

Model Based Process Control ensures predictable process operation

This article, based on a paper presented at the 1999 Glass Problems Conference*, shows how process models and model based control systems can be used to push industrial processes closer to their physical limits in order to obtain a better economic result. By Ton Backx, Jobert Ludlage and Anton Koenraads.***

1. Introduction

In the past decade the glass industry, like most process industries, has been confronted with major changes in the marketplace. Competition has increased drastically and environmental legislation has tightened severely. The strong growth in production capacity has exceeded the growth in market demand. This has resulted in a market that is largely customer controlled and that is showing saturation.

One of the major reasons for these changes is globalisation - one of the consequences of the recent developments in the fields of telecommunication, transportation and advanced automation, emerging from the rapid developments in information technology. As a result process industry nowadays is confronted with a strongly competitive market. The market has developed from a supplier driven market to a demand driven market. These changes have far reaching consequences for producers.

In order to prepare for these drastic changes, tight control of the production processes over a broad operating range is needed. Process operation has to enable a completely predictable and reproducible changeover to different operating points that correspond with the processing of different raw materials and semi-manufactured products, production of various product types and different economic objectives (minimise costs, maximise production rate, minimise stock, benefit from fluctuating prices).

2. Model Predictive Control

A Model Predictive Control (MPC) system is an ideal tool for controlling multi-variable processes. Multi-variable processes are processes whose inputs influence more than one process output simultaneously. Characteristic for MPC is that the control strategy can be adjusted for each calculation of the next control action. As a result, MPC is very flexible for changing requirements, such as switching-off or failure of sensors and actuators. Moreover MPC can deal with constraint type of requirements, that is it can keep both manipulated as well as controlled variables in certain predefined ranges. MPC has been developed in response to the industry's need to operate tighter processes within operational and physical constraints and closer to the operating constraints that maximise margins. From its initial development [1, 2] MPC has become a proven technology pushing the controlled process to operating conditions that maximise margins and minimise process variability. In glass manufacturing the benefits mostly stem from tight control of product quality, better efficiency and lower energy consumption.

The success of MPC is for a major part due to the fact that it meets industrial requirements. These requirements can be roughly discerned into three groups.

- Operational requirements - processes have to be operated within a predefined region (safety, environmental load, wear).
- Product quality requirements - products have to be produced to specifications.
- Economic requirements - products must be produced in such a way that margins are maximised, without violating operating constraints.

