GAINING CONTROL OF PLASTICS FORMING MACHINES WITH NEW TECHNOLOGY FOR ON-LINE ADJUSTMENTS

by:

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ABSTRACT

Exceptional cost savings and quality improvements are being obtained from existing plastics forming machines by implementing a new management technique for adjusting set points and control inputs, i.e., through more effective supervisory control.

Personal experience and tests such as Design of Experiments (DOE) are traditionally used to adjust these machines. Computer simulation software can also give some insights. The new technology is called "Sequential Process Optimization" (SPO), and it is much more thorough in satisfying customer, business, and technical needs. SPO is faster, less expensive, simpler and more adaptable than DOE or simulation; and more quantitative, disciplined and permanent than personal experience.

Practical methods to apply SPO to plastic forming production include streamlined approaches for people to focus on the critical items for each part/machine. This results in management, operators and the technology having a common understanding of the needs and of the potentials being harnessed. SPO is used to both control and improve measurable aspects of performance such as all quality attributes, cycle times, scrap/rework rate, costs, and safety. The software sequentially uses actual operating data, develops and updates models based on this data, and recommends better settings on a run-by-run basis to achieve maximum overall results, and maintain them as various conditions change. It quickly adapts to changes in materials, environment and customer specifications.

Examples of actual applications in the plastic molding industry are included.

BACKGROUND

It is extremely difficult to truly optimize the adjustments of plastic forming machines to maximize production performance because the relationships between the inputs and the outputs are too many, too complex, and usually not constant. Let us review some traditional methods:

- *Computer simulation models*: They are based on knowledge of first principles, and are useful for the design and redesign of processes. However, they take a long preparation time and are too inaccurate for practical on-line optimization of adjustments.
- *Design of Experiments (DOE)*, the best including *Response Surface Methodology (RSM)*: An excellent reference is Box & Draper (1987)[1]. The virtue of DOE/RSM is that it deals with the process as it actually is, not as limited by theoretical knowledge. On the other hand, it requires performance to be measured with sufficient accuracy to distinguish important differences. The problems with DOE/RSM are: it is lengthy and expensive, it requires statistical expertise, and it is often not suitable

for periodic readjustments to reflect changing requirements and conditions. A re-application of DOE/RSM after the machine is in operation is particularly expensive as it typically requires production stoppage because otherwise there is a high risk of making off-spec production with significant loses. A comparison between DOE and SPO is given in Moreno (1993)[2].

- *Evolutionary Operations*: The limitations of DOE/RSM were well recognized in the 1960's, when early streamlined extensions to DOE solutions were published (without RMS), such as EVOP (Box & Draper, 1969[3]) and SIMPLEX (Spendley et al, 1962[4]; Adelman & Stevens, 1972[5]; Walters et al, 1991[6]). While they were a step forward, they are still too disruptive to be used on-line, and very inefficient when there is significant unexplained variability in results, as it is typical in production. SPO was still placed in this family of solutions as of 1987 (Nachtsheim, 1987[7]).
- *Personal Experience:* Due to the cost and inefficiency of the above methods, today many processes are still being adjusted and tweaked based on people's knowledge and experience. These procedures tend to be very fast, but frequently yield grossly sub-optimal adjustments, and result in instability of the process when run in significantly different ways by different crews, and in performance being affected negatively by people turnover.

"Sequential Process Optimization" (SPO) has been developed to enable easy and cost-effective process adjustments, and to eliminate many of the negatives of the older methods. *Significant bottom-line improvements are typically obtained within one or two weeks of applying this method to manage adjustments in production processes.*

The next section describes the key features of SPO and their advantages.

SPO CONCEPTS AND FEATURES

These are some of the major concepts and features of Machine Adjustments through Sequential Process Optimization (SPO).

- **Sequential on-line adjustments:** A process run consists of making a set of adjustments, making, e.g., an hour's production such as several injection cycles, and collecting performance data. Every time data from a process run is available (to the computer), there is a new analysis with all the accumulated data to generate Advice on how to readjust all the control inputs for the next run (which in turn will produce additional run data, etc.). These two steps put together is an "Adjustment or SPO cycle", which takes place on-line, during normal production. This sequence of adjustments moves the inputs from the current settings to near-optimal ones, and maintain them as conditions and objectives change.
- **User Control /Automatic SPO:** Users are not required to follow the new adjustment advice, the user is in full control until he/she validates the application and is ready to yield control to SPO.

