

MPC IN STATOIL – ADVANTAGES WITH IN-HOUSE TECHNOLOGY

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Abstract: Statoil has used an in-house developed MPC since 1997. Several applications are running in closed loop today, with quite a good performance and average service factors of approximately 99%. All application projects have used internal resources only, which means that the competence has been aggregated within the company and that the best practice has been integrated in the MPC software. The total cost of software development is less than or similar to the alternative external vendor license fees, and the application project costs are definitely low. *Copyright © 2003 IFAC*

Keywords: Predictive control, model-based control, control applications, constraints

1. INTRODUCTION

Statoil started the development of SEPTIC (Statoil Estimation and Prediction Tool for Identification and Control) in 1996, with the goal of getting an in-house software system for model predictive control (MPC), real time optimisation (RTO), dynamic process simulation for simpler case studies, and off- and on-line parameter estimation in first principle based process models. The first MPC application with the new software came in 1997 (Skoftealand, *et al.*, 1998), and the significant increase in process regularity opened up for applications also at other production sites. 26 MPC applications are running closed loop in the company today, and the use of internal software and engineering resources for MPC projects has become the standard solution in the company. This may be a somewhat different strategy than other oil and gas production and processing companies apply, but does imply some clear advantages that will be explained in this paper.

The application of MPC in Statoil does not cover a lot of principally different processes, as 20 of the 26 applications control distillation columns. The general philosophy is to keep the applications as small as possible, but still represent the important interactions between process units. In total, the 26 applications have 148 manipulated variables (MV), 185 controlled variables (CV), and 87 disturbance

variables (DV). 42 of the controlled variables are inferential models for product quality control.

It is not the intention to discuss advantages with different types of MPC controllers in this paper. The technology has been thoroughly focused by academia since the first MPC controllers came in the 1970's. Much attention was paid to the model choice in the late 1980's (Strand, 1991), and several applications have been reported with the use of non-linear first principles based models since then. However, the MPC applications reported in this paper show good performance with the linear and experimental models that are described in Section 2. There is still an option however, to use non-linear models in SEPTIC should the application require that.

Section 3 describes some system realization issues, while Section 4 discusses the real success factors like project organization, application maintenance, competence development and best practice accumulation. Section 5 draws the conclusions of this work.

2. MPC ISSUES

The implemented controller does most probably not differ much from those provided by commercial

vendors. This section will clarify some requirements for typical industrial applications and at the same time stimulate some discussion on alternative ways of meeting them.

2.1 Control Specifications

The CVs are specified with set point, high limit and low limit. Each of these can be turned on or off independently. The MVs have high and low as well as rate of change limits that are always activated, and optionally ideal values.

2.2 Quadratic Program

The quadratic program of equations (1)-(5) is solved each control sample to find the optimal control actions.

$$\min_{\Delta u} y_{dev}^T Q_y y_{dev} + u_{dev}^T Q_u u_{dev} + \Delta u^T P \Delta u \quad (1)$$

$$u_{min} < u < u_{max} \quad (2)$$

$$\Delta u_{min} < \Delta u < \Delta u_{max} \quad (3)$$

$$y_{min} < y < y_{max} \quad (4)$$

$$y = M(y, u, d, v) \quad (5)$$

The quadratic objective function (1) penalizes CV (y) deviations from set point, MV (u) deviations from ideal values, and MV moves. The constraints are: MV high and low limits (2); MV rate of change limits (3); and CV high and low limits (4). The dynamic model (5) predicts the CV response from past and future CV and MV values as well as past DV (d) values and estimated and optionally predicted unmeasured disturbances v .

2.3 Model Representation

Currently, all running applications are built with experimental SISO step response models. They are easy to build, understand and maintain. Although linear and based on the superposition principle, they also to a large extent represent the process dynamics sufficiently accurate to achieve good controller performance. Each model has a model file that is read by initialisation. Models can be generated, changed and activated from the user interface while the controller is running.