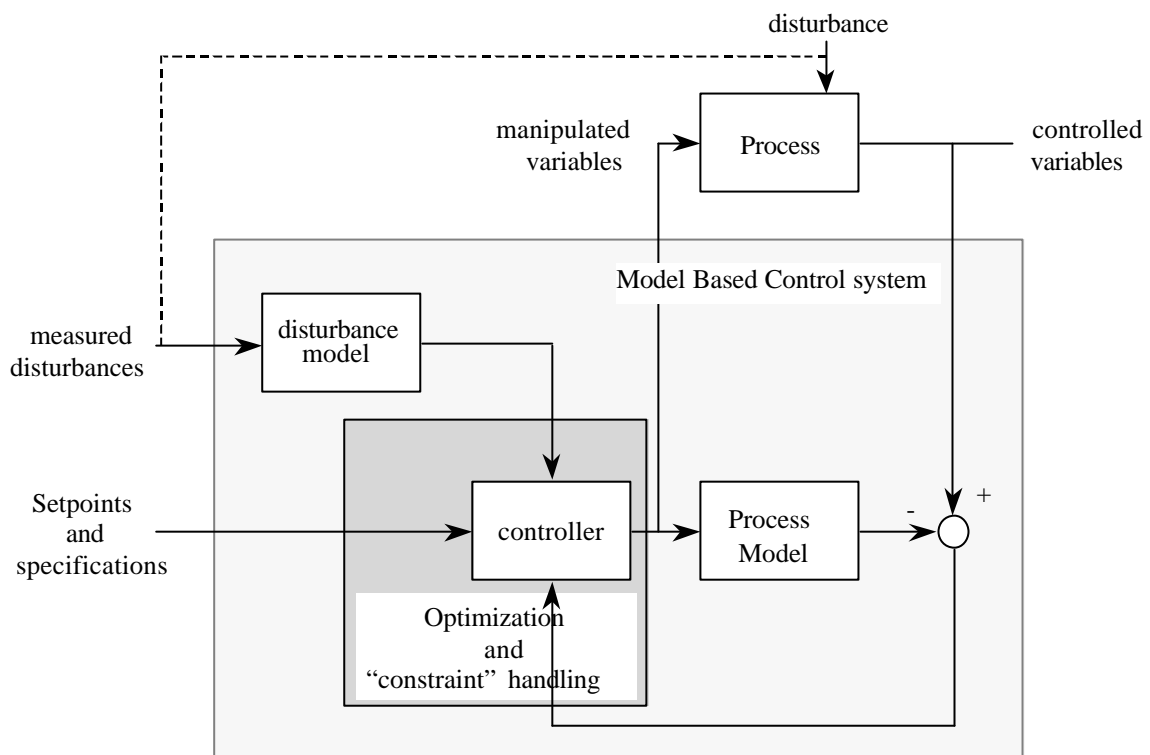


Fig. 1 Schematic representation of a model based process control system

Fig 1 shows a block diagram of an MPC control system. Initially, MPC did not explicitly take constraints into consideration. Refinements of the technology developed at the end of the 1980s allow constraints on both input and output variables to be considered in the control strategy. A recent paper [3] gives a good overview of the MPC technology currently used in industry.

3.1. Basic principle of MPC

The principle of a model predictive control system is to use knowledge of the process transfer characteristics from manipulated process variables and measured process disturbances to controlled process variables to continuously feedforward drive the process to desired operating conditions. The model predictive control system directly anticipates the effects that disturbances have on the process outputs that are controlled as soon as these disturbances are observed. It directly steers the process to new operating conditions at product type changes. A traditional feedback control system like a PID

controller on the contrary first needs to observe the effects of disturbances at the controlled process outputs before it can start counteracting these disturbances. Especially in the case where it takes a while before the effects of disturbances on the controlled process outputs can be measured, significant damage may already have been caused by the disturbances in driving the process away from desired operating conditions before the feedback control system can start taking counteractions. Feedforward driving therefore is advantageous over feedback control as long as it is known how to drive the process to anticipate the effects of disturbances or how to get to desired new operating conditions. Accuracy of the knowledge of the dynamic behavior of the process and of the transfer characteristics of process disturbances to the process outputs determines how well the process can be driven directly to desired conditions.

Two models form the backbone of a model predictive control system to enable this feedforward driving. The first model accurately reflects the relevant dynamic behavior between the manipulated variables of the process and the variables that need to be controlled. The second model describes the dynamic transfer characteristics from measured process disturbances to the controlled variables. These models enable prediction of the future process outputs as a function of the process inputs applied to the process and of the measured disturbances that have entered the process in the (recent) past.

The control cycle starts with measuring the current process output values. The model predictive control system uses the models to predict the future process output responses. The measured values of the process outputs are compared with the predicted values of these process outputs. The differences represent the current disturbances at the process outputs. The output responses predicted by the models are compared with the desired future output responses of the process. The model is now applied again to calculate the future manipulations of the process that minimize the difference between the predicted and the desired process output responses. Of this optimum sequence of process input manipulations only the first input manipulation is applied to the process. After application of this input manipulation the whole sequence of measuring the process output values, predicting future output responses and calculating optimum input manipulations starts all over again. An economic objective function is used for the calculation of the optimum input manipulations. The contents of this objective function may be changed at each sample interval. Changing the objective function is equivalent to changing the control strategy applied for controlling the process.

The calculation of the optimum process manipulations can be done respecting given operating constraints of the process inputs. Also constraints on the process outputs can be specified. These constraints may be both absolute value constraints as well as rate of change constraints. The optimization that has to give the optimum future input manipulations can be specified as a multiobjective optimization. This implies that multiple categories of objectives can be specified with different priorities. The optimizer will try to achieve the objectives specified for each category in subsequent optimization cycles. A solution found for a higher priority category is applied as a constraint in subsequent

optimizations for calculating optimum future process manipulations. Each specified category of objectives may consist out of one or more mutually weighed objectives that are simultaneously chased.

The various categories are applied for specifying different priorities in process operation. The highest priority category is oriented towards safe operation of the process within specified operating constraints. The next categories are focussing on the realization of specified product qualities and imposed processing conditions. Final categories of objectives strive for operation of the controlled process at conditions that maximize margins. The optimizer applied within the model predictive control system tries to achieve as many as possible of the specified objectives. To do so only those variables are actually controlled that need attention. Controlled variables whose predictions of future behavior remain within specifications are not controlled. This way the number of available degrees of freedom in process operation is maximized.