  Adjustment cycles can be stopped at any time -- after which the machine can continue to be run while taking advantage of the gains achieved so far. Later on, you can continue exactly where you left off.

  In a closed-loop installation of SPO the user can yield -- and take away -- control to automatic SPO. Alarms will indicate unusual events so that the automatic control can ring the alarms or stop automatic control altogether.

- **SPC Detection:** SPO indicates when the results obtained do not match expected results for the new adjustments (regression SPC). Regular SPC can also be used within each run (outside SPO) for a finer detection of special causes.
- **Multiple inputs, multiple outputs:** SPO deals with multiple inputs (some adjusted, some uncontrolled) affecting multiple outputs (some directly measured, some calculated with internal equations written by the user). See generic arrows in Figure 1, and specific plastic molding examples at the end of the article. Control inputs include directly adjusted variables, setpoints, and control parameters (such as gains for first-level controllers). Outputs may be single measurements; summaries of various measurements such as percent defective, averages and standard deviations; or calculations based on the values of other variables. Outputs may be scales of subjective quality measures.
- **Multiple objectives:** Process performance is evaluated quantitatively based on the values of the input and output variables. The objectives may relate to a variety of quality measures (weights, sinks, dimensions, flack, etc.), cycles times, economic evaluations, safety, etc.

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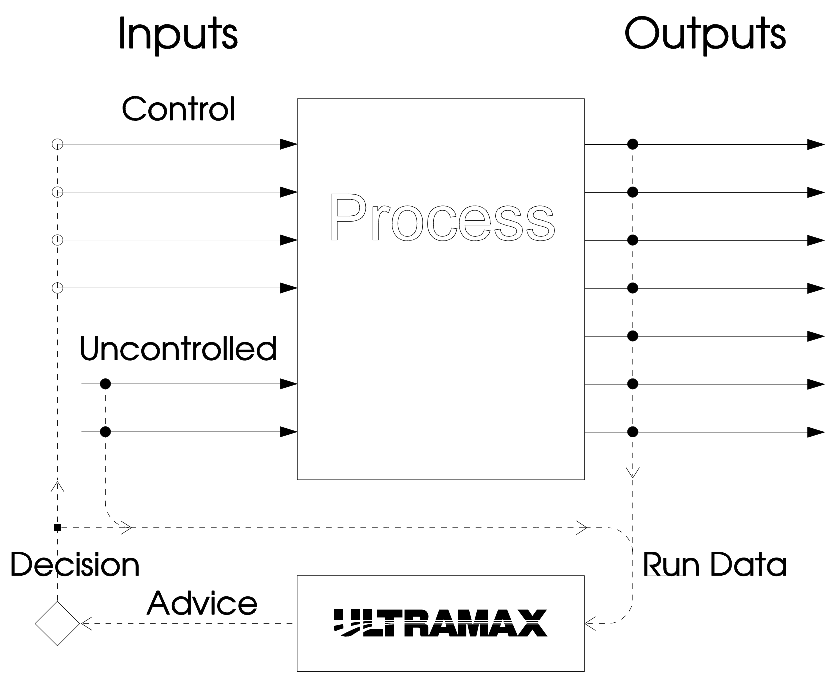

Figure 1: The ULTRAMAX Decision Input/Output Diagram. The specific variables are defined by the users in the "Problem Formulation" stage.

Two frequent types of calculations are:

1. representation of consistency vs. tolerances, such as CPK and Loss Functions, to control the incidence of individual measurements violating specifications; and
2. economic equations such as material and burden costs.

Basically, any aspect of performance that can be measured with sufficient accuracy and on a timely basis (to learn from it), can be taken into account for doing SPO.

Overall goals are represented by:

- an "objective function", an output to be maximized or minimized (which can be a directly measured value, or a function of other variables),
- necessary constraints on inputs and outputs.

The operating "adjustment window" can include the criterion of being far from constraints, to make the machine settings more insensitive to possible perturbations.

