CONTROL OF POLYMER PROCESSING

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1 INTRODUCTION

Process control has been recognized as an important means of improving the performance and consistency of thermoplastic parts. However, no single control strategy or system design has been universally accepted, and the manufacturing systems continue to produce defective components during production. This chapter provides an overview of modeling, measurement, and control strategies in polymer processing, and discusses some of the difficulties posed by their complex and distributed nature.

Most plastic parts are fabricated by thermoforming, extrusion, or injection molding. In thermoforming and its variants (vacuum forming, blow molding, male forming, drape forming, plug-assist forming, etc.) a continuous sheet of material is first heated until it becomes pliable (elastic modulus of approximately 0.5 Mpa), and then it is expanded at strain rates of approximately 100% per second to assume the shape of an evacuated mold. The hot sheet is then cooled by conduction of heat to the mold, which itself is cooled with conditioned recirculated water. The resulting part typically exhibits thickness distributions from 10% to 90% of the initial sheet thickness, with mold cycle times varying from fifteen seconds to five minutes per part.

Unlike thermoforming, which is a cyclic process, extrusion is a continuous and steady state process. In extrusion, solid thermoplastic pellets are fed into a rotating screw to be compacted into a tightly packed solid bed. The thermal energy for melting comes from the mechanical power of the motor that is consumed to rotate the screw. The tapered flight on the screw geometry is designed to match the rate of dissipative melting to present minimum flow restriction and smooth flow. The resulting homogeneous melt is then forced at constant rate through a complex profile die designed such that the material exits the die at uniform temperature and velocity. The continuous extruded part is fed through a series of cooling molds to maintain and set the part geometry, after which sections are cut to length while the extrusion process continues. Extrusion rates of approximately twenty feet per minute are typical. While the majority of extruded parts are simple round or square tubing, the process is capable of producing intricate profiles such as window casings and structural members.

Injection molding consists of several stages: plastication, injection, packing, cooling, and ejection. It is the most complex of the above processes, and capable of producing very complex components to tight specifications. 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-varying 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. In this chapter, we focus on modeling and control strategies applied to injection molding, in order to present a general overview of issues involved in control of polymer processing.

2 PROCESS DESCRIPTION

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 molded part measures of 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.

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 control 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.

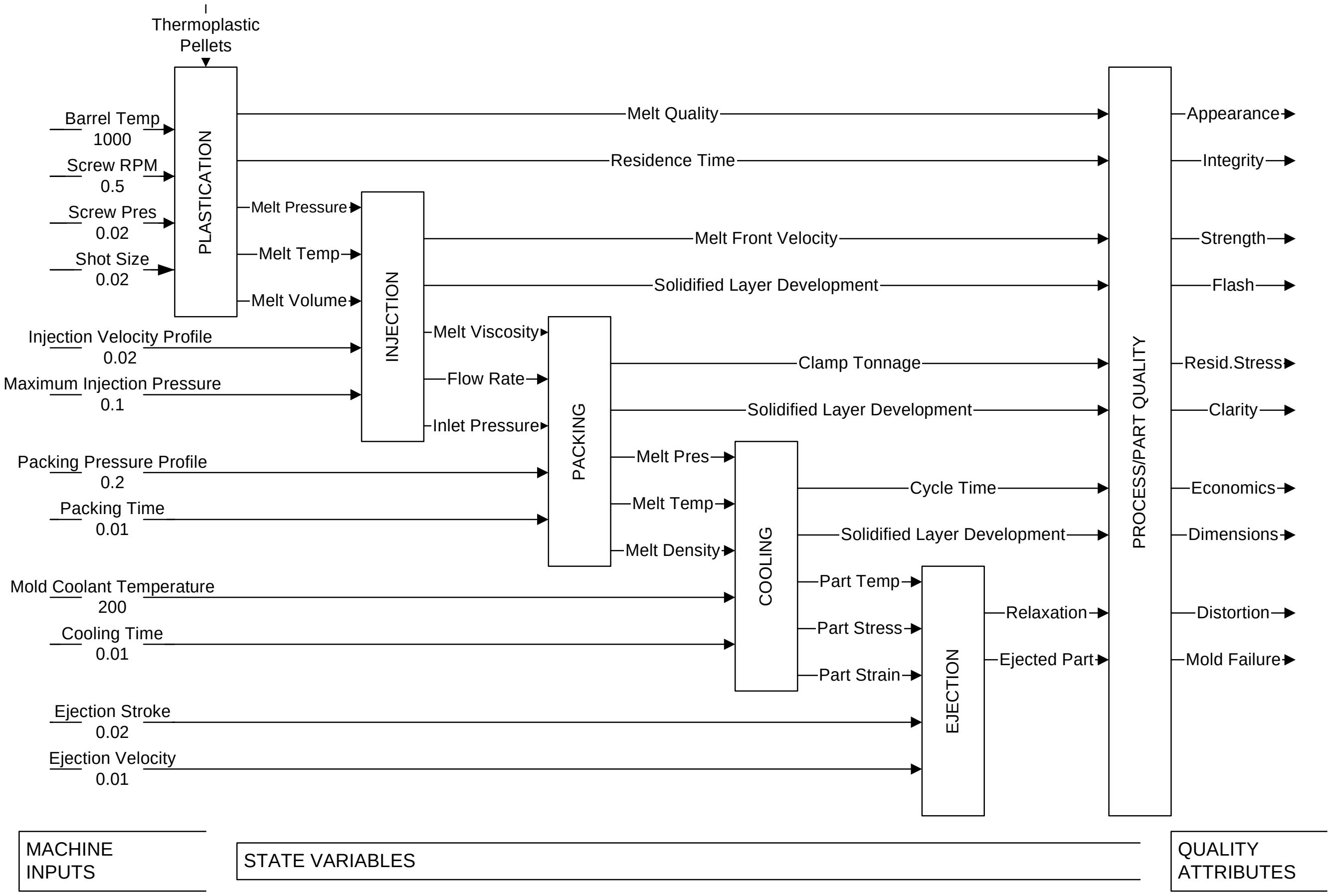

Figure 1: System's view of the injection molding process

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 generation 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 and velocities 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 would result in uncontrolled melt viscosity, solidified layer distribution, and temperature/pressure contours (see Figure 2).

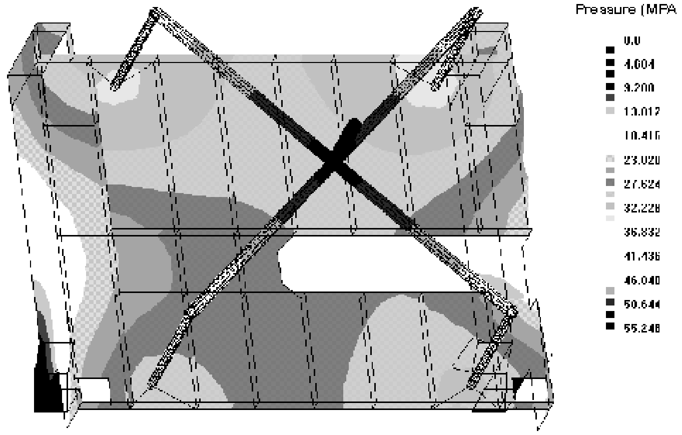

Figure 2: Pressure distribution of a typical molding at the end of the injection stage

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 predominates the molding cycle, 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.

3 PROCESS VARIABILITY

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 [2]. 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 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 [3] has characterized and described a machine evaluation methodology that quantifies the process consistency of any molding machine. The plastics industry is rapidly adopting this methodology, which categorizes machines into capability classes from 1 to 9 with pre-defined variances as shown in Table 1.

Table 1: Magnitude of process variation by machine input

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	0.09
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’ [4] 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.

4 MODELING

As previously discussed, the primary barrier to control of injection molding stems from the distributed nature of the polymeric material. This demands models that can represent the state of the material both spatially and temporally. For example, state variables such as the melt velocity, melt pressure, and melt temperature are not only functions of time but are inhomogeneous both through the thickness and across the mold.

Fundamental research of the injection molding process began with Spencer’s empirical investigation of melt flow advancement [5]. Harry and Parrott later utilized a finite difference form of the heat equation to predict the melt flow advancement along a long, narrow strip for a specific material and injection pressure [6]. Williams and Lord [7] advanced the simulation of the injection molding process by discretizing both the length and thickness dimension to track the melt front propagation while simultaneously performing heat transfer calculations. This was the first analysis to consider the dynamic build-up of a solidified skin layer as well as the polymer’s complex non-Newtonian (shear dependent) rheological behavior. Based on these analyses, sophisticated simulations were soon introduced for use in part design and process troubleshooting [8]. More advanced numerical schemes based on hybrid finite element/finite difference method were then introduced to simulate melt propagation in arbitrarily complex three-dimensional geometries [9, 10], such as those presented in Figure 2. Continuing research seeks to predict the residual stresses [11-13], fiber orientation [14, 15], and other properties of the final molded product [11, 16, 17]. These simulation softwares are now standard tools in the design of thermoplastic parts, as well as verification of various control strategies.

The modeling advances in injection molding, however, have not yet significantly impacted control of these processes. 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 [18-20], 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, 22]. In such cases, the state of the material at only a point within the mold is modeled and controlled. Another approach used for representing the melt behavior is neural network modeling [54, 55], where the distributed nature of the melt can be represented by multi-input multi-output patterns.