The multi objective optimization automatically implies that freedom in process operation is exploited for maximizing economic performance of the controlled process. Smooth operating conditions with minor disturbances result in highest possible margins as a maximum number of degrees of freedom can be used for maximizing margins and economic performance. If severe disturbances upset the process more freedom in process operation has to be used to remain within specified operating ranges and to achieve product specifications.

The quality improvement of critical product properties that can be obtained with the MPC system is restricted by the quality of the models applied in the controller. The more accurate the models predict process outputs the better the performance of the controller. This is important for problems were quality control, i.e. control of the so-called C_{pk} values, is an important objective (see Fig 2).

Process identification techniques are applied for determination of the models for the MPC system. On-line testing of the process is necessary to get data of the process that reflect relevant process dynamics. These tests may cause a temporary increase of loss of production. The associated high costs related to these losses and to testing currently severely restrict the application field of MPC technology.

Current process identification techniques almost always result in linear dynamic models. Sometimes simple static non-linear functions at the inputs and outputs are applied to approximately describe non-linear process behavior. This type of MPC systems is therefore restricted in its ability to control fast change-overs between different operating points of the process.

Hybrid models, i.e. models obtained from the integration of first principles based process models (e.g. CFD models) and models obtained with process identification techniques, are applied in latest MPC systems. Hybrid models can not only increase the accuracy of predictions, but they may also drastically reduce the costs associated with the modeling phase.

The latest generation of MPC systems copes with the above-discussed problems. These systems enable operation of processes closer to their operating limits (physical, chemical, biological), such that the problems, that have been posed in the introduction with regard to flexibility, predictability and complete reproducibility of process operation conform defined specifications, are solved.

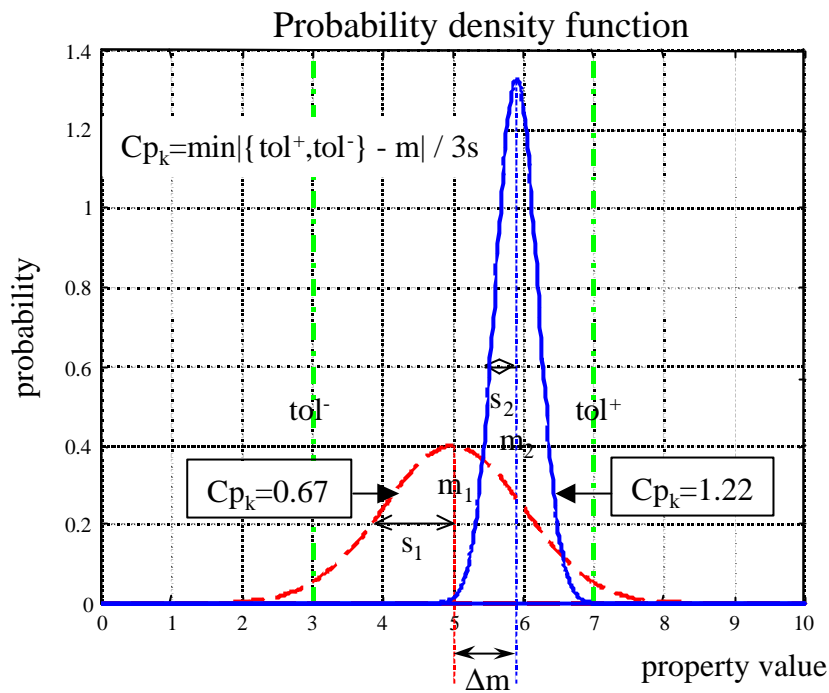


Fig. 2. Optimization of the “capability” (Cp_k) of important process variables and product parameters using model predictive control

3. MPC in the glass industry

Typical applications of MPC in the glass industry are the control of crown-, glass- and bottom temperatures in the melting furnace, refiner and forehearth and for the production of TV panels/funnels as well as for container and flat glass.