In some applications an alternative state-space representation would have improved the prediction error propagation through the inherent structure. Nevertheless, the simplicity still favours the SISO step responses by experience gained from all applications.

Some CV responses are quite non-linear, the most typical being valve positions and distillation column flooding indicators. Both of them are close to integrators at the preferable operating point while they show nice and fast first-order like responses far from the constraining limit. Constraint distance

based model gain scheduling has proven to handle such non-linear behaviour satisfactorily, by increasing the model gain as the variable comes closer to the limit.

SEPTIC is also capable of running generally non-linear models implemented in a compact model object. Simulation studies with first-principle based models have proven the concept, though it still remains to identify an application with satisfactory delta benefit compared to experimental models. The non-linear model is used to predict the open-loop response, i.e. the future based on the past, and optionally with best available guess of future manipulated variables. Linearisation is performed around the open-loop trajectories and the standard QP is solved. The resulting linearisation error is tested with closed-loop non-linear simulation that may lead to a combination of line search, repeated linearisation and a new calculation of optimal manipulated variables. This mechanism is preferred to the use of a standard NLP solver.

2.4 Identification

The experimental models are found by step-testing the plant. A Pseudo Random Binary Sequence (PRBS) of test signals for multivariable excitation can be generated automatically by SEPTIC, and this functionality has been used extensively to shorten the model identification period compared to the single-input step testing procedure. In these cases the off-line commercial product Tai-Ji ID (Zhu, 2000) has been used to identify the dynamic models and produce correct model file format directly.

However, some applications or part of applications are so sensitive to multiple input changes that single-input step testing is preferred. Such a test also gives the opportunity to fully understand the observed responses and do some trouble-shooting on the way. Some simple SISO identification techniques built into the system facilitate on-line model building along with the step test sequence.

The model identification for a medium-sized application takes normally about a week to complete due to the long time constants of the process.

2.5 Computational Efficiency

The MPC applications typically have controlled variables with quite different open-loop dynamics, and also the desired closed-loop response times differ between them. The maximum controller sampling time is limited by the shortest closed-loop response time, hence the model lengths typically span from 10 to 150-200 samples to reach the approximate steady state. Considering the desired closed-loop dynamics and CV-response decoupling capability, some MVs should have a quite fine resolution in the near future while others should still have reasonable resolution towards the middle region of the prediction horizon.

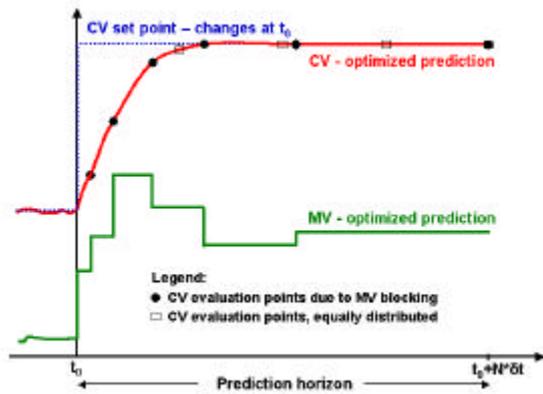


Fig. 1. MV blocking and CV evaluation

In this light, a number of configurable features in the controller are available to reduce computing time without too much performance degradation.

MV blocking. The MV in figure 1 is parameterised by 6 blocks and kept constant within each of them, which means that the controller has to calculate 6 moves for this MV. The illustrated block sizes increase over the horizon, which is a typical choice. While the number of blocks may span from 1 to N, most often 4 to 8 provides a good balance between computational effort and performance. Each MV is configured with individual blocking.

CV prediction horizon. With the step-response models, the prediction horizon for each CV is calculated automatically so that the modelled steady state is reached after the last MV moves. It is however possible to decrease the horizon manually. Altogether, this means that the prediction horizon may differ between the CVs.