Objectives can change at any time, and the technology can take advantage of old physical data, where new evaluations are implemented through the new calculations and constraints.

- **Processes with noise:** SPO needs to deal effectively with machine outputs which have some "noise". Noise is the level of output measurement variations when inputs remain constant, as may be obtained from several replicates. Typical sources of noise are:

  1. variations in unknown inputs,
  2. variations in known uncontrolled inputs during the run,
  3. variability in the process (both common and special causes, e.g., due to the performance level of first level control devices),
  4. inconsistent implementation of procedures,
  5. errors in measurement, and
  6. using invalid data.

  Note that in SPO there is no such a thing as variations in control inputs during the run, because they are defined and selected as those inputs which change only when the user decides to change them. For instance, in the case of input "zone 1 temperature", the decision or control input is the value of the setpoint (the target value) for the controller, not the actual physical nozzle temperature after the effects of the controller. This requirement, which can always be met, lends simplicity and effectiveness to the supervisory control method.

  The effectiveness of SPO degrades with excessive noise. Roughly speaking, SPO needs that the noise level be less than the potential improvements. Frequent ways to reduce noise are: recognize an input which changes from run to run, install better controllers and/or better measurement methods, have more repetitive procedures.

- **No prior run data, no prior models:** SPO does not require that the user provide process run data to get started, neither from normal operating data nor from DOE tests. SPO does not require that the user provide mathematical / computer models of the behavior of the process. These are critical reasons why SPO can produce improved results in a few days and at low cost. However, if any such valid prior data or valid models already exist, SPO can take advantage of them to learn even faster how to adjust the machine inputs.

- **Feed-forward adjustments:** SPO can determine optimal adjustments for known values of uncontrolled inputs (e.g., % regrind, cooling water temperature, etc.). This is feed-forward adjustments, based on past learning, without waiting for the machine to significantly sacrifice objectives before corrective action takes place, such as in feedback control.
- **Feed-back adjustments:** SPO can do feed-back optimization adapting to slow changes in unknown factors, such as wear and tear.

SPO Advantages

The net advantages of a process adjustment technology with the above attributes are:

1. Adjustment optimization can be started as soon as important objectives are defined and the ability to measure is determined
2. Optimization can be maintained as changing conditions and requirements take place.
3. The organization quickly achieves positive control of the process. It is a substitute for "tweaking", thus providing consistency from shift to shift and with people turnover.
4. Due to being restricted to gradual variables, and that model creation and interpretation is fully automated, only awareness of basic SPC statistical concepts are necessary.
5. Due to the tools available to define multiple objectives, management has a direct way to manage production in a consistently balanced and dynamically profit-oriented fashion.
6. Due to the procedures to define the problem and the way performance is measured and documented, this is an excellent training mechanism for new people and new teams.

A technological implementation of SPO together with a streamlined methodology to implement it on the production floor for Process Optimization is ULTRAMAX , a product developed by Ultramax Corporation in Cincinnati, Ohio, USA. The particular technology developed for this SPO has been described by Moreno (1986)[8], Moreno & Yunker (1992)[9] and Hurwitz (1993, describing the Bayesian statistical methods used)[10]. It overlaps areas of Artificial Intelligence (see Moreno & Yunker, 1993[11]). The numerical analysis is embodied in a rather complex and well time-tested software, whose analyses operate largely behind the scenes, unless the users wish to look into it.

THE ULTRAMAX METHOD

The implementation of SPO implies a slight cultural change, an enhanced philosophy of profit achievement by moving from largely reactive to proactive management and control, moving from the normally accepted "as is" to the innovative "could be". This is the fundamental objective of the ULTRAMAX Method to implement SPO, which consists of three basic stages.

1. Problem Formulation
2. Sequential Adjustment Cycles (the SPO proper)
3. Engineering Analysis

as described in more detail below:

1. Problem Formulation

In this stage the team spends two to four hours performing the following procedures. One of the outcomes of this stage is to have a clear picture of the specifics in the Decision Input/Output diagram in Figure 1, with sketches illustrated in the Examples at the end of the article:

- Describe the objectives for the production system in terms of business needs, including how process/product performance will be measured. This might include any mixture of input/output measures, e.g., related to cycle times, quality levels (including consistency), costs/profits, safety, etc. Overall goals are defined in terms of some measure or calculation to be maximized or minimized, plus constraints on inputs and/or outputs. Define the Minimum Important Difference for those variables as it relates to the business objectives, to properly sensitize the statistical analysis, to recognize important opportunities and ignore unimportant issues.