A melting furnace has very slow dynamics, typically with response times of several hours upto one or more days. This is where model predictive control performs well, because it consistently updates and keeps track of all applied changes in heating/cooling adjustments, and the way they work out on all individual glass temperatures taking into consideration the full history of process manipulations over several shifts. Moreover, the process of glass melting is a highly interactive system with both spatial and temporal flow patterns that connect glass temperatures and the related glass processing conditions in a dynamic way. Every change in heating/cooling simultaneously effects almost all glass temperatures and therefore the processing conditions relevant for glass quality.

Finding an optimum for the operation of such a process is not a straightforward task.

In general there are three optimization criteria, that should be satisfied with decreasing priority:

1. *safety* : constraint demands to protect the construction and the equipment from damage
2. *quality* : control to meet product specifications and imposed environmental constraints
3. *economic optimization of operation* : maximize efficiency and minimize energy consumption

To protect the furnace from unacceptable control solutions (e.g. changing the heating/cooling too fast, damaging the construction), constraints on heating/cooling levels, crown temperature profile and -range are applied. This means that the MPC will never violate these safety constraints in order to satisfy a control objective of a lower priority: “Safety first !”

Most of the time the process is controlled in a safe operating region, with room to move the MV’s for the purpose of keeping quality variables on target with minimum variability; despite the ever present disturbances, such as changing batch compositions and temperature disturbances.

A final optimization objective is minimization of the operating costs. In glass industry this mostly means: saving energy and maximizing efficiency. For each particular control interval, the “cheapest” solution is determined, that satisfies all constraints and quality requirements. The combined adjustments on all heating and cooling flows is additionally chosen to minimize costs. Especially for melting furnaces, which typically consume a lot of fuel, the potential for cost reduction is considerable in general.

Normally a refiner connects to a number of forehearths for the distribution of the glass melt to the forming equipment (e.g. a press for TV panels/funnels, containers and equipment for drawing tubes).

Production problems or product change-over on one forehearth can severely degrade the operation of the other forehearths in the form of (inlet) temperature disturbances.

Applying MPC on the refiner can anticipate problems and minimize the disturbing effects. Furthermore, the individual MPC of each forehearth can compensate for the remaining disturbances, long before the effect is felt at the forehearth exit, where the forming process takes place.

Because normal forehearths use both heating and cooling, conflicting simultaneous adjustments of heating and cooling flows can be avoided, thus saving some energy, without giving up on quality control.

Figure 3 shows the interaction matrix of a typical control configuration, showing the model (step response) from each MV to each CV and the corresponding sensitivity of a glass process. As can be seen almost all CV’s are simultaneously influenced by almost all MV’s. This is called the “multivariable” character of the process.

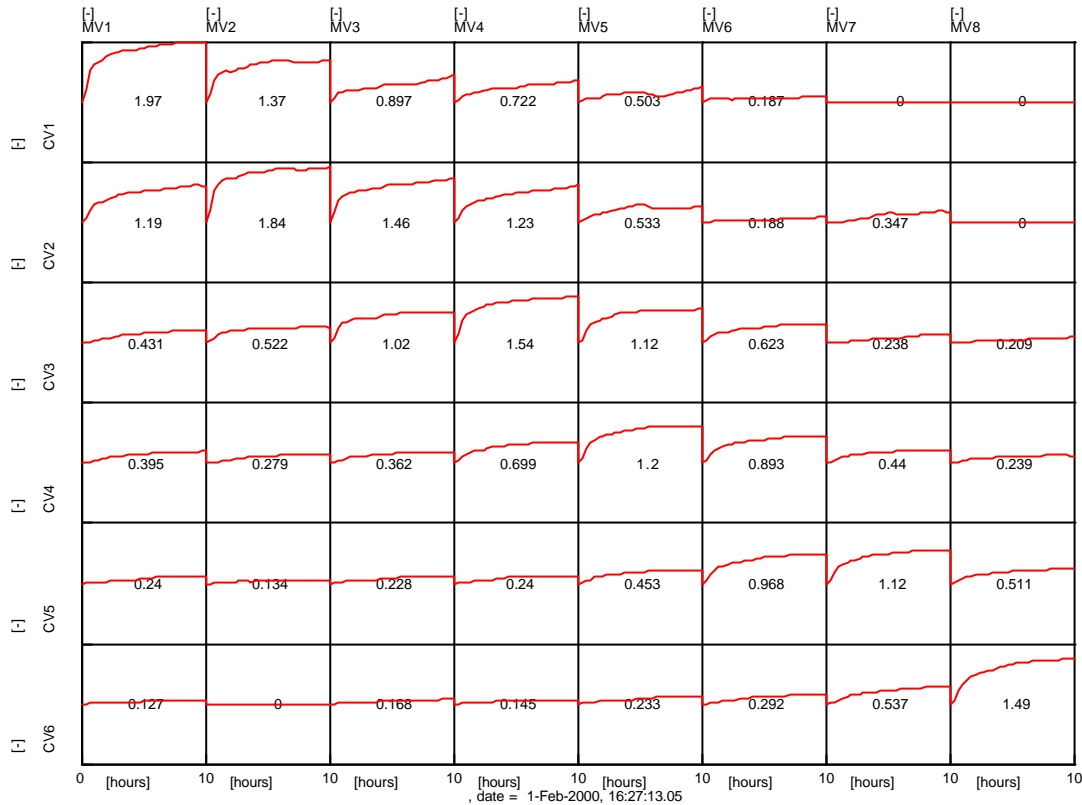


Fig 3. The multivariable character of a typical glass process used in model predictive control

A control objective for MPC control on a forehearth in general is to drive glass temperature distribution on a vertical cross section near the bowl to a specified profile. The aim is to improve the temperature homogeneity conditions of the glass to an optimum for further processing.

Figure 4 shows a typical operator interface to an MPC controlled forehearth (ProfileExpert).

Notice the graph, showing converging glass temperatures, after the MPC was switched on.

Fig 5 shows these converging temperatures in more detail. Figure 6 shows a comparison of the behavior of model prediction versus the actual behavior of one of the controlled temperatures. The actual temperature changes match the prediction very closely.

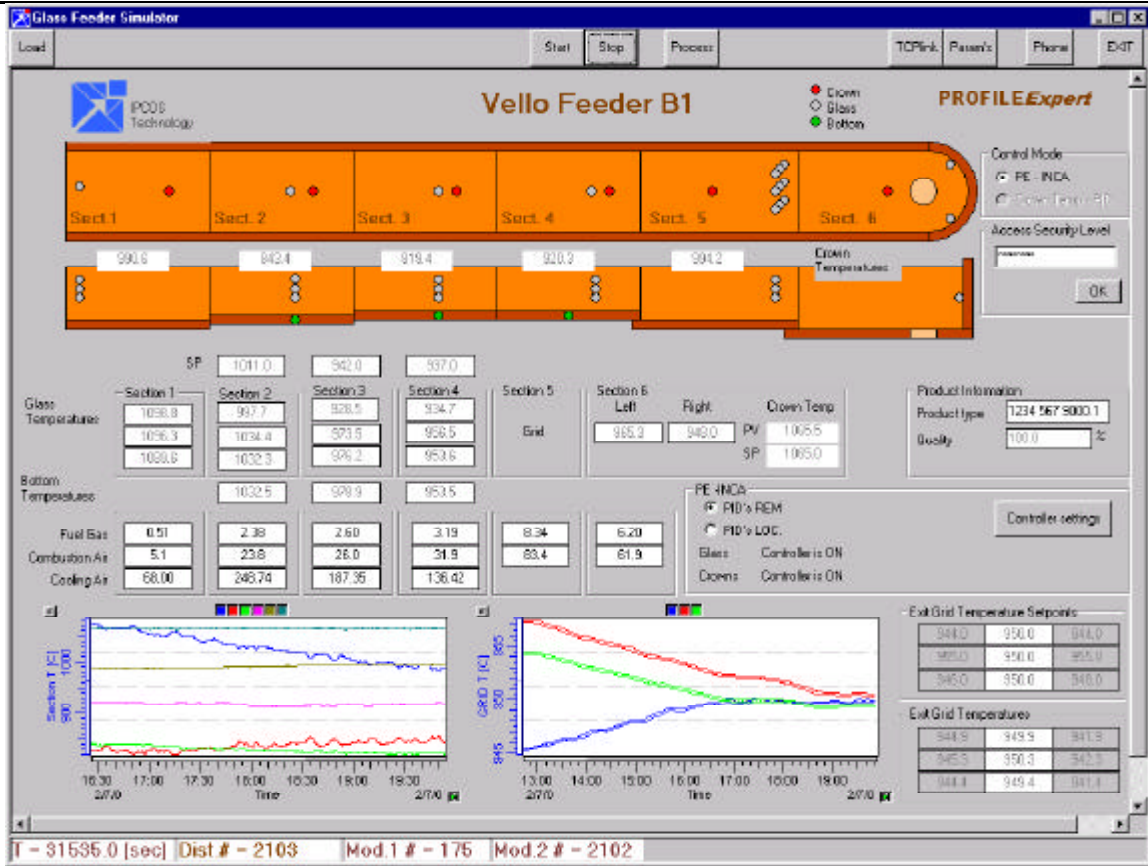


Fig. 4. A Model Predictive Controller, applied to control glass temperature homogeneity