5 PROCESS CONTROL

A fundamental difficulty in control of injection molding is that none 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 or structural integrity prior to opening of the mold and ejection of the part. Therefore, part quality is satisfied through a combination of on-line state variable control (through continuous control of the melt state) and off-line cycle-to-cycle adjustment of the machine set points. These two modes of control give injection molding the characteristic of both a continuous and discrete process.

An overview of injection molding control is shown in Figure 3. At the innermost level, only the machine actuators are regulated. This level of control will ensure proper execution of the programmed machine inputs (see 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.

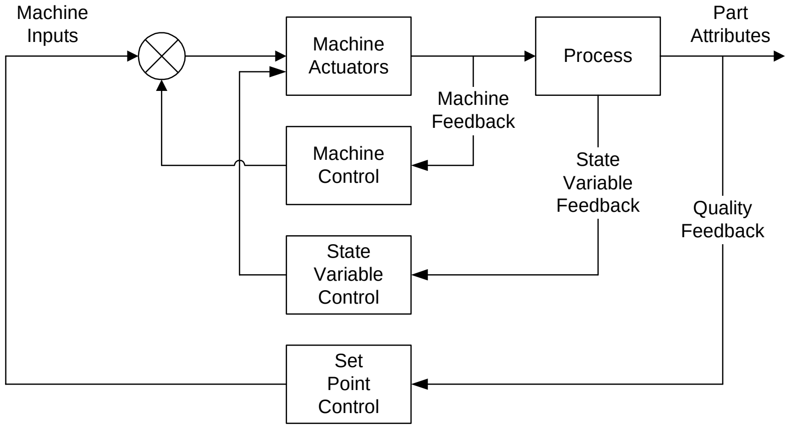

Figure 3: System diagram of injection molding control

The logic behind the control strategy in Figure 3 can be explained by an example. Consider specification of packing pressure profile as a machine input for control of the part width in Figure 2. In this case, the machine actuator will be the hydraulic servovalve 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 shown 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 input to 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 may still not lead to a satisfactory molded part because of a poorly-specified cavity pressure. Set point control is incorporated to adjust the specified cavity pressure. Each of these control levels will be discussed next.

5.1 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 servovalve spool position was set so as to provide a specified screw velocity and pressure profile. Since the advent of programmable logic control, the majority of machine input variables have become individually controlled via 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 control.

The first modern computer-controlled injection molding machine was described by Carl Ma in 1974 while employed at Cincinnati Milacron [23]. 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 [24]. In theory, machine control algorithms are simple enough to enable the molder to properly tune them. 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 would increase the resistance to flow and would increase the load on the screw, as would a decrease in melt temperature. Each of these cases would require a different set of controller parameters. In an effort to improve 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 [25], or 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 [22].

5.2 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 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 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]. 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.

5.3 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.

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 [41-44]. 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 large job operations is to develop an empirical model based on data obtained from a set of designed experiments [45]. 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 [46-48], 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 [49]. 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 [50]. 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 [51]. 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 4. 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.

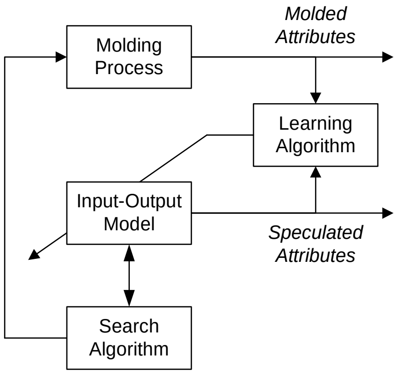

Figure 4: Diagram of the Virtual Search Method of tuning

6 CONCLUSIONS

The polymer processing industry utilizes sophisticated control algorithms for machine control. However, two significant barriers prevent 100% quality assurance and true cost minimization. First, the relationships between the machine input variables and final quality attributes are not precisely known. Second, these processes are largely over-constrained, such that improvement in one part quality attribute is not feasible without reducing other quality attributes or increasing cost. In theory, more accurate process simulations could eliminate the need for costly molding trials and mold tooling iterations. In reality, even the most advanced analyses remain incapable of representing the process accurately given the uncertainty of material properties and variability of the process.

Several development issues need to be addressed towards meaningful control of polymer processing. First, more comprehensive models need to be developed that can provide accurate estimate of part quality attributes for various sets of machine inputs, material properties, and mold configuration. Second, robust and miniaturized sensors should be developed to provide feedback about the state of the melt inside the mold. Third, advanced actuators need to be developed that can provide the multi-degree of freedom required for control of the melt in a distributed manner. The ultimate aim is a machine that will produce no scrap material at increased production rates, and will require less labor skill, less energy, and minimal maintenance.

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