CV evaluation points. For each CV, one evaluation point is placed automatically at the end of each MV block for all MVs with a model to the actual CV. In addition, equally distributed evaluation points are configured separately for each CV, as illustrated in figure 1. The number of evaluation points per CV normally spans from five to twenty.

2.6 Control Specification Priorities

Quite often an application lacks degrees of freedom to meet all the control specifications. Hard CV constraints may then lead to both dynamical and stationary infeasibilities, while the use of soft penalties for all CV specifications lead to a very difficult or impossible tuning problem to realise all the requirements for different combinations.

An explicit priority mechanism is available in SEPTIC in order to avoid these problems. MV rate of change limits are always respected, as are MV high and low limits unless there is a conflict with the rate of change limit. Then a sequence of steady-state quadratic programs is solved to respect the remaining specifications *iii) - vi)*:

- i) MV rate of change limits
- ii) MV high and low limits
- iii) CV hard constraints, hardly ever used
- iv) CV set point, CV high and low limit and MV ideal value with priority level 1
- v) CV set point, CV high and low limit and MV ideal value with priority level n
- vi) CV set point, CV high and low limit and MV ideal value with priority level 99

Each stage in the solution sequence respects the achievements from earlier stages. Weights may play a role for specifications at the same priority level when not all can be met.

When the achievable steady-state targets have been calculated, the control specifications are adjusted accordingly for the dynamic optimisation problem. This flexibility has proven its value in many applications.

2.7 Application Sub-Grouping

Normally the full application is running, which means that all MVs and CVs are active, and the different constraint situations that arise are handled with the control specification priority mechanism. However, when a CV gets a bad value, or the operator deactivates an MV or a CV for some reason, the correct consequence will often be to deactivate some other variables automatically to avoid undesired actions. Further, some applications cover parallel processing trains, which may not be running all at the same time. Generally spoken, certain conditions and events imply activation or deactivation of application sub-groups.

In order to meet these requirements, an application can be specified with up to eight groups, and each variable (MV, CV, DV) can be a member of freely chosen groups. Each variable may also be defined as critical to one or more groups to which it belongs, with the effect that it suspends the group if it for some reason is deactivated.

This mechanism has proven its value in many applications, and for some of them all the available eight groups are used to realize the necessary condition-based logics.

2.8 Tuning

Unmeasured Disturbances. The CV bias update to capture the discrepancy between the process and the model response provides integral action to the controller and removes the steady-state offset to the controlled variables. This discrepancy may stem from imperfect models or real process disturbances that are not measured.

The bias update may be subject to a low-pass filter to reduce the sensitivity to measurement noise. It is however highly recommended to use appropriate

filtering at the Digital Control System (DCS) level due to the higher sampling rate. Most often a DCS low-pass filter with 10 to 30 seconds time constant removes the need for MPC bias update filtering in applications that run with the typical one minute sampling time, getting the most out of the disturbance rejection capabilities of the constant bias prediction.

Constant bias prediction fits to an assumption of a step disturbance acting directly to the CV. This disturbance model will hardly ever be correct, and may lead to unacceptable slow disturbance rejection. On the other hand, many disturbances stem from the process input like unmeasured feed composition changes, or have their origin within the process with a certain response time before they fully affect the controlled variables. Hence the controller is equipped with an optional first-order disturbance model, assuming that the observed CV bias trend is due to an input step disturbance giving a first-order CV response. The time constant is tuneable.

The first-order bias prediction improves disturbance rejection capabilities, and modelling certain constraints like flooding indicators as pure integrators is not necessary. If the observed model error stems from wrong model dynamics or oscillating disturbances however, the closed-loop behaviour may clearly be worse by applying such a disturbance model that can be thought of as introduction of controller derivative action.

These considerations are valid for the experimental step-response models only, since a true MIMO model representation to a larger extent has inherent disturbance propagation capabilities.