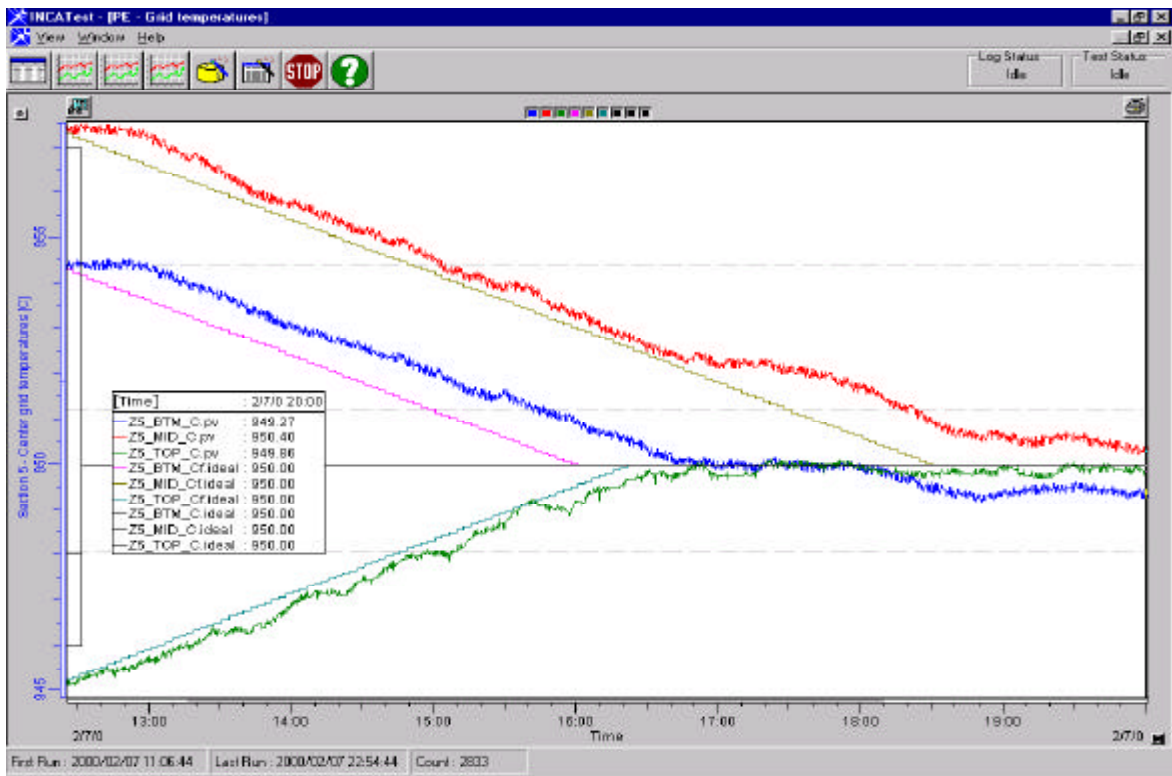


Fig 5. Converging glass temperatures near the bowl (maximum homogeneity objective)



Fig. 6. Actual and model predicted temperature during the converging phase.

4. Conclusions

This article provides an overview of model based control systems used increasingly in process industry. MPC technology is emerging as a new technology in glass manufacturing. The driving force behind the application of this technology is its widely demonstrated capability to improve business performance, generally within one year.

The development of MPC technology for a broader range of processes is ongoing. The latest developments enable the design of: robust, high performance control systems that reduce the variance of critical product parameters and process variables to a desired level; control systems that perform changeovers from one operating point to another, along a trajectory, in a completely predictable and reproducible way); control systems that provide a good balance between development and maintenance costs and profitability.

The dense interaction matrix of a typical glass process, combined with its extreme slow dynamics make these applications ideally suited for MPC technology. And dedicated MPC based applications for a broad range of glass manufacturing processes are entering the market now.

References:

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