature may affect the effectiveness of evaporative coolers that determine the temperature of the plant water. Indoor temperature can likewise have significant effect on the mold wall temperature as well as the post-molding behavior of the molded parts. Humidity can effect the dryness of the polymeric material entering the barrel, thus, introducing further quality inconsistencies.

Six Sigma Guidelines: The moniker "Six Sigma" increasingly refers to corporate initiatives with multiple levels of trainers and trainees, with content frequently including: Quality Function Deployment, Failure Modes & Effects Analysis, Statistical Distributions & Process Capability, Design of Experiments & Response Surface Methods, Statistical Process Control, Optimization & Robust Design. However, the most fundamental tenet of Six Sigma, from which the name is derived, is that six standard deviations of performance should be maintained between the performance mean and the closest specification limit as shown in Figure 4. In this chapter, *LSL* and *USL* correspond to the lower and upper specification limit on a CTQ, while μ and σ represent its observed mean and standard deviation. Statistically, such a condition would correspond to three defects per million opportunities (DPMO).

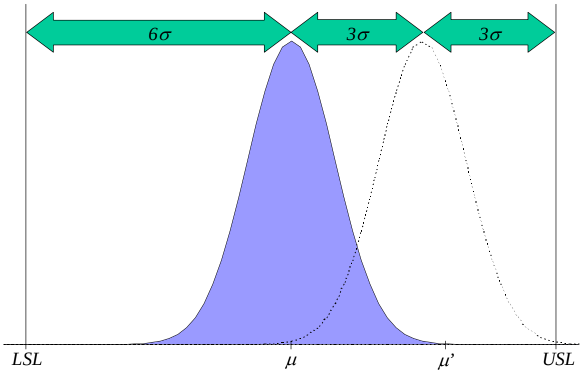


Figure 4: Six Sigma Manufacturing

In the development of Six Sigma, there are two somewhat different motivations for achieving Six Sigma [6]. First, it has been argued that Six Sigma is necessary in large systems containing many opportunities for defects. Since the system may fail with any given component, reliability theory states that the DPMO must be extremely low to achieve reasonable yields in production, typically greater than 95%. An alternate motivation in Six Sigma pertains to the product development process and ensuring long term stability in the product quality. Specifically, Six Sigma can permit a long term shift of three sigma in the mean or specifications while ensuring three sigma for short term, random variation. As such, a 99.87% yield should be achieved 99.87% of the time.

Whichever the motivation for Six Sigma, a process capability index, *Cp*,

$$Cp = \frac{USL - LSL}{6\sigma} \tag{1}$$

or the asymmetric process capability index, *Cpk*,

$$Cpk = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right) \tag{2}$$

is frequently utilized as a measure of robustness [7-9]. The *Cpk* index has two advantageous properties: 1) application to one-sided specifications, and 2) denotes a loss in quality due to shifts of the mean off the target center. In either case, however, a process capability equal to one generally implies product performance at the target level with three standard deviations to the closest specification limit.

The process capability should be at least two to meet Six Sigma guidelines. Many cynics and opponents of Six Sigma programs suggest that manufacturers frequently broaden the specification range (the numerator in equations 1 and 2 to artificially improve the process capability. Such criticisms are valid if the specification range does not meet the customer requirements and results in a lessening of the product value. However, precision injection molding, by its definition, requires a narrow specification range and precise process control. As such, the prediction and characterization of variance in CTQs is vital to technical and economic feasibility.

<u>*Prediction of Variance*</u>: Variation in the CTQs of the molded components stems completely from uncontrolled variations in the process and its inputs. If the process was deterministic and there was no input variation, then all molded components would be exactly the same. In reality, the variance of a CTQ, y_1, will tend to increase with variation in KPVs, x_j, and the strength of the relation between KPVs and the CTQ. As an example, Figure 5 shows the dependence of a molded product attribute, y_1, on two process variables, x_1 and x_2. A normal probability density function is applied to each of the two process variables. While the relation between x_1 and y_1 is complex, variation in x_1 will lead to a lesser variation in y_1. Examining the relationship between x_2 and y_1, it is observed that the same variation in x_2 will lead to a broad and undesirable distribution in y_1.

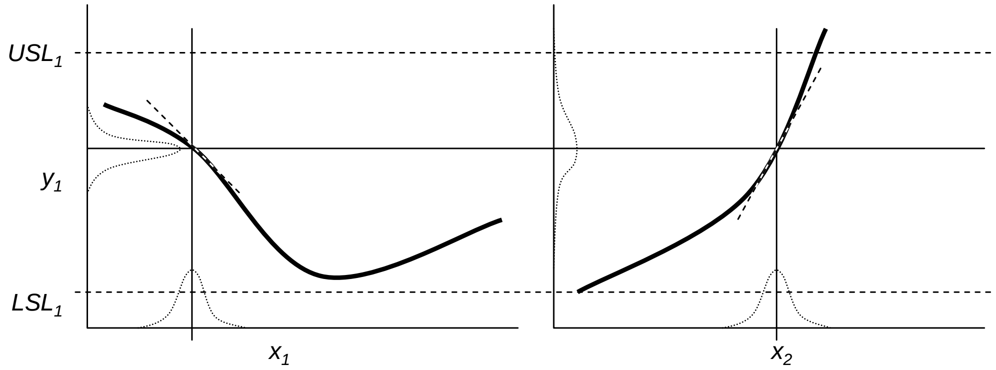


Figure 5: Effect of Process Behavior on Propagation of Variance

This propagation of variance is well understood, and can be exactly modeled through the moment matching method for an output, *y*, as a function of linear, independent variables, x_j [10]:

$$\sigma_y = \sqrt{\sum_{j=1}^{m} \frac{dy}{dx_j} \sigma_{x_j}^2} \qquad (3)$$

This relationship is useful in estimating the variation and related process capability in CTQs from Eq. (2). Moreover, reverse application of the moment matching method can lead to good estimates for the allowable control limits on KPVs, from which changes in process subsystems often become apparent.

It is also desirable to estimate the process capability index for multiple CTQs, and also estimate the joint probability that all CTQs are within specification. It has been proposed [11, 12] that the process capability of a system with multiple quality attributes may be evaluated via the joint probability of likely acceptance as:

$$P_{system} = \prod_{i=1}^{n} P_i \qquad (4)$$

where

$$P_i = P(LSL_i \le y_i \le USL_i) = 1 - 2\Phi(-3 \cdot Cp_i) \qquad (5)$$
$$\Phi \equiv \text{Normal Cumulative Density Function}$$

Combining these two equations gives:

$$\overline{\overline{Cp}} = \frac{-1}{3}\Phi^{-1}\left(\frac{1}{2} - \frac{1}{2}\prod_{i=1}^{n} P_i\right) \qquad (6)$$
$$\Phi^{-1} \equiv \text{Inverse normal cumulative density function}$$
$$n \equiv \text{Number of quality attributes}$$

Thus, the aggregate process capability index considers the likelihood of each quality attribute being acceptable. It has been argued that this measure generally provides a reasonable estimate of system robustness, and does possess several beneficial properties useful in system design including [12]: 1) models multiple design objectives; 2) convex behavior allows for global optimization; 3) allows for direct inclusion of different kinds of specifications; 4) consistent with Taguchi's concept of tolerance design since it promotes central tendencies with small deviations in product properties, rather than a goal post mentality [10]; and, 5) consistent with many design axioms to minimize information content since the production yield will tend to decline geometrically as the number of requirements rise [13, 14].

Meaning of the Terms "Robust" and "Optimal": The term **robust** is generally defined an insensitivity of product performance (CTQs) to uncontrolled variation (KPVs). As such, robust product and process designs should possess low variance compared to the specification limits, which will naturally lead to high process capability indices and processing yields of acceptable molded product. In multi-input processes, it is desirable to select the KPVs such that the CTQs are centered between the specification limits and possess low variation. For the example of Figure 5, this may be achieved by selecting a lower x_1 and x_2, with the resulting y_1 shown in Figure 6.

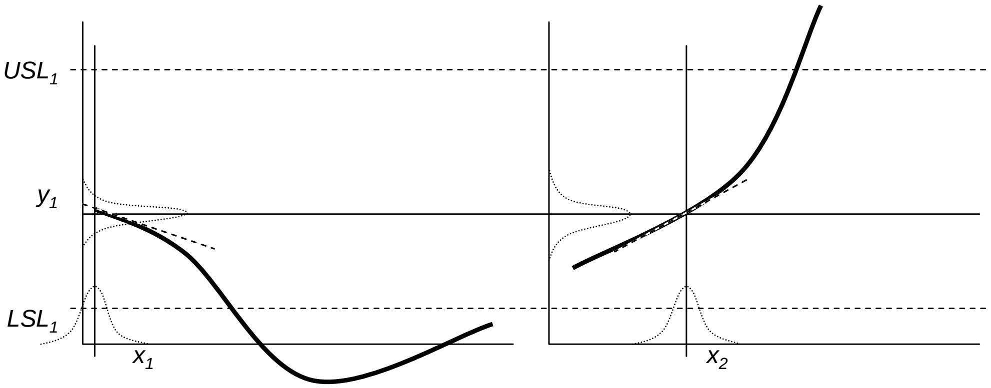


Figure 6: Robust Process Selection for Minimal Variance

In precision injection molding, the term **optimal** implies more than robustness. First, the process should produce a maximal percentage of acceptable molded products. Second, the process should operate efficiently, with minimal cycle time, energy consumption, and material waste. While the first condition strongly encourages robustness, the second criterion provides a practical limit on the desirability of that robustness. Specifically, it is desirable to minimize the total system cost, which is a function of 1) the marginal processing cost of the materials, labor, and machine; 2) the processing yield of acceptable parts, and 3) the marginal cost of molding defective product:

$$C_{system} = \frac{C_{product}}{P_{system}} + \left(1 - P_{system}\right) \cdot C_{defect} \tag{7}$$

These concepts have been well investigated in the management sciences [15, 16], with a cost of quality model generally accepted. Specifically, this approach suggests that balance is needed in developing robust processes that result in low defect costs yet do not incur excessive compliance costs in fulfilling the product specifications. Figure 7 illustrates these concepts. In general, defect costs will approach zero as quality levels approach 100%. However, such increases in quality levels frequently require increased investment, processing time, and inspection such that the compliance costs may increase dramatically at very high quality levels. As such, there may be a broad processing region that it economical yet provides adequately high levels of quality. The location and breadth of this region, together with the technology required to deliver it, is application dependent. Precision injection molding, however, certainly requires precision in process monitoring and control to avoid producing a large quantity of defective moldings, many of which may unintentionally enter end-use and incur a high penalty cost in demanding technical applications.

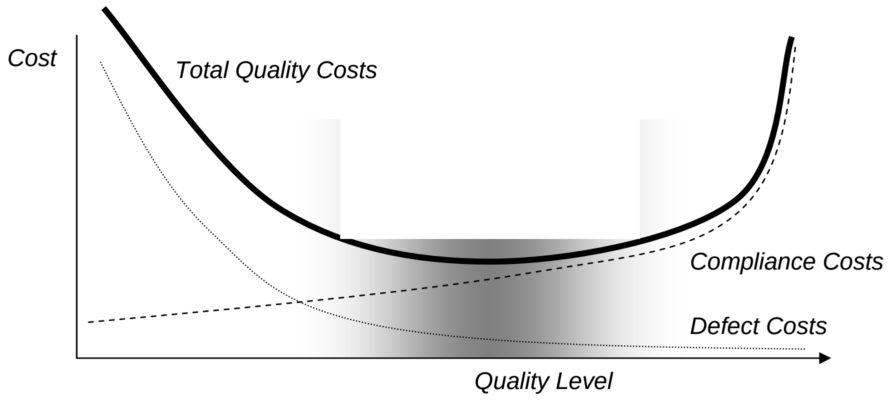


Figure 7: Quality Cost Model Identifying Desirable Level of Robustness

With this review of underlying principles, this chapter will next turn to the current state of process control technologies that may be used for precision injection molding. Afterwards, a methodology for their specific application is subsequently presented.

3 PROCESS CONTROL TECHNOLOGIES

An overview of the injection molding machine control architecture is shown in Figure 8. At the innermost level, only the machine elements are regulated. This level of control will ensure proper execution of the programmed machine inputs as indicated by the inputs in Figure 1. At the second level, state variables such as melt temperature and melt pressure are controlled to track pre-specified profiles. This will provide more precise control of the state of the melt. At the outermost level, the machine inputs are adjusted so as to improve the quality of the part through better set points given feedback of part quality.

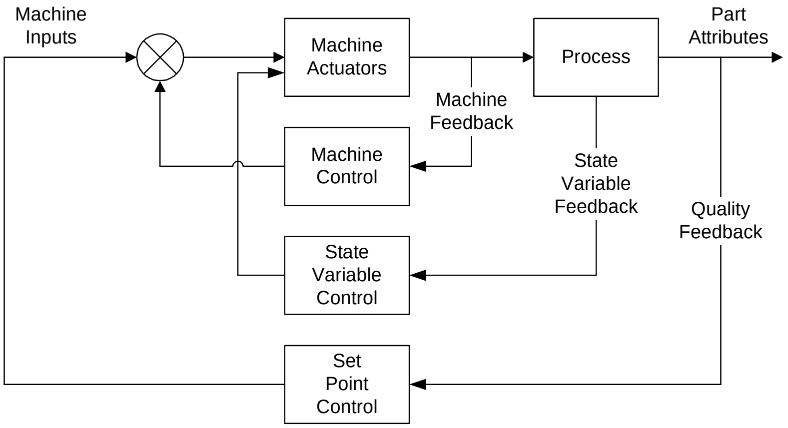


Figure 8: System diagram of injection molding control

The logic behind the control strategy in Figure 8 can be explained by an example. Consider the specification of packing pressure profile as a machine input for control of the part diameter shown in Figure 2. In this case, the machine actuator is the hydraulic servovalve regulating hydraulic flow to the injection cylinder, and **machine control** will ensure a specified packing pressure at the melt inlet. However, the packing pressure will be non-uniformly distributed in the mold, as implied in Figure 2. This motivates **state variable control** to regulate the cavity pressure more precisely based on feedback of measured pressure inside the mold. In this case, the dynamic control of the hydraulic servo-valve will be augmented to provide the additional level of precision. While this additional level of control ensures realization of the specified cavity pressure, it still may not lead to a satisfactory molded part because of a poorly-specified cavity pressure. An outer **set point control** is incorporated to adjust the specified cavity pressure. Each of these control levels will be discussed next.

3.1 Machine Control

Prior to the 1970s, the majority of molding machines utilized open-loop control for most subsystems. For example, heater wattage was set to achieve a pre-specified barrel temperature, or the hydraulic pressure relief valve was set so as to provide a specified screw velocity and pressure throughout the filling and packing stages. Since the advent of programmable logic control, the majority of machine input variables have become individually controlled via parallel single-input, single-output PID algorithms. Among the machine inputs listed in Figure 1, the melt temperature, the packing pressure profile, and the injection velocity profile have been considered the most important to precisely control.

The first modern computer-controlled injection molding machine was described by Carl Ma in 1974 while employed at Cincinnati Milacron [17]. Ma's work led to the development of modern control systems for injection molding machines and enabled current closed-loop control systems for ram velocity and injection pressure [18]. Since then, most machine manufacturers have adopted the use of standard programmable logic controllers in which multiple analog and digital input and output modules are used to acquire or transmit necessary feedback and control signals. The control signals may be generated through the CPU module in the PLC or alternatively through the use of axis controllers for faster response. Increasingly, industrial PCs are being used as an interface between the process controller and the operator, such that the PC provides enhanced ease of use, process diagnostics and maintenance, network connectivity, upgradeability, and access to 3rd party software [19].

In theory, machine control algorithms are simple enough to enable the molder to properly tune them on the production floor. In practice, molders find controller tuning difficult, so controller parameters are rarely changed from their factory defaults. Poor or infrequent controller tuning results in reductions in process capability since one set of controller parameters will not be appropriate for all molding applications. For example, an increase in polymer viscosity or decrease in melt temperature will increase the resistance to flow and would increase the load on the screw. As such, changes to the material properties, process settings, or mold flow conductance would require a different set of controller parameters for best machine response.

Worse, poor controller tuning may lead to deviations from the specified machine set-points such that large deviations are misinterpreted as attributable to errors in machine setup rather than poor controller performance. For instance, the start of the injection stage is extremely transient, with the screw starting at rest with low flow resistance. As such, the ability of the machine to follow a specified velocity profile is dependent upon the shape of the velocity profile, the mold and material properties, and the specific control law and tuning. Frequently, the velocity profile exhibits a transient overshoot in velocity that can be associated with excessive integral wind-up or other control dynamic, followed by a dramatic reduction in velocity associated with corrective control actions or coincidental changes in the velocity profile. A molder viewing the trace data, however, may interpret the behavior to a frozen nozzle or cold gates, and unnecessarily modify other machine set-points trying to smooth the process behavior.

In an effort to improve the machine control performance, more sophisticated control methods than PID have been investigated. For example, Pandelidis and Agrawal demonstrated the application of linear quadratic control to tracking ram velocity [20]. Tsai and Lu developed a multivariable self-tuning predictive controller for improving set-point tracking performance, disturbance rejection, and robustness of a temperature control system for an extruder barrel [21]. Machine manufacturers have been responsive in improving their machine controllers, and have incorporated such adaptive control techniques [22, 23] and auto-tuning algorithms in PID controllers [24, 25]. As such, machine control has and will continue to improve and will not frequently be a limiting constraint in precision injection molding.

3.2 State Variable Control

While machine control is important, it is the polymer state (pressure, temperature, and morphology) which directly determines the molded part quality [26, 27]. As such, recent technology developments have rightly focused on closing the loop between the machine parameters and the polymer state. If achieved, these advanced control strategies would provide increased molded part quality and consistency.

The dichotomy between the machine inputs and state variables is illustrated in Figure 1, where every input variable that utilizes closed-loop control has been identified with a numeric subscript that quantifies the approximate time response of the controlled parameter in seconds. Also indicated in this figure is the role of state variables as intermediate variables between the machine inputs and the final part quality attributes. A fundamental difficulty in precision injection molding control is the lack of models to define the relationships from inputs to state variables and from state variables to outputs. For example, melt temperature is known to be affected by barrel temperature, screw rotational speed, and thermal properties of the melt. However, only 20% to 50% of the energy required for melting originates from the barrel heaters, and the exact relation to melt temperature is a function of polymer properties and screw/barrel design. Similarly, melt temperature is widely accepted to affect cycle time and part dimensions, but the precise one-to-many relationships are generally not available prior to molding. Although the void for mechanistic relationships is often filled with empirical or heuristic models in state variable control, empirical modeling has not been adopted by industry due to the cost of experimentation.

The two dominant variables defining the state of the melt are temperature and pressure. Typical strategies used for melt temperature control are discussed in [27, 28]. The main effort in these studies has been to identify the control method that can best achieve a pre-specified melt temperature. In addition to the lack of a systematic method of specifying the melt temperature, melt temperature control suffers from the absence of reliable sensors for melt temperature measurement. Intrusive thermocouple probes placed in the viscous melt stream fail quickly [29], and infrared pyrometers do not calibrate automatically with changes in resin color, filler content, or emissivity [30]. A review of temperature sensors available for injection molding is provided in [31].

Another fundamental state variable that can be regulated during the cycle is cavity pressure. Closed-loop control of cavity pressure could automatically compensate for variations in melt viscosity and injection pressure to achieve a consistent process and uniform set of product attributes [31]. Mann introduced one of the first pressure control schemes by using modulated pressure relief valves [32], and Abu Fara developed a process control model by relating the cavity pressure response to open-loop perturbations [33]. Srinivasan later used these models to propose a learning controller for closed-loop cavity pressure control [34]. Adaptive control methods have also been proposed to track cavity pressure profile at usually one location in the mold [35-37].

Like melt temperature control, cavity pressure control suffers from the lack of a systematic method of determining the pressure profile. In addition, it is handicapped by the absence of appropriate actuators for distributed pressure control, as conventional molding machines are equipped with only one actuator (the screw) which does not allow simultaneous cavity pressure control at multiple points in the mold. A step towards solving this problem has been the development of dynamic melt flow regulators that allow control of the flow and pressure of the polymer melt at multiple points in the mold [38], and will be discussed in more detail later as a process design example. Similar concepts regarding dynamic thermal actuation are discussed in [39].

Further advancements in state-variable control are becoming possible through development of remote smart sensors. Packing time, for example, is currently controlled open-loop, using a fixed time delay specified by the machine operator. Thomas et. al. [40] have developed new sensors that infer the solidification of polymer in the mold, and have devised a closed-loop strategy where pack time is automatically controlled based on feedback from a solidification sensor. Using this strategy, the pack time can be set once in reference to the sensor signal, making it possible to provide a minimum pack time for each part under changing processing conditions.

3.3 Set Point Control

The adjustment of machine inputs is a discrete control process, where the molded part quality attributes from the cycle just completed are utilized to determine the magnitude of the machine inputs for the next molding cycle. Ideally, these set points should be specified so as to produce parts with acceptable part quality attributes, which for an injection molded part would typically be size, surface topography, and/or mechanical properties (e.g., tensile strength, flexural strength). However, the molding process is typically over-constrained, so a trade-off needs to be made between multiple quality objectives and cost in specification of the set points.

In theory, sophisticated injection molding simulations could provide the functional relations between CTQs and KPVs needed to setup and optimize the machine setpoints. [41-50]. After all, these simulation programs are now standard tools in the design of the product and mold geometry. These modeling advances, however, have not yet significantly impacted control of the process. The primary reason is the unsuitability of the developed mechanistic models for control analysis and design. Although there have been applications of these mechanistic models in controls [51-53], by and large, they have not been directly used in control. As an alternative, models in the form of time series or auto-regressive moving average (ARMA) have been developed empirically for control design [21, 54].

The traditional approach to machine input selection (tuning) in the plastics industry has been trial and error. For this, shots are taken during start-up and part quality attributes are measured after each shot to evaluate the acceptability of produced parts. The process engineer then uses his/her knowledge of the process to select the machine inputs in such a way as to improve the quality of the part from shot to shot. This tuning exercise is repeated until the specifications for part quality are satisfied. The main drawback of the traditional tuning approach is its inefficiency due to its 'ad hoc' nature. An alternative to the traditional trial and error approach is the use of expert systems where corrective guidelines are presented in the form of if-then rules [55-58]. The main shortcoming of expert systems is that a generalized set of rules may not be applicable across a broad range of part geometries, material properties, and machine dynamics.

The predominant practice for set point specification in precision injection molding is to develop an empirical model based on data obtained from a set of designed experiments [59]. Based on this model, the objective function of an unconstrained optimization problem is defined as a function of the part quality attributes, and the set of inputs that produce the best quality attributes are obtained as the optimal point of this optimization problem. Design of Experiments (DOE) based methods offer a systematic approach to tuning that can also be used for mold qualification [60-63], but they often require significant investment in training and technology.

Alternative approaches have been utilized to relate machine inputs to the observed part quality attributes. Woll and Cooper trained a backpropagation network (BPN) as an inverse model relating discretized patterns of cavity pressure as inputs to the corresponding values of holding pressure and barrel temperature that had produced them via simulation as outputs. The values of holding pressure and barrel temperature were then adjusted from cycle to cycle by comparing the actual cavity pressure pattern with a desired pattern, using the learned patterns as baselines [64]. A similar approach was utilized by Demirci et. al. to determine the inlet flow rate to the mold given the current position of the flow front during the filling stage [65]. This control scheme was based on a neural network that was trained with data obtained from a mechanistic model. The network was trained to estimate the position of the next flow front as output given the present position of the flow front and the inlet flow rate as inputs. Using this network as a forward model, a search was conducted to determine the inlet flow rate to the mold, based on the present position of the flow front and its desired next position. With this strategy one could specify a desired flow progression scheme and the controller would iteratively take corrective actions to realize this scheme. The drawback of the above approaches is the considerable time they require to develop the underlying models off-line.

A similar approach to the above methods for set point control is the Virtual Search Method (VSM) that also uses a forward model and search to determine the machine inputs [66]. However, VSM has the advantage of not requiring an off-line model by developing the I-O model concurrent with the process. The block diagram of VSM is shown in Figure 9. It consists of an 'input-output (I-O) model' which estimates the corresponding changes to the part attributes, a 'search algorithm' that determines prospective changes to the machine inputs for the next part, and a 'learning algorithm' to update the I-O model after each cycle based on part quality measurements. VSM exhausts the search based on the current I-O model and refers to the process in order to (1) test the feasibility of the best set of inputs obtained from the I-O model and (2) to update the I-O model using the measurements of part quality attributes obtained from the process. According to this scheme, the I-O model is updated only when it no longer provides guidance towards the feasible region, thus, enabling efficient utilization of the I-O model to its fullest capacity before updating it. VSM's interleaved approach to tuning and model development has been shown to require fewer process iterations than DOE methods, which require a comprehensive model of the process over a broad range of machine inputs.

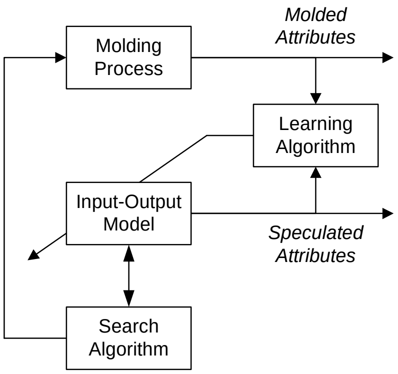


Figure 9: Diagram of the Virtual Search Method of tuning

4 PRECISION PROCESS CONTROL DEVELOPMENT

4.1 Methodology

The foregoing discussion of the fundamentals and current state of precision process control technology is intended to be more demonstrative than exhaustive. It should be clear that precision molding applications will frequently require process control development to ensure the quality and consistency of molded products. As such, the chapter now focuses on a practical approach to the development of precision process control for industry applications. The methodology is presented in Figure 10. Each step of the methodology will be discussed in some detail, after which two case studies will be presented.

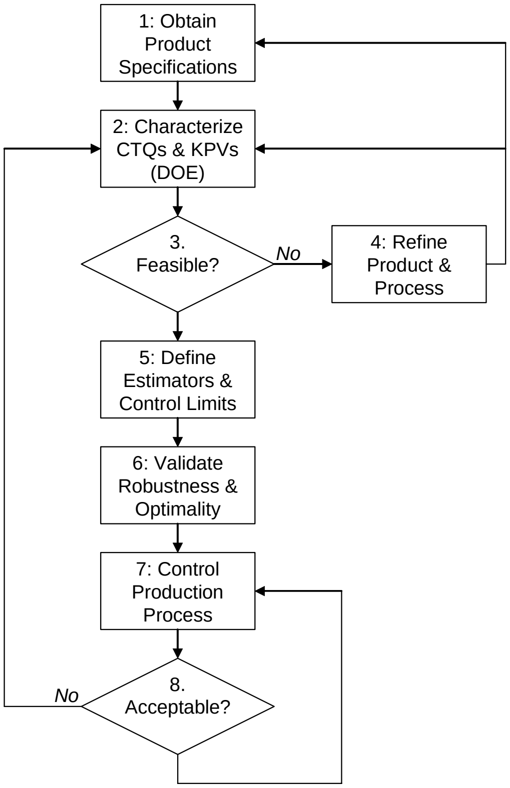


Figure 10: Application Development Methodology for Precision Process Control

1. Obtain Product Specifications: The precision molder must obtain the critical specifications (CTQs) for the product to be molded. A typical precision molded product may have twenty or more “critical” dimensions, all of them specified as critical. There may also be other assumed specifications that have not been specifically defined. At this point, the manufacturer should revisit the specifications. Frequently it is possible to refine the list such that only a **critical few**, perhaps three or four of the twenty, can be used to determine the acceptability of the moldings. Typically, these critical few specifications are the most demanding and/or are strongly coupled with other critical specifications, such that their satisfaction guarantees the acceptance of other critical specifications.

2. Characterize KPCs and KPVs: Next, the manufacturer needs to define the means for measuring the acceptability of the moldings, and also needs to characterize the relationships between the CTQs and the KPVs. In precision injection molding, both of these tasks can be daunting. Specifically, the metrology and quantification of product quality is complicated by the required resolution of dimensional measurements coupled with errors caused by compliance of the part and the transient errors caused by stress relaxation in the part obtaining equilibrium. While 100% inspection of moldings at the machine is desirable, it is frequently technically or economically infeasible and thus the molder may result to periodic sampling methods to achieve quality. As such, it is vital that the quality measurement systems themselves be characterized and well understood before pre-production process characterization.

The precision molder should then characterize the CTQs as a function of KPVs. At the minimum, the molder should perform a simple design of experiments (DOE) in which the main effects of the KPVs on the CTQs are graphed. This can be accomplished through one-at-a-time inspection of each of the KPVs at upper and lower processing limits, or better through fractional factorial design of experiments, or even better through more sophisticated DOEs such as Box Bhenkin or Central Composite Designs. However, increasing levels of sophistication require increased investment and risk if the runs or subsequent analysis are not correctly completed. At a minimum, the molder should quantify:

- the main effect of each KPV on each CTQ,
- the achievable range of each CTQ,
- the standard deviation of each CTQ,
- the feasible range of each KPV.

3. Establish Feasibility: Given the characterized process, the manufacturer needs to establish feasibility. Specifically, the manufacturer needs to consider the mean of each CTQ relative to the specification limits as, for example, in Figure 4. If any of the CTQs are outside the specification range, or are close to a specification limit, then changes should be made to the process to center the mean and reduce the standard deviation of the CTQs. Frequently this can be accomplished by altering the setpoints of the molding process as, for example, in Figure 6. Sometimes, however, multiple CTQs conflict in such a way that no feasible process setting can be established, and mold or material changes are required.

4. Refine Product and Process: If simple alteration of the machine settings does not provide for a feasible process, then the precision injection molder may need to refine the product and process. In many cases, a straightforward (though sometimes costly) alteration of gate dimensions, thickness, or shrinkage factor can place the conflicting CTQ within specification. In other cases, it may be possible to change the specifications and/or other components in the product assembly to proceed with the current product and process design. Both of these approaches are common, and may result in resolution of the conflict.

In very demanding precision molding applications, however, such changes in product and mold design may not be practical or effective in achieving the desired level of precision or performance. In some cases, the variation may simply be excessive. In other cases, there may be strong, even mutually exclusive, conflicts between different CTQs. Both of these cases require improvements in the process control, though of different strategies and magnitudes.

First consider the case where the mean of the CTQs are satisfactory, but one or more CTQs exhibit excessive variation leading to very low yields of acceptable moldings. In this case, the main effects plot (resulting from step 2) should be utilized to identify the most critical KPVs and improvements in process control made to reduce the corresponding sources of variation. Examples of such activities may include the adoption of a molding machine with better control, the tuning of controller parameters, the use of a material with tighter specifications, the addition of a sensor at the end of flow to control switchover from filling to packing [67], or direct cavity pressure control with a transducer near the gate. Such relatively minor process development activities can frequently enable a marginal precision molding application to be efficiently and economically produced.

In the case where one or more CTQs conflict and/or are far outside of specification, more substantial process development activities may be necessary. Specifically, it may be necessary to add complexity to the precision molding process to effectively add degrees of freedom and improved control of multiple CTQs. Such examples of process development may include the use of sophisticated and dynamic temperature, velocity, or pressure profiling during the molding cycle, switching to injection-compression molding rather than conventional injection molding, or use other control technologies like Dynamic Feed ™. Of course, the precision molder should understand their own capabilities, and be selective in undertaking significant investment and risk in creating new capabilities.

5. Define Estimators and Limits: Once a feasible process and product is established, a set of estimators and control limits should be defined. The objective of this activity is to provide 100% quality assurance without 100% inspection of the molded products. As such, the molder should investigate the use of in-mold sensors and other devices to provide a reasonable measure of automated quality assurance. Common strategies may include:

- the use of plastication time to ensure material consistency [68];
- the use of cavity pressure transducers at end of flow to guarantee cavity filling [67];
- the use of cavity pressure transducers near the gate to indicate repeatability of packing [69];
- the use of tie-bar strain gauges to estimate pressure and tonnage across all cavities [70];
- the use of ultrasonic transducers to estimate solidification [71];
- the use of part weight to estimate dimensions [72];
- the use of robots, measurement fixtures, and/or laser metrology to estimate dimensions [73-75];
- the use of cameras to ensure ejection of parts from the cavities [76];
- and others [77-79].

It is not the objective of this chapter to define all the possible sensors and process data features that could be used for quality assurance. However, the precision molder should consider the use and fusion of such techniques to provide an automated assessment that there are no gross errors in the molding process [80]. The use of such an approach may capture a significant fraction of defective products to more productively utilize the operator. There are “lights out” operations effectively using robust process control approaches for round the clock, automated production of precision parts in which a small percentage of suspect molding are discarded without human inspection. On the other hand, improper use of such estimators may prove worthless or negative in value by continuously accepting defective moldings and/or rejecting acceptable moldings. As such, automated on-line quality assurance must be validated continuously with off-line, higher fidelity metrology techniques.

6. Validate Robustness and Optimality: It is next desirable to investigate the robustness and optimality of the production molding process. This may be readily achieved by perturbing the KPVs on the production machine by amounts that could be expected in production. For instance, the molder’s experience or Hunkar class factor (ref. Table 1) may indicate the expected range of variation in each of the machine’s set-points. Given this information, the molder should purposefully vary each set-point by this amount to validate that the moldings continue to meet their specifications. This investigation can be very useful in identifying the possibility of producing defective moldings given natural variation in the machine (move the process away from the set-points causing the defects), or by identifying the possibility of producing acceptable moldings more economically (move the process towards lower temperature and time settings). This validation step also provides a final opportunity to fine-tune the product, process, and QA estimators prior to high volume production.

7&8. Production Process Control: By validating the robustness of the production process, the developed process monitoring and control should be effective. However, the precision molder should check that the production process is, in fact, being controlled. Specifically, it is quite common for steps 1 to 6 to be effectively developed, only to have the working systems degrade with use, be switched off, or rendered ineffective through external changes to the molding process. As such, it is advantageous to provide operators training regarding the implemented process control system together with a monitoring and communication system to control the process control system. Such management structures are useful in determining the effectiveness of the systems and their impact on molding productivity. In the event that defects arise in production, or the process control system is ineffective, process development should be revisited as described in steps 2-6.

4.2 Example #1: Process Window Determination for DVD Manufacturing

The first process control example is intended to demonstrate the complexity of precision molding applications with respect to control of variation and uncertainty in the process behavior [81]. It also demonstrates the use of an augmented control system to attain CTQs that are not achievable with conventional injection molding. Specifically, a Central Composite Design [82, 83] was utilized in an experimental study of six processing variables (defined in Table 2) and eight quality attributes (defined in Table 3) regarding the production of digital video disc (DVD) molded substrates. The resulting design of experiments (DOE) had 45 individual run conditions, with five replicates molded at each run condition for a total of 225 molded samples. All laboratory experimentation was conducted at General Electric Plastics Polymer Processing Development Center, in the Optical Media Development Center (OMDC). The quality characteristics were measured with a TopoMetrix Atomic Force Microscope, Dr. Schenk Optical Disk Scanner, and CD Associates Stamper Player Signal Analysis instrument [84].

Table 1: Key Process Variables (KPVs)

Process Parameters, ***x***		
LCL$_j$	*Parameter*	*UCL$_j$*
368	x_1≡Melt Temperature (C)	382
98	x_2≡Mold Temperature (C)	112
1.2	x_3≡Cooling Time (sec)	2.0
14	x_4≡Stage 1 Tonnage (Tons)	22
0.1	x_5≡Stage 1 Time (sec)	0.9
7	x_6≡Stage 2 Tonnage (Tons)	13

Table 2: DVD Critical to Quality Attributes (CTQs)

Quality Attributes, ***y***		
LSL$_j$	*Attribute*	*USL$_j$*
-300	y_1≡OD Deviation (deg)	300
-100	y_2≡Dishing (deg)	100
-50	y_3≡Min Birefringence (μm)	50

-50	y_4≡Max Birefringence (μm)	50
-0.8	Y_5≡Min Radial Dev (nm)	0.8
-0.8	Y_6≡Max Radial Dev (nm)	0.8
-0.3	y_7≡Min Tangent Dev (deg)	0.3
-0.3	y_8≡Max Tangent Dev (deg)	0.3

The process characterization methods used and the resulting system characterization are at least typical or better than industry standards. Figure 11 provides the resulting graphical function matrix plotting the mapping from each process input to each process output, with confidence intervals generated at the 95% confidence level. An inspection of this figure indicates that y_2, dishing, is the most sensitive CTQ while x_2 and x_6 are the most critical KPVs across all quality attributes. Another important realization from the figure, which is generally ignored in industry practice, is that there is substantial uncertainty regarding the true behavior of this molding process. As such, it is desirable to operate the DVD manufacturing process far from its specification limits, such that the yields will be high regardless of either uncontrolled variation or behavioral uncertainty.

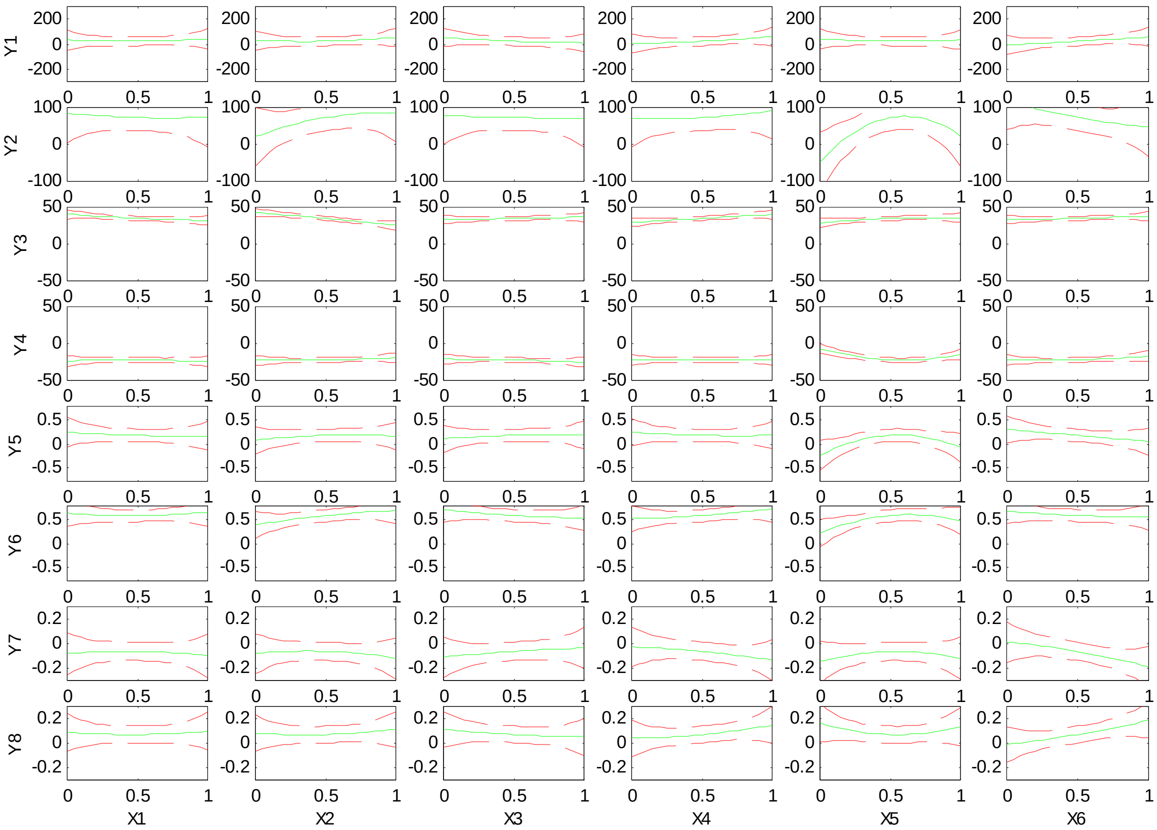


Figure 11: Derived 2nd Order Model of DVD Manufacturing Process with Confidence Intervals

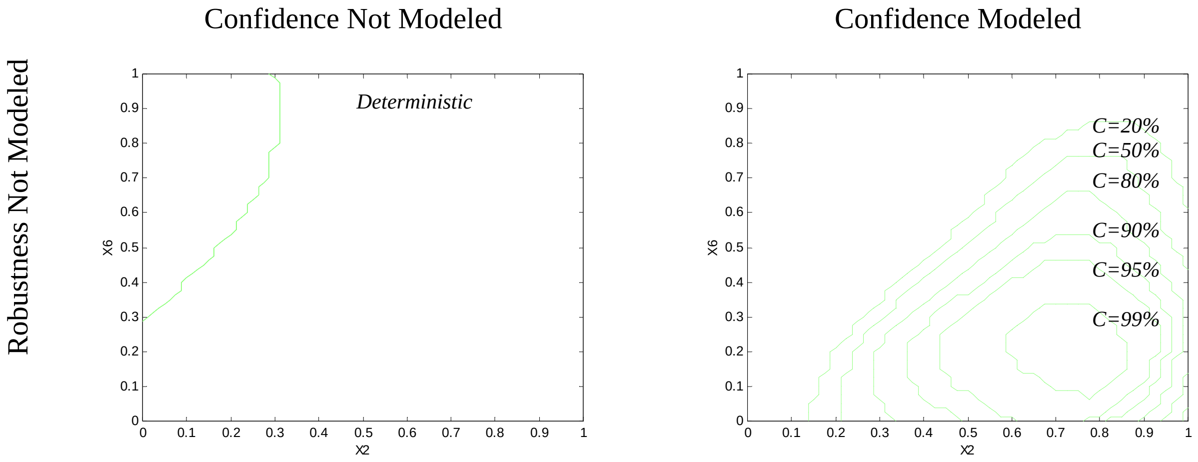
The process performance was evaluated given the stated specification limits in Table 3 and the observed standard deviation of the quality attributes y_1 to y_8 as [12.2958, 14.1598, 2.0661, 1.0528, 0.0684, 0.0537, 0.0242, 0.0237, 10.3711]. Subsequent optimization indicates that the process best operates at maximum x_2 with x_6 in the lower third of its processing range. The aggregate process capability index (ref. Eq. 1-6) is 1.31, corresponding to a 4σ capability, a projected yield of 99.996%, and forty defects per million opportunities.

Given the competitiveness in precision molding applications, there is a trend to continuously improve processes and report ever-increasing process capability indices. In fact, commercial applications have been reported with *Cp* values greater than ten, indicating at least thirty standard deviations between the mean and the closest specification limit. While conceptually and qualitatively useful, the use of the process capability index assumes a known, deterministic behavioral model between CTQs and KPVs, as well as the appropriateness of normal statistics. However, long run manufacturing studies indicate that processes typically exhibit significantly broader tails than characterized by a short run variation study [85]. As a result, the explicit and focused use of the process capability index may lead to acceptance of defective products, or rejection of acceptable products.

Recalling that one intent of the original Six Sigma programs [86] was to provide 99.87% yield (3σ for variation) in 99.87% of engineering applications (3σ for uncertainty), precision molders should not rely on excessive *Cp* levels, and should actively consider the uncertainty in the process behavior that relates inputs to outputs (e.g. Figure 11) as well as the trade-off between the level of different CTQs relative to the overall product performance and cost (e.g. Figure 7). Application of statistical methods to such complex precision molding processes indicates that the effect of uncertainty regarding the true process behavior may far exceed the quality loss due to manufacturing process variation.

The application of response surface methods and numerical sampling techniques provides insight to the effect of uncontrolled variation compared to behavioral uncertainty. For the sake of explicitness, robustness to variation is defined as the probability of a quality attribute being within specification limits given random variation, evaluated according to eq. (4). Confidence against uncertainty is defined as the probability of a quality attribute being within specification limits given model uncertainty, evaluated with confidence intervals on the model behavior according to varying levels of error, α.

As such, Figure 12 plots the allowable process window for x_2 and x_6 with levels of varying robustness and/or confidence equal to 20%, 50%, 80%, 90%, 95%, 99%. For instance, the upper left graph shows a conventional process window, in which any selection of x_2 and x_6 is commonly believed to produce acceptable molded products. However, consideration of uncertainty and variation significantly reduces the allowable process window. The upper right graph provides the feasible processing window given varying levels of confidence from 20 to 99%, while the lower left graph shows the process window given specified processing yields from 20% to 99%. The lower right graph shows the process window assuming equal values of robustness and uncertainty corresponding to 20%, 50%, 80%, and 90%.



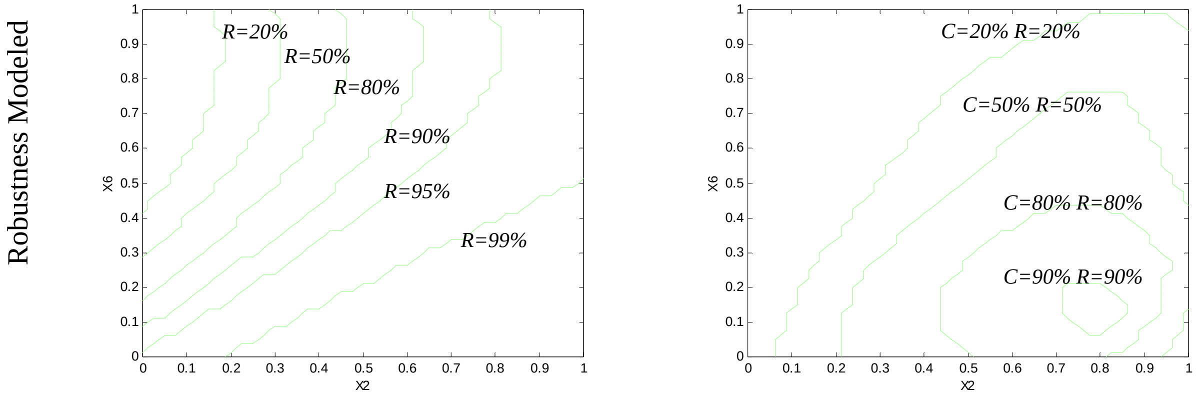


Figure 12: Process Windows for Varying Levels of Robustness and Confidence

Figure 12 demonstrates some very interesting concepts pertaining to precision process control. First, the process optimization to maximize the process capability index does provide a reasonable selection of machine setpoints with respect to variation alone, indicating that the process should be operated at minimal x_6. However, it is observed that consideration of model uncertainty will tend to move the desired processing point away from the previously considered robust point. Moreover, it is observed that the process window for the DVD manufacturing process exists for a maximum joint probability of 90% uncertainty and robustness, compared to 99+% levels for robustness and confidence alone. As such, the precision DVD molding process, which appears to be have a high process capability index and appears very feasible, is (in practice) much more difficult to operate given its behavioral complexity and uncertainty.

It should also be noted that process control of conventional, generic molding machines was not sufficient for precision molding of CDs and DVDs. As such, dedicated precision molders and machine builders introduced advanced process control systems and clamping technologies to provide significant added process capability. Specifically, control systems used in this industry provide better control system time response (typically less than 100 μSec vs. a more general 2 mSec widespread in across the plastics industry) as well as higher performance valves and hoses to provide faster injection velocities and process response times. Moreover, it was found that the use of injection compression provided more uniform pressure across the cavity compared to conventional injection molding, which in turn allowed for improvements in CTQs and significant reductions in cycle times.

4.3 Example #2: Dynamic Feed

The use of injection compression in the molding of CDs and DVDs was an enabler of the economical manufacture and widespread adoption of the media. Similar advances are possible in many areas of precision injection molding, in which integrated development of the molded product with the molding process enables previously unavailable process and product capabilities. One of Nam Suh’s axioms [87] of design states that “independence of functional requirements should be maintained,” which in other words means that each CTQ should be directly matched to a KPV. Such manufacturing processes, if successfully developed, are controllable by definition and could provide any desired set of CTQs.

In precision injection molding, control of flow and pressure at multiple points in an injection mold is not feasible in conventional molding. Rather, the flow and pressure originating from the nozzle of the injection molding machine is inherently coupled through the static feed system and geometry in the mold. To increase the controllability of the injection molding process, multiple melt valves were inserted into the drops of a hot runner system for control of melt flow and pressure in the mold cavity [88]. As shown in Fig. 4, the pressure drop and flow rate of the melt is dynamically varied by the axial movement of each valve stem which controls the gap between the valve stem and the mold wall. By de-coupling the control of the melt at different valve stem positions, melt control at each gate can override the effects of the molding machine and provide better time response and differential control of the melt. Each valve acts as an individual injection unit, lessening dependency on machine dynamics. For closed loop control, melt pressure transducers were used in the runner drops instead of in the cavity. This implementation not only provides lower cost and greater reliability, but also renders a conventional appearance for the system.

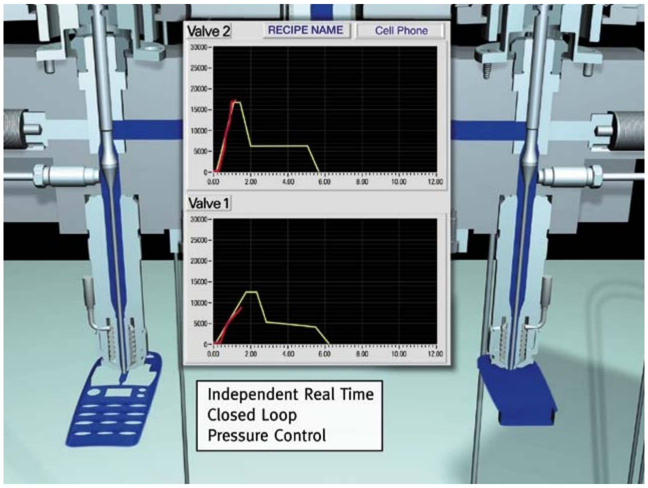


Figure 13: Dynamic Flow Regulation Design

The resulting controllability of the injection molding process is demonstrated in Figure 14 where multiple pressure profiles can be maintained in the mold cavity of a single multi-gated part. In the same cycle, three different magnitudes of melt pressure were exerted at different gates in the same mold cavity. The control pressure for the holding stage at Gate 1 is 41.4 MPa (6000 psi), Gate 2 is 41.4 MPa (6000 psi), Gate 3 is 20.7 MPa (3000 psi), and Gate 4 is 62.1 MPa (9000 psi). In conventional injection molding, the melt pressure would be the same at all gates. This level of process control had not previously been achieved by any molding technology thus far. Each gate can exert a specific holding pressure.

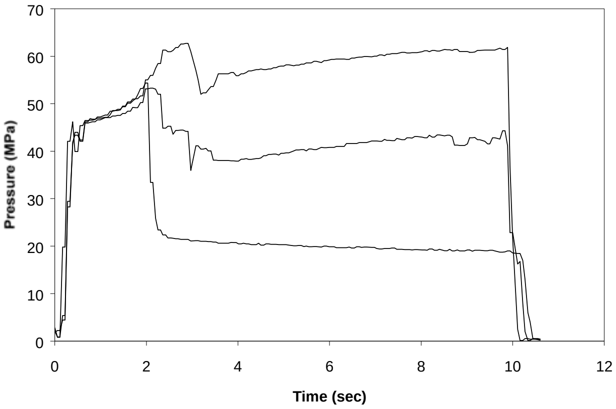


Figure 14: Dynamic Pressure Control

As is well known in precision molding, the material shrinkage and dimensions change at differing locations in the part based on the pressure contours and histories throughout the cavity. The ability to change individual dimensions or other quality attributes without re-tooling mold steel provides significant process flexibility. As such, it is possible to augment the main effects of the molding machine with the additional degrees of freedom and determine the controllability of the three part dimensions:

Conventional	*Dynamic Feed*	
$\begin{bmatrix} L1 \\ L2 \\ L3 \end{bmatrix} = \begin{bmatrix} 0.57 & -0.10 & 0.43 & 0.02 \\ 0.51 & -0.18 & 0.29 & 0.00 \\ 0.23 & -0.05 & 0.18 & 0.10 \end{bmatrix} \begin{bmatrix} Pressure \\ Velocity \\ Temperature \\ ScrewSpeed \end{bmatrix}$	$\begin{bmatrix} L1 \\ L2 \\ L3 \end{bmatrix} = \begin{bmatrix} -0.02 & -0.05 & 0.08 & -0.01 \\ -0.03 & -0.09 & 0.05 & 0.00 \\ -0.01 & -0.02 & 0.03 & 0.01 \end{bmatrix} \begin{bmatrix} Pressure \\ Velocity \\ Temperature \\ ScrewSpeed \end{bmatrix} + \begin{bmatrix} 0.00 & 0.31 & 0.60 & 0.00 \\ 0.10 & 0.17 & 0.00 & 0.16 \\ 0.00 & 0.02 & 0.00 & 0.21 \end{bmatrix} \begin{bmatrix} P1 \\ P2 \\ P3 \\ P4 \end{bmatrix}$	(8)

There are two significant implications of this result. First, the closed loop control of cavity pressures has significantly reduced the dependence of part dimensions on machine settings, as evidenced by a measured reduction in the magnitude of coefficients for the primary machine settings. This effect has also been evidenced by reductions in the standard deviations of multiple part dimensions by an average factor of five, resulting in an increase in the process capability index, *Cp*, from less than 1 to far beyond 2.

Second, the second matrix in eq. (8) is evidence of the improved dimensional controllability provided by the dynamic regulation of the cavity pressure distribution. In general, changing the cavity pressure at the gate closest to a dimension provides the major effect on part dimensions. Additionally, independent control of the valve stems provides the capability to vary dimensions at one location without interfering with dimensions at another location. This flexibility does not exist in conventional molding because hold pressure changes intended to influence one area of the part can be transmitted to other areas of the part through the static feed system. It should be noted, however, that the total magnitude of dimensional change available with dynamic pressure regulation is approximately the same as for conventional molding.

These results may have a significant impact on the product and tooling development process. Currently, numerical mold filling simulations and expert judgments are combined to estimate the process behavior and make critical design decisions. If these decisions are incorrect, then tooling modifications may be required. Improved controllability of the injection molding process permits correction for many design inaccuracies during the mold commissioning stage without retooling. Such a change in the development process could substantially reduce the tool development costs, shorten the development cycle, and hasten time to market.

The described process is also significant in that it moves polymer control from the molding machine to the mold itself. This reduces the molding machine to a ‘polymeric pump.’ Variations in injection pressure, flow rates, pack pressures, or pack times are all compensated through dynamic pressure and temperature control. The market repercussions could be significant, as 1) an old machine without closed loop control can provide consistency equal to modern machines, and 2) a mold commissioned on a molding machine in the United States is ensured to produce consistent parts on a molding machine overseas. The mold becomes its own self-contained quality control mechanism. As such, the potential productivity and quality gains in precision molding are substantial.

5 CONCLUSIONS

The technical requirements of precision injection molded components demands a heightened level of process performance, and with it an exacting level of process monitoring and control technologies. Effective precision molding requires increased levels of process capability, efficiently operating at economic conditions. Specifically, precision molders should be aware that critical to quality attributes (CTQs) are rarely observable from the process. As a result, estimators should be developed and validated with corresponding control techniques to guarantee a reasonable level of assurance of the quality of the moldings. In precision molding, moreover, the CTQs possess very tight specifications which may conflict with other CTQs and thus lead to an infeasible process. In such cases, the product specifications and or process design may need to be altered to shift the performance mean, reduce the standard deviations, or otherwise add processing variables to increase the controllability of the CTQs. In some cases, these changes may require minor mold or process changes. In other cases, a substantial improvement in process capabilities necessitates significant development of new process technology.

Given the application dependence of precision process control, a methodology was presented for developing precision injection molding process capabilities. The methodology is based on a standard decision making process of 1) measure, 2) analyze, 3) improve, and 4) control. Where possible, standard practices and suggestions have been made for precision injection molding. Two recent examples of precision process control development were demonstrated. The first example showed the characterization and analysis of a fairly complex DVD manufacturing process, and was included to lessen the industry’s increasingly myopic focus on process capability measures when compared to uncertainty in the process behavior and other external factors. The second example shows the development of an advanced molding process to improve the controllability of multiple CTQs, and provide some motivation for development of other techniques to enable precision injection molding.

6 ABOUT THE AUTHOR

Dr. Kazmer is recognized for his expertise in plastics product and process engineering. Prior to his appointment as Associate Professor in the Department of Plastics Engineering at U. Mass Lowell, he was faculty in the Department of Mechanical Engineering at U. Mass Amherst, beginning in 1995. Dr. Kazmer’s funded research exceeds $2 million to date. He is the recipient of ten different recognition awards and the author of more than one hundred technical articles. His industry experience includes positions as Director of R&D at Synventive Molding Solutions as well as Technology Programs Manager, Process Development Engineer and Applications Engineer at GE Plastics; and Mechanical Engineer at GE R&D. Kazmer holds a PhD from the Mechanical Engineering Design Division of Stanford University, an MS in Mechanical Engineering from Rennselaer Polytechnic Institute, and a BS in Mechanical Engineering from Cornell University. David_Kazmer@uml.edu.

7 REFERENCES

1. Anon, *Information Guide to Temperature Controls For Injection Molding/Extrusion.* Plastics Design & Processing, 1975. **15**(3): p. 17-19.
2. Franklin, G.F., J.D. Powell, and A. Emami-Naeini, *Feedback control of dynamic systems*. 3rd ed. Addison-Wesley series in electrical and computer engineering. Control engineering. 1994, Reading, Mass.: Addison-Wesley. xx, 778.
3. Poslinski, A.J., C.A. Deborski, and S. Aslam. *Effects of small changes in the melt viscosity on the filling and packing stages of injection molding*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. 1994. San Francisco, Ca, Usa.
4. Hunkar, D.B. *Managing the future with dynamic statistics*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. 1995. Boston, Ma, Usa.
5. Morris, N.M. and W.B. Rouse, *Effects of Type of Knowledge Upon Human Problem Solving in a Process Control Task.* IEEE Transactions on Systems, Man and Cybernetics, 1985. **SMC-15**(6): p. 698-707.
6. Fan, B. and D. Kazmer. *Simulation Based Optimization of Injection Molding.* in *17th International Meeting of the Polymer Processing Society*. 2001. Montreal, Quebec.

7. Bothe, D.R., *Measuring Process Capability: Techniques and Calculations for Quality and Manufacturing Engineers*. 1997: McGraw-Hill.
8. Kotz, S. and N.L. Johnson, *Process Capability Indices*. 1st ed. 1993, London: Chapman & Hall.
9. Kane, V.E., *Process Capability Indices.* Journal of Quality Technology, 1986. **18**(1): p. 41-52.
10. Devore, J.L., *Probability and Statistics for Engineering and the Sciences*. 4th edition ed. 1995: Wadsworth.
11. Ford, R.B., *Process for the Conceptual Design of Robust Mechanical Systems going beyond Parameter Design to Achieve World-Class Quality*, in *Mechanical Engineering*. 1996, Stanford University: Stanford.
12. Kazmer, D. and C. Roser, *Evaluation of Product and Process Design Robustness.* Research in Engineering Design, 1999. **11**: p. 20-30.
13. Suh, N.P., A.C. Bell, and D.C. Gossard. *On an Axiomatic Approach to Manufacturing and Manufacturing Systems*. in *American Society of Mechanical Engineers Winter Annual Meeting*. 1977.
14. Suh, N.P., *Axiomatic Design: Advances and Applications*. 2001: Oxford University Press.
15. Lenane, D.-M., *Accounting for the Real Cost of Quality.* Quality Progress, 1986. **January**.
16. Plunkett, J.J. and B.G. Dale, *Quality Costs: a critique of some ' economic cost of quality' models.* International Journal of Product Research, 1988. **26**(11): p. 1713-1726.
17. Ma, C.Y.W., *A Design Approach to a Computer-Controlled Injection-Molding Machine.* Polymer Engineering and Science, 1974. **11**(14): p. 768-772.
18. O'Bryan, J.E., *Injection molding machines meet automated manufacturing demands. Proportional valves, microprocessors, and closed-loop control keep plastics molders competetive.* Hydraulics & Pneumatics, 1989. **42**(3): p. 95.
19. Sparer, R.M. and D.P. Werle, *Logic controlled plastic molding machine with programmable operator interface*. 1991, Cincinnati Milacron, Inc.
20. Pandelidis, I.O. and A.R. Agrawal, *Optimal Anticapatory Control of Ram Velocity in Injection Molding.* Polymer Engineering and Science, 1988. **28**(3): p. 147-156.
21. Tsai, C.-C. and C.-H. Lu, *Multivariable self-tuning temperature control for plastic injection molding process.* IEEE Transactions on Industry Applications, 1998. **34**(2): p. 310-318.
22. Yang, Y. and F. Gao, *Adaptive control of the filling velocity of thermoplastics injection molding.* Control Engineering Practice, 2000. **8**(11): p. 1285-1296.
23. Lu, C.-H. and C.-C. Tsai, *Adaptive decoupling predictive temperature control for an extrusion barrel in a plastic injection molding process.* IEEE Transactions on Industrial Electronics, 2001. **48**(5): p. 968-975.
24. Zhang, W.D., Y.X. Sun, and X.M. Xu. *Modified PID controller based on H infinity theory*. in *IEEE International Conference on Industrial Technology*. 1996.
25. Tan, Y. and R. De Keyser. *Auto-tuning PID control using neural predictor to compensate large time-delay*. in *IEEE Conference on Control Applications*. 1994. Glasgow, UK.
26. Coates, P.D. and R.G. Speight, *Towards intelligent process control of injection moulding of polymers.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 1995. **209**(B5): p. 357-367.
27. Dubay, R., A.C. Bell, and Y.P. Gupta, *Control of plastic melt temperature: A multiple input multiple output model predictive approach.* Polymer Engineering and Science, 1997. **37**(9): p. 1550-1563.
28. Gomes, V.G., W.I. Patterson, and M.R. Kamal, *Injection Molding Study: Evaluation of Alternative Control Strategies For Melt Temperature.* Polymer Engineering and Science, 1986. **26**(12): p. 867-876.

29. McCullough, T.W. and M.A. Spalding, *Predicting actual temperature distributions in a polymer stream using an adjustable-depth, exposed-tip thermocouple assembly.* Journal of Reinforced Plastics and Composites, 1997. **16**(17): p. 1622-1630.
30. Lai, G.-Y. and J.X. Rietveld, *Role of polymer transparency and temperature gradients in the quantitative measurement of process stream temperatures during injection molding via IR pyrometry.* Polymer Engineering and Science, 1996. **36**(13): p. 1755-1768.
31. Langkamp, U., *Pressure and temperature sensors.* Kunststoffe Plast Europe, 1996. **86**(12): p. 1804-1812 German.
32. Mann, J.W., *Process Parameter Control: the Key to Optimization.* Plastics Engineering, 1974. **30**(1): p. 25-27.
33. Kamal, M.R., et al., *Dynamics and Control of Pressure in the Injection Molding of Thermoplastics.* Polymer Engineering and Science, 1987. **27**(18): p. 1403-1410.
34. Srinivasan, K. and T. Brinivasan. *Learning control of melt pressure in injection molding processes*. in *American Society of Mechanical Engineers, Dynamic Systems and Control Division (Publication) DSC*. 1991. Atlanta, GA, USA.
35. Gao, F., I.A.N. Patterson, and M.R. Kamal, *Self-tuning cavity pressure control of injection molding filling.* Advances in Polymer Technology, 1994. **13**(2): p. 111-120.
36. Chiu, C.-P., M.-C. Shih, and J.-H. Wei, *Dynamic Modeling of the Mold Filling Process in an Injection Molding Machine.* Polymer Engineering and Science, 1991. **31**(19): p. 1417-1424.
37. Nunn, R.E. and C.P. Grolman, *Closed Loop Cavity Pressure Control in Injection Molding.* J. Reinforced Plastics and Composites, 1991. **9**: p. 2121.
38. Kazmer, D.O. and P. Barkan, *Multi-Cavity Pressure Control in the Filling and Packing Stages of the Injection Molding Process.* Polymer Engineering and Science, 1997. **37**(11): p. 1865-1879.
39. Jansen, K.M.B., *Heat transfer in injection moulding systems with insulation layers and heating elements.* International Journal of Heat and Mass Transfer, 1995. **38**(2): p. 309-316.
40. Thomas, C.L., et al., *Solidification sensing for closed loop control of injection molding hold time.* Advances in Polymer Technology, 1996. **15**(2): p. 151-163.
41. Hieber, C.A. and S.F. Shen, *Flow Analysis of the Non-Isothermal Two-Dimensional Filling Process in Injection Molding.* Israel Journal of Technology, 1978. **16**(5-6): p. 248-254.
42. Wang, V.W., C.A. Hieber, and K.K. Wang, *Filling of an Arbitrary Three Dimensional Thin Cavity*. Journal of Polymer Engineering, 1986. **7**: p. 21.
43. Kamal, M.R., et al., *Computer Simulation of Injection Mold Filling For Viscoelastic Melts With Fountain Flow.* Polymer Engineering and Science, 1986. **26**(3): p. 190-196.
44. Chang, R.Y. and B.D. Tsaur, *Experimental and theoretical studies of shrinkage, warpage, and sink marks of crystalline polymer injection molded parts.* Polymer Engineering and Science, 1995. **35**(15): p. 1222.
45. Zoetelief, W.F., L.F.A. Douven, and A.J.I. Housz, *Residual thermal stresses in injection molded products.* Polymer Engineering and Science, 1996. **36**(14): p. 1886-1896.
46. Liu, S.-J., *Modeling and simulation of thermally induced stress and warpage in injection molded thermoplastics.* Polymer Engineering and Science, 1996. **36**(6): p. 807-818.
47. McGrath, J.J. and J.M. Wille, *Determination of 3D fiber orientation distribution in thermoplastic injection molding.* Composites Science and Technology, 1995. **53**(2): p. 133-143.
48. Verleye, V., A. Couniot, and F. Dupret. *Prediction of fiber orientation in complex injection molded parts*. in *American Society of Mechanical Engineers, Applied Mechanics Division*. 1993. New Orleans, LA.
49. Chen, S.-C., et al., *Integrated simulations of structural performance, molding process, and warpage for gas-assisted injection-molded parts. I. Analysis of part structural performance.* Journal of Applied Polymer Science, 1998. **68**(3): p. 417-428.

50. Friedrichs, B., M. Horie, and Y. Yamaguchi, *Simulation and analysis of birefringence in magneto-optical discs. Part A: formulation.* Journal of Materials Processing and Manufacturing Science, 1996. **5**(2): p. 95-113.
51. Rafizadeh, M., W.I. Patterson, and M.R. Kamal, *Physically-Based Model of Thermoplastics Injection Molding for Control Applications.* International Polymer Processing, 1996. **11**(4): p. 352.
52. Kazmer, D., J. Rowland, and G. Sherbelis, *Foundations of intelligent process control for injection molding.* Journal of Injection Molding Technology, 1997. **1**(1): p. 44-56.
53. Coates, P.D., A.R. Haynes, and R.G. Speight, *In-line characterization of polymer deformation in melt and solid phase processing.* Polymer, 1994. **35**(18): p. 3831-3843.
54. Bulgrin, T.C. and T.H. Richards, *Application of advanced control theory to enhance molding machine performance.* IEEE Transactions on Industry Applications, 1995. **31**(6): p. 1350-1357.
55. Huh, Y.J., S. Han, and K.K. Wang. *Knowledge-based synthesis system for chip encapsulation*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. 1995. Boston, Ma, Usa.
56. Shelesh-Nezhad, K. and E. Siores, *Intelligent system for plastic injection molding process design.* Journal of Materials Processing Technology, 1997. **63**(1-3): p. 458-462.
57. Catic, I., et al. *Expert system aided troubleshooting in polymer engineering*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. 1996. Indianapolis, In, Usa.
58. Bernhardt, A., G. Bertacchi, and A. Vignale. *Rationalization of molding machine intelligent setting & control*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. 1998. Atlanta, Ga, Usa.
59. Luftig, J.T. and V.S. Jordan, *Design of experiments in quality engineering.* 1998, New York: McGraw-Hill. vii, 343.
60. Leartcheongchowasak, S., et al. *Robust parameter design of the precision injection molding process*. in *20th Design Automation Conference*. 1994. Minneapolis, MN: American Society of Mechanical Engineers, Design Engineering Division.
61. Meheran, P.J. and P.J. Blyskal. *Design of experiments for the injection molding process (qualifying materials to produce equivalent parts)*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. 1995. Boston, Ma, Usa.
62. Liu, C. and L.T. Manzione, *Process studies in precision injection molding. I: process parameters and precision.* Polymer Engineering and Science, 1996. **36**(1): p. 1-9.
63. Viana, J.C., P. Kearney, and A.M. Cunha. *Improving impact strength of injection molded plates through molding conditions optimization: A design of experiments approach.* in *Annual Technical Conference - ANTEC, Conference Proceedings*. 1998. Atlanta, Ga, Usa.
64. Woll, S.L.B. and D.J. Cooper, *Pattern-based closed-loop quality control for the injection molding process.* Polymer Engineering and Science, 1997. **37**(5): p. 801-812.
65. Demirci, H.H., J.P. Coulter, and S.I. Guceri, *Numerical and experimental investigation of neural network-based intelligent control of molding processes.* Journal of Manufacturing Science and Engineering, Transactions of the ASME, 1997. **119**(1): p. 88-94.
66. Ivester, R. and K. Danai, *Automatic tuning and regulation of injection molding by the virtual search method.* Journal of Manufacturing Science and Engineering, Transactions of the ASME, 1998. **120**(2): p. 323-329.
67. Smith, J.J. *Switchover methods*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. Atlanta, GA: Society of Plastics Engineers.
68. Atkins, H. and A. Gilead. *SPC and injection molding*. in *Annual Technical Conference - ANTEC, Conference Proceedings*. San Francisco, CA: Society of Plastics Engineers.

69. Varela, A.E., *Self-tuning pressure control in an injection moulding cavity during filling.* Institute of Chemical Engineers, Part A: Chemical Engineering Research and Design, 2000. **78**(1): p. 79-86.
70. Muller, D.H. and Y. Feng, *Reducing mould-gap widths: Avoiding flash in the parting plane of injection moulding machines.* Kunststoffe Plast Europe, 1996. **86**(9): p. 7-9.
71. Jiang, M., et al. *New ultrasonic solidification sensing techniques for injection molding*. in *CAE and Intelligent Processing of Polymeric Materials*. 1997. 1997 ASME International Mechanical Engineering Congress and Exposition: American Society of Mechanical Engineers, Materials Division.
72. Vaatainen, O., P. Jarvela, and K. Valta, *The Effect of Processing Parameters on the Quality of Injection Moulded Parts.* Plastics, Rubber, and Composites Processing and Applications, 1994. **21**(4): p. 211.
73. *Mate punch and die automates production and inspection.* Robotics World, 1991. **9**(2): p. 28-29.
74. Ehrenweber, R., *Testing quality characteristics with a robot.* Kunststoffe Plast Europe, 1996. **86**(4): p. 12-13.
75. Timmers, W., et al. *Metrology of injection molded optical components with multiple optical functions*. in *Gradient Index, Miniature, and Diffractive Optical Systems*. 1999: SPIE - The International Society for Optical Engineering.
76. Oehlmann, J., *Intelligent camera.* Kunststoffe Plast Europe, 1999. **89**(11): p. 21-22.
77. Burger, T., *100% control of surface quality.* Kunststoffe Plast Europe, 1996. **86**(11): p. 13-14.
78. Lu, X. and S.K. Lau, *A statistical experimental study of the injection molding of optical lenses.* Journal of Materials Processing Technology, 2001. **113**(1): p. 189-195.
79. Byun, J.-H. and Y.B. Kim, *Design and implementation of evolutionary operation for three practical issues: Prior information, robustness, and multiple responses.* Journal of Engineering Valuation and Cost Analysis, 2000. **3**(4): p. 233-244.
80. Chien, L.-J., C.L. Thomas, and D.R. Lawson. *Sensor/model fusion for improved process understanding and control in injection molding*. in *CAE and Intelligent Processing of Polymeric Materials*. 1997. Dallas, TX: ASME International Mechanical Engineering Congress and Exposition.
81. Kazmer, D., L. Zhu, and D. Hatch. *Investigation of variation and uncertainty in Six Sigma*. in *ASME Design Engineering Technical Conferences, Design for Manufacturing Conference*. 2002. Montreal, Quebec.
82. Box, G.E.P. and K.B. Wilson, *On the Experimental Attainment of Optimum Conditions.* Journal of the Royal Statistical Society, Series B, 1951(13): p. 1-45.
83. Myers, R.H. and D.C. Montgomery, *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, in *Wiley Series in Probability and Statistics*. 1995, Wiley Interscience. p. 248.
84. Hatch, D. and D.O. Kazmer:, *Process Transfer Function Development for Optical Media Manufacturing.* Int J Adv Manuf Technol, 2001. **18**(5): p. 357-365.
85. Cacoullos, T., *On Upper and Lower Bounds for the Variance of a Function of a Random Variable.* Annals of Probability, Vol. 10, No. 3. (Aug., 1982), pp. 799-809., 1982. **10**(3): p. 799-809.
86. Fan, J.Y. *Achieving 6 Sigma in design*. in *Annual Quality Congress Transactions*. 1990. San Francisco, Ca, USA.
87. Suh, N.P., et al. *Manufacturing Axioms and their corollaries*. in *The SME Seventh North American Metalworking Research Conference*. 1979.
88. Kazmer, D. and D. Hatch, *Towards controllability of injection molding.* Journal of Materials Processings & Manufacturing Science, 2000. **8**(2): p. 127-140.