- Identify which inputs (controlled and uncontrolled) would affect achieving objectives. Select which control inputs will be adjusted and their current adjustment ranges, and the uncontrolled inputs to be taken into account and their expected ranges. Barring a predicament, the other control inputs must remain fixed (constant). The other uncontrolled inputs will be taken as a source of noise (unexplained variations in outputs).

The above gives the goals and the scope of process adjustments, and together, the new discipline for performance optimization.

2. Sequential Adjustment Cycles

In this stage a couple of team members spend about 20% of their time from typically three days to three weeks to:

- First, make several runs of the machine at the constant, current values of the inputs (***replicates***) to determine the baseline to evaluate improvements, and the noise level to determine if the machine is sufficiently stable to proceed with SPO. If not sufficiently stable, then the situation should be resolved, for instance, by recognizing the existence of an input which is not constant, or by fixing an improperly operating first-level control device or some measurement method.
- Then, run SPO adjustment cycles (typically with runs one to two hours long), consisting of:

a. Re-adjust the control parameters or inputs for the next production run.

b. Run the machine, make product, let the process stabilize, and then gather representative data from parts and the process for the rest of the production run. Calculate summaries: the run data to evaluate performance.

c. Enter the run data into the computer. The computer program will:

- report on how well constraints were satisfied and whether the machine was under control with the last adjustments,
- update the internal prediction models with the new data and indicate how suitable they are for SPO (whether the noise level is acceptable),
- using the updated models generate new advice for the next cycle, together with expected results, the accuracy of the predictions, and how well constraints will be satisfied.
- provide status reports indicating past progress and how close to optimal the process is, and what extra steps to take (if any).

The sequential adjustment cycle is illustrated by the information flow in the dotted lines of Figure 1.

As production proceeds under the discipline of SPO, the team will sharpen their awareness of a variety of issues, such as satisfaction of constraints, levels and sources of noise, completeness of goals, irrelevant and obsolete considerations. This is part of what is called "discovery".

Production during the first twenty to fifty adjustment cycles bring the machine from the beginning adjustments and results to the near-optimal ones.

Thereafter, the adjustment cycles are continued as frequently as necessary to ***compensate*** for known changes in requirements (such as changes in targets, tolerances, costs) and in uncontrolled inputs (such as material characteristics, operating conditions), and to ***adapt*** to changes in the machine behavior (such as wear-and-tear, buildup of materials, etc.).

Note: *Compensation* is achieved through feed-forward analysis, based on past learning. *Adaptation* is done through feed-back.

3. Engineering Analysis

After the production system reaches maximum results performance through adjustments of control inputs, Engineering Analysis leads to understanding the behavior of the system and to evaluate the effects of certain desirable changes:

- ***Sensitivity to changes in the inputs***. This analysis helps understand the nature of the behavior of the system for engineering insights. For instance, it enables one to determine the robustness of the solution (how accurately the inputs need to be set), and the requirements for first-level control devices. Also, it may help discover a principle whose effects is much greater (or lower) than expected from prior experience, which may lead to better machine re-engineering in the future.
- ***Sensitivity to the parameters in the Problem Formulation***, such as the values of the imposed constraints, the values of tolerance requirements, costs factors, etc. For instance, the sensitivity of a fill speed constraint may indicate significant increases in machine performance by enabling higher speeds, if it can be done at a reasonable re-engineering cost. Similarly, one may discover opportunities for further process performance improvements through eliminating old obsolete constraints, re-negotiating targets and tolerances, controlling currently uncontrolled inputs, etc.

SUMMARY

The ***ULTRAMAX Method*** for maximizing process performance consists of the following stages:

1. Do ***Problem Formulation*** to define goals and the scope of the machine adjustments. This relates machine adjustments to accounting, quality control, process control, and production planning.
2. Do **SPO** to achieve Results Maximization by doing sequential adjustment of the inputs.
3. Do ***Engineering Analysis*** to understand bottlenecks, identify efficient re-engineering projects and consider changes in business parameters to further expand the profitability contribution of the process. This relates machine adjustments with engineering, product development, quality control, purchasing and marketing.
4. ***Discovery****:* In addition, due to the sharper awareness of issues and the proactive attitude instilled by this method, people will be more prone to ***discover*** important issues as it relates to the definition of performance, the operations of the process, and the nature of the process/product. With this raised awareness the team will be able to redirect any of the three stages above for even greater overall performance.

Performing these proactive actions enables you to gain control of plastics forming machines, and drives the people and the process to continuous improvements and maximum overall performance and profitability.

EXAMPLES

At the end of this article there are six one-page summaries of applications ULTRAMAX's SPO on a variety of plastic forming production equipment. Other background material is found in Redlinger (1993)[13].

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This paper draws elements from Documentation and Training within Ultramax Corporation, and shares material with Moreno 1993[12], Moreno & Yunker 1993[11], and Moreno 1993[2].

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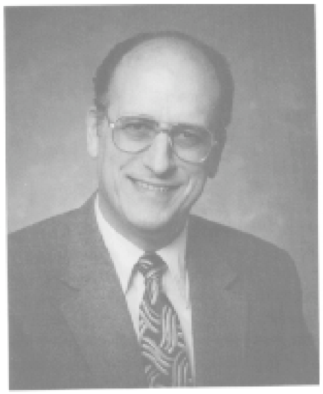
BIOGRAPHY



Dr. Carlos W. Moreno is Founder and Chairman of Ultramax Corporation in Cincinnati, Ohio. Since 1982 Ultramax Corporation has been providing industry with the most effective technology for adjusting the inputs to production processes to maximize their quality, productivity, safety and cost performance.

Prior to Ultramax, for fourteen years, Carlos was a corporate internal consultant at the Procter & Gamble Company in the areas of Decision Making Processes in production and development.

He has taught graduate courses at Bradley University, Xavier University, and the University of Cincinnati, mostly in the areas of operations research and quality control.

He holds a Ph.D. in Industrial Engineering from Purdue University, a MS. in Mechanical Engineering from the California Institute of Technology, and a BS. in Engineering Science from the Case Institute of Technology.

ULTRAMAX APPLICATION PROFILE

INDUSTRY: **PLASTICS**

PROCESS: **INJECTION MOLDING - LARGE PARTS**

DESCRIPTION OF PROCESS:

The operation set up in the machine makers test facility used a very large twin screw injection molding machine equipped with a flash gate mold for making auto fenders. Quality was a combination of visual defects and dimensional requirements.

PURPOSE OF APPLICATION:

The development of a production method for a new material to replace an existing steel part containing many variables but a specific goal, that of production quality parts at a reasonable rate.

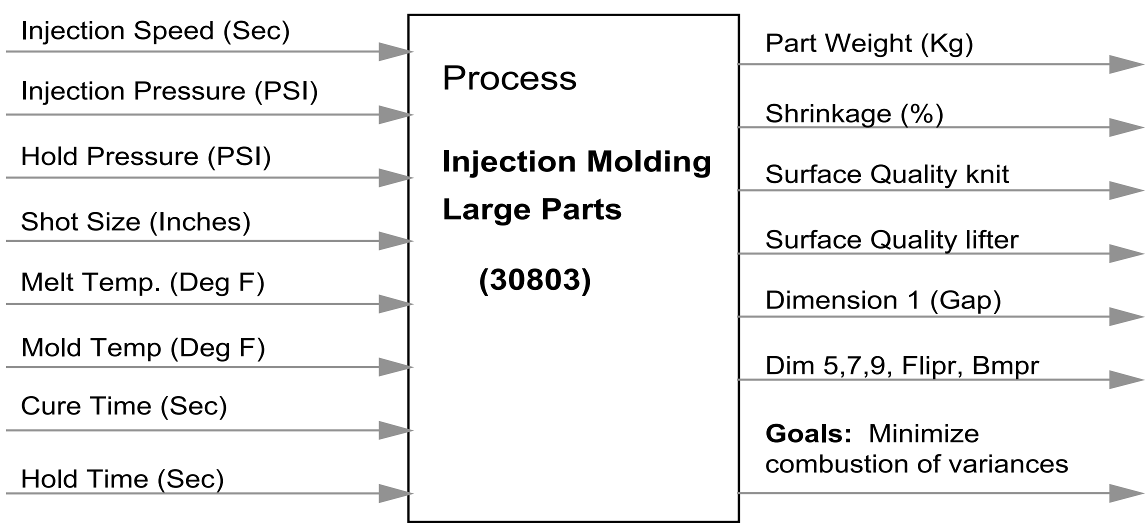
APPLICATION GOAL:

Minimize deviation from target dimensions at maximum quality index.

RESULTS SUMMARY:

Superior production quality parts were produced in short order allowing the level runs to begin based on the developed operating procedure. An interesting point was the data base and models were further investigated for each of the gap test points for optimal control settings and it was discovered that the top corner and pillar required 3 times the “hold time” of the optimal overall part. This prompted the mold makers to open the flash gate at these points to cause greater plastic flow to these areas.

DECISION DIAGRAM



CYCLE TIME:

RUN TIME: 1 hour
ANALYSIS TIME: 2 hours
SPECIAL CONDITIONS: Staggered experiments to cover analysis time.

APPLICATION TEAM MEMBERS (TITLES):

Customer Product Engineer
Plastics Manufacturer Technical Rep.
Molding Machine Maker

ULTRAMAX APPLICATION PROFILE

INDUSTRY: **PLASTICS**

PROCESS: **INJECTION MOLDING - SMALL & MULTIPLE PARTS**

DESCRIPTION OF PROCESS:

A 64 cavity injection molding machine capable of making nearly 25,000 parts per hour is evaluated for visual and dimensional qualities every four hours. If the samples taken do not meet the stated criteria, all parts for the last period are lost. Therefore the objective is to maintain all specifications while increasing production based on the number of available cavities.

PURPOSE OF APPLICATION:

To improve production rate of quality parts from each molding machine in a high volume environment.

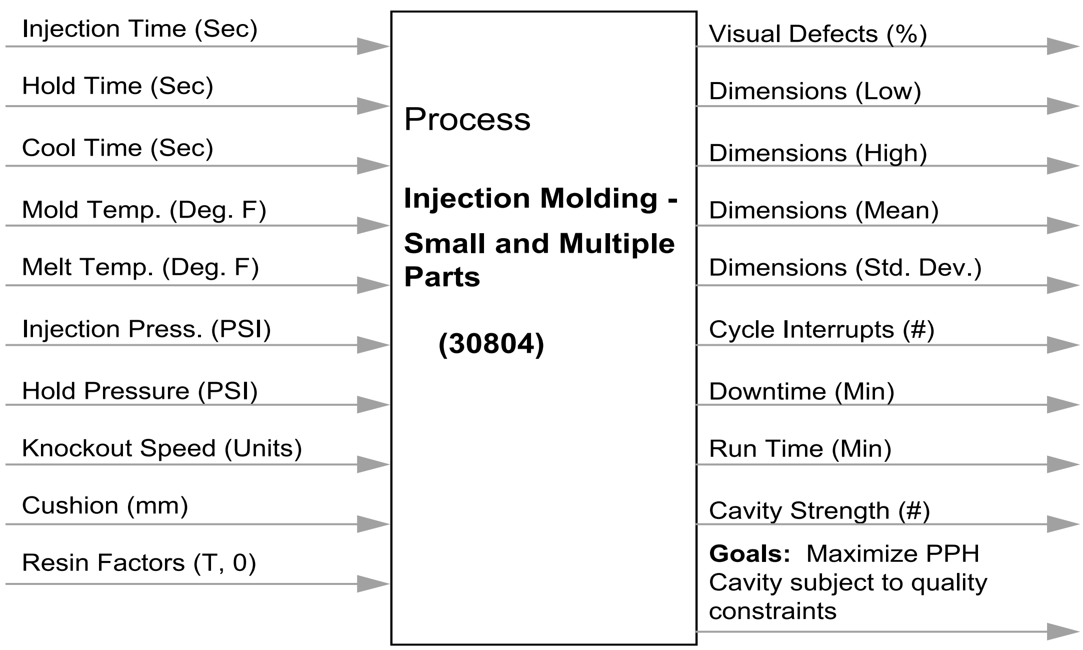
APPLICATION GOAL:

Maximize productivity.

RESULTS SUMMARY:

After an extended period of one experiment per day, production leveled at 10 to 15% higher with nearly zero recycled lots.

DECISION DIAGRAM



CYCLE TIME:

RUN TIME: 4 hour
ANALYSIS TIME: 2-4 hours

APPLICATION TEAM MEMBERS (TITLES):

Process Engineer
Maintenance Engineer and Operator
Q.C. Supervisor

ULTRAMAX APPLICATION PROFILE

INDUSTRY: **PLASTICS - AUTOMOTIVE**

PROCESS: **SMC MOLDING**

DESCRIPTION OF PROCESS:

Compression Molding of SMC materials for one piece truck fenders.

PURPOSE OF APPLICATION:

Implement methodology on an established process and improve productivity.

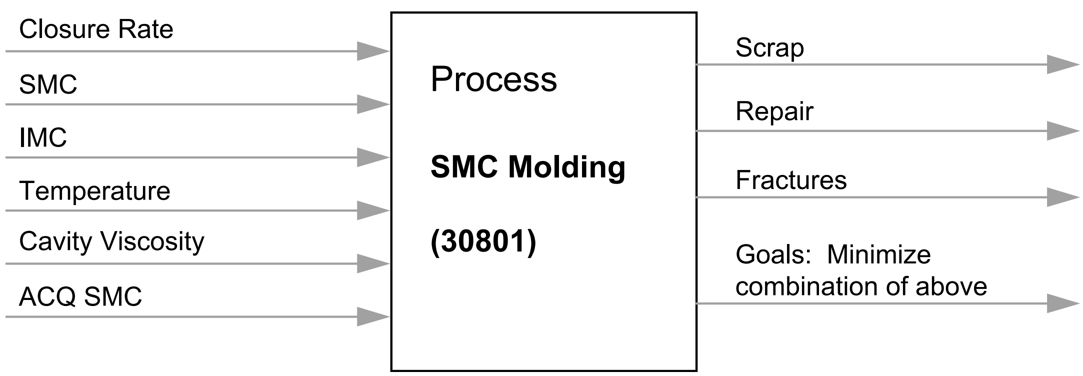
APPLICATION GOAL:

To improve surface quality and reduce scrap and defect occurrences.

RESULTS SUMMARY:

Internal scrap rate was reduced 57% and surface quality improved 412% for an annualized savings of greater than $2.4 million.

DECISION DIAGRAM



CYCLE TIME:

RUN TIME: 1 hour
ANALYSIS TIME: 15 minutes

APPLICATION TEAM MEMBERS (TITLES):

QC Engineer
Process Engineer
Supervisor
Operator

ULTRAMAX APPLICATION PROFILE

INDUSTRY: **PLASTICS**

PROCESS: **BLOW MOLDING OF BOTTLES**

DESCRIPTION OF PROCESS:

This operation has an extended set up time and has a wide specification range for part weight that allows for cost reduction if the spec can be met on the low side of the range, especially at a rate of 90,000 parts/day.

PURPOSE OF APPLICATION:

Improve overall operating efficiencies for both setup and extended runs in a job shop environment where multiple molds and multiple machines are used.

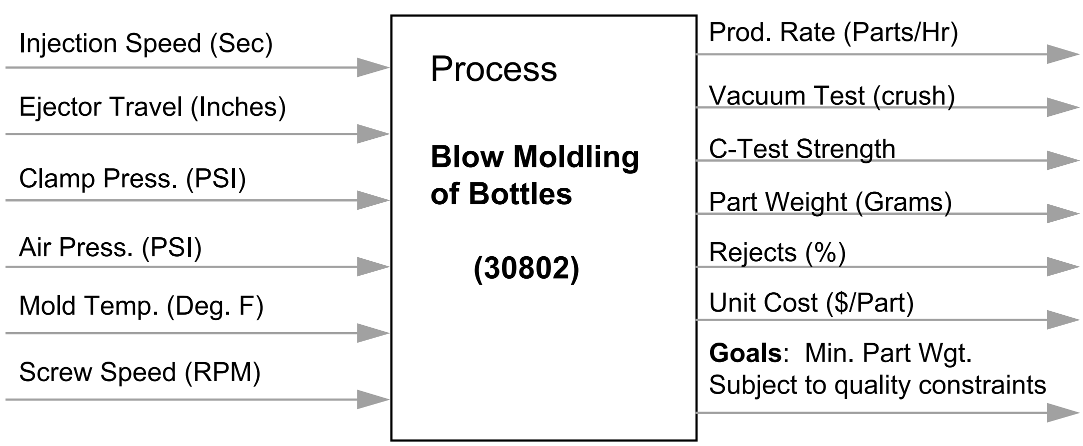
APPLICATION GOAL:

Part weight average reduction to the lower end of the specs, while maintaining quality.

RESULTS SUMMARY:

Results at first were clouded by the fact that operators were not included in the “Problem formulation” stage because they had the ability to counteract PLC settings with manual adjustments. However, once they were included, the part weight achieved a steady 7% (approx. 2 gm.) reduction from previous averages.

DECISION DIAGRAM



CYCLE TIME:

RUN TIME: 1 hour
ANALYSIS TIME: 2 hours

APPLICATION TEAM MEMBERS (TITLES):

Production Supervisor
Production Manager
Q.C. Supervisor

ULTRAMAX APPLICATION PROFILE

INDUSTRY: **PLASTICS - PACKAGING**

PROCESS: **CONTINUOUS PLASTIC EXTRUSION**

DESCRIPTION OF PROCESS:

The operation was a continuous concentric extruder for the manufacture of toothpaste tubes which requires a high degree of GMP, as well as a high regard for appearance to the customer.

PURPOSE OF APPLICATION:

This process was in the start up phase and the requirement was to make zero defect parts while maintaining the needed production level as quickly as possible. The goal was to reduce quality variance to a minimal level.

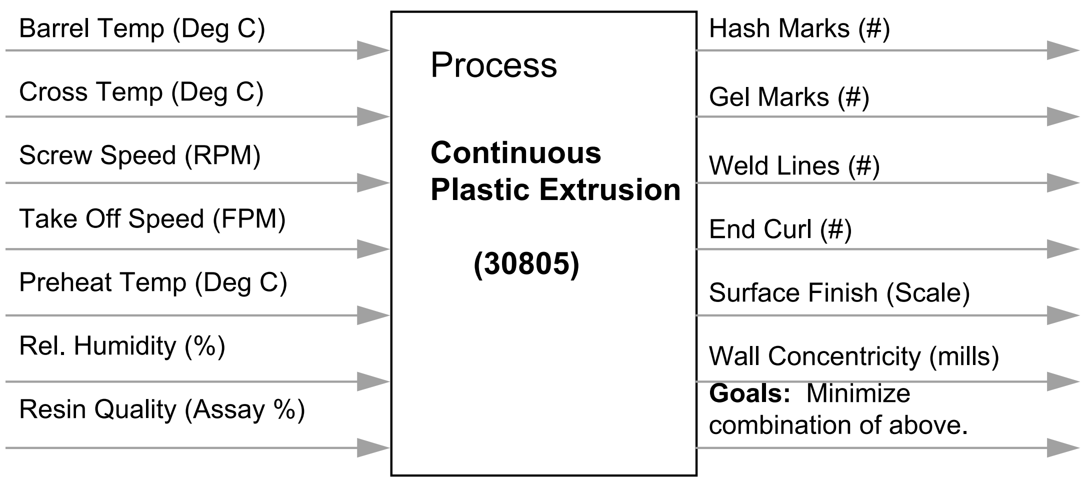
APPLICATION GOAL:

Maximize production with minimum defects.

RESULTS SUMMARY:

Day shift experimentation only was done for one week where production levels were met and surpassed and specification variances were well below desired maximums.

DECISION DIAGRAM



CYCLE TIME:

RUN TIME: 1 hour samples
ANALYSIS TIME: 1 hour

APPLICATION TEAM MEMBERS (TITLES):

Two Process Engineers
Q.C. Supervisor