CV Set Point Filter. Set-point controlled CVs can normally be kept closer to their desired values by increasing the deviation penalty and by applying an appropriate disturbance model, leading to more aggressive use of the corresponding manipulated variables. The MV variation is faster but not necessarily larger since immediate action stabilizes the process. However, a set point change may require large steady-state MV moves, which should be slowed down so that the remaining application is able to keep the whole process under control. The use of a tuneable low-pass filter to set-point changes balances the otherwise two conflicting desires of fast disturbance rejection and slower response to meet the new set point.

MV Rate of Change Towards Ideal Value. MV ideal values often relates to beneficial operating points to go after when other specifications related to product qualities, operability and safety are met. Ideal value deviation has a quadratic penalty in equation (1), which means that the MV rate of change towards its ideal value depends on the distance to go. To avoid too high rate of change far away and too low rate of change with short distance, a desired rate of change may be defined in SEPTIC, which is used whenever there is freedom to move in the desired direction.

2.9 Documentation

By pushing a single menu button in SEPTIC, the running application automatically generates an HTML-based documentation, with all the current tuning parameters and models. This saves a lot of time for the application developers.

3. SYSTEM ISSUES

The SEPTIC system is object oriented and programmed in C++, and it is configured from a text file that is read at the time of initialisation. The configuration may include several individual applications of different or similar category, which are executed according to the configuration sequence. This means that an application performing pre-calculations can be configured before the MPC application, which is now and then followed by some post-calculations as well. It also means that several MPC applications can be configured into the same executable, which reduces the number of Graphical User Interfaces (GUIs) for the process operators.

3.1 Process Interface

There are several process interfaces in SEPTIC at the moment being, though recent developments indicate that the OPC technology will dominate the future. The currently running applications connect to the process by:

- i) ABB Bailey DCS via InfoPlus from AspenTech
- ii) ABB Bailey DCS via ABB Operate IT (OPC)
- iii) ABB Bailey DCS via Matrikon OPC server
- iv) ABB H&B DCS via ABB H&B Syslink
- v) Honeywell TDC3000 DCS via CM50
- vi) Kongsberg Simrad AIM1000 as integrated modules

In addition there is an OPC-based interface to the dynamic simulator OTISS from AspenTech. For simulation purposes it is also quite straightforward to change the real process interface with either a data file interface or an object that simulates the process with experimental or first-principles based models.

3.2 Calculation Module

Most applications need some pre-calculations ahead of the control calculations. The calculation module allows these to be programmed in the configuration file, while interpreting the equations at initialisation. They may also be changed from the graphical user interface on line. The most common pre-calculations are: raw measurement filtering in lack of appropriate lower level filters; inferential models for product quality control based on raw process measurements; inferential model corrections from on-line analysers; model gain scheduling as function of actual operating point; and some fuzzy logics to change CV limits based on variance calculations.

3.3 MPC Module

This module is thoroughly described in Section 2. A free number of modules can be configured into the same running system.

3.4 Graphical User Interface

The Graphical User Interface (GUI) is a useful tool both under application development and for the process operators. There are four levels of users defined with appropriate password protection. The lowest level user can only look at trends and predictions for application variables, the operator can activate variables and change set points and limits, while the application manager can do the tuning and the application root level has all rights.

The GUI runs remotely as an independent application that communicates with the master application by TCP/IP. Remote GUIs can be connected to the master from any site that has a network connection, and this is routinely exploited to share application development and maintenance work.

4. APPLICATION AND SYSTEM DEVELOPMENT

This section describes and discusses the typical MPC project execution in the company, and shows the impact on competence and system development.

4.1 Competence and Roles

The R&D Process Control group has been working within the field of model-based control since late 1980's, and the competence background is academic studies, a lot of implementations and the development of two different MPC control packages, including the one presented in this paper. Process control is defined as important technology to the company, which is to be supported by a corporate group.

The different production sites have their own application groups. Those at the two refineries Mongstad and Kalundborg have long experience with advanced applications, and currently they are fully capable of developing MPC applications without a close cooperation with the R&D group. Other sites are not that experienced and still gains from a close cooperation, also when it comes to application maintenance.

4.2 Application Development and Maintenance

Most application development projects are carried through as a joint project of site personnel and the R&D group. This balances both competence and available resources, stimulates knowledge transfer between production sites, helps integrating the total

company knowledge and founds the basis for further software tool development.

The stages of a typical development project are outlined in the following.

Potential. Operational knowledge indicates potential process operation improvement by the use of MPC. At some sites this leads to a more detailed cost and benefit analysis, while the more experienced MPC end users just starts the project according to the accepted strategy. Currently, there is a trend to define the MPC level already in the process design phase.

Organization. This depends on the experience gained by the site personnel and the work organization at the site. Local process control and process operational expertise is essential; sometimes this can be covered by a single control engineer who communicates well with the process operators, and sometimes this means that both a process control and a process engineer as well as an experienced operator should take active part in the project. The involvement from the R&D group varies from some fine-tuning assistance to the main responsibility for application development. By the use of company-internal resources only, the project organization is less formalistic and more flexible compared to those that involve external vendors.

Design and Preparation. For the first MPC project at the actual production site one has to decide which computer is to run the application. There might be a tradition to run applications on standard DCS-vendor platforms; there might be other stand-alone existing machines or no preferences at all. The available data interfaces to the DCS system and to the IMS system may influence the solution. Apparently the OPC standard will dominate the future, the PC-based servers being provided by the DCS vendor or by a third party. Currently all production sites have their unique platform solution.

Once the goals of the MPC application are set, the selection of MV, CV and DV variables comes easy. The DCS preparation phase follows the design, including basic control tuning, instrumentation issues, configuration of MV handles, communication logics with safe guards and so on. Some experience transfer between different sites occurs, but there are also DCS-specific realizations and site-specific preferences to be considered in this preparation.

Training. Operator training is preferably offered two times during the project, firstly in advance of the plant step testing and secondly when the complete application is up running. This is very important for the first applications at the panel, while the MPC familiarity reduces the training efforts for later applications. One great advantage of having an experienced operator as a full-time project team member is that he becomes a super-user who educates and supports the other process operators.

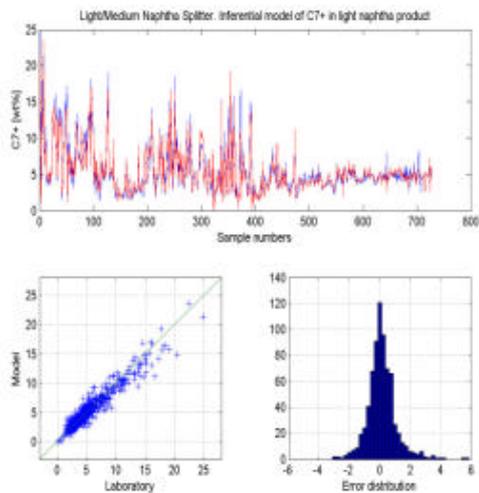


Fig. 2. Inferential model for the C7+ impurity over top of a light-medium naphtha splitter. About 3% of the samples have been classified as outliers and removed before the modelling. MPC quality control was commissioned around sample 500.

Inferential Models. Product qualities are usually part of the MPC control specifications. Quality measures like product impurities and distillation curve cut points are either available from laboratory samples or on-line analysers. The historical data of laboratory samples may be sufficiently rich to build representative inferential models from process measurements, but quite often there is a need to run a sample campaign to enrich the data. Typically, an acceptable initial product quality model for a multi-component distillation column can be built from 50-70 laboratory samples when they reflect sufficient process variability and sufficiently steady process conditions up front of the sampling time.

Product qualities like Naphtha and Gas Oil 95% boiling points are often modelled to a prediction error standard deviation of approximately 2°C when obvious outliers are removed, given that the sampling and analysis procedures are well designed. This is comparable to the repeatability of the laboratory results. The inferential model in figure 2 represents a typical achievable fit to the laboratory data.

The prediction error of inferential models built from laboratory results are routinely investigated by the application engineer, which may lead to re-modelling in cases of increasing discrepancy; e.g. due to sensor drifting, process equipment faults or unmeasured feed variations. Alternatively, some sort of automatic model updating could be used, but has been rejected in view of the possible pit-falls.

When an on-line analyser measures the product quality, there is still incentive to build an inferential model for the CV, due to the time delay and the out-of-service periods for the analyser. Automatic, safeguarded and relatively slow bias updating is commonly used in those cases.

Commissioning. The commissioning phase starts with the process step testing for dynamic modelling, as described earlier either by applying multi-variable PRBS type of signals or by single variable stepping, or by a combination of both. With all detectable responses available, the next step is to judge which connections should be utilized to fulfil the control task. Some effects are too small to let the MPC see the possibility, i.e. the MV-CV model is eliminated. Other effects are clear but left out as MV-CV model for reasons like operator acceptance or process or application stability. Now and then MVs are duplicated with DVs to account for such clear effects by a feedforward, but with implications to the application tuning. The remaining active MV-CV matrix is then inspected for steady-state singularity, which has led to some gain adjustments for distillation applications. The application engineer carries through this analysis manually.

The application is then normally simulated before any control loop is closed. It is a one-minute job to convert the application configuration file to a simulated application, and most of the application tuning can be done in a simulated environment.

With the simulation done, the application is brought on line and loops are closed gradually, until satisfactory performance is achieved for the complete application. For moderate-sized applications a period of two weeks is normally sufficient for the commissioning phase from the test period for dynamic modelling starts till the application runs well.

Benefit Evaluation. The applications are always evaluated, though not formally, against the designed performance. Product quality control is always considerably improved, and the applications run consistently against the relevant set of constraints. The process operator acceptance is generally high. A rigid profit post-calculation is rarely carried through, but the MPC project payback times are typically 2-4 months.

Maintenance. Sufficient resources must be devoted to application maintenance. The inferential quality models are important to follow closely and recalibrate if necessary, usually more frequently during the first year than later. Evidently, the applications also run into operating regimes that were not foreseen during commissioning, which means that new variables or considerable re-tuning may be needed. Last but not least the communication with the process operators and process engineers is a continuous task for the application engineer. Saying that an application engineer would spend 20% of his time to maintain 10 medium-sized applications over the year should not be too far away. When the maintenance is done properly, the experience shows application service factors of 98-99%.

Competence Benefits. The process focus in the MPC project gives additional benefits to operations through increased process understanding. Now and

then abnormal operation or abnormal operating points like distillation column flooding is detected and explained, and more often control valve problems or other instrumentation issues are pinpointed.

Each MPC project also increases the application development skills in the company, so that the “best practice” is continuously improving. The transfer of these skills across different production sites is mainly taken care of by the R&D group participation in most projects, but also by the yearly user group meeting focusing both on technology, projects and applications. Some best-practice elements are also built into the software code, which is brought on to the next project and hence integrates much of the developing competence.

4.3 Software Development

The decision to develop SEPTIC as an in-house tool for MPC and other on-line model based applications came in 1996, and the first MPC application was commissioned one year after with the software development efforts of approximately two man-years. Today the integrated R&D funding for the MPC software development has reached approximately five man-years, with the current focus on user interface improvements and process interface developments.

The use of in-house MPC technology implies that application and system development are closely connected, as new functional requirements arising in a certain application project are rapidly realized in the software tool and used in the actual and later projects. One of the refineries has more or less volunteered to be the software testing site, as the experiences with respect to quick response times by far outweighs the obvious drawbacks of rapid code development. This attitude contributes to a large extent to the low-cost MPC development.

4.4 End User Perspective

There are several advantages seen from the end users with the combination of an in-house MPC tool, a corporate application group and the internal project organization that is established.

The projects are done to a really low cost, and the way of doing them stimulates competence development within the company and ensures appropriate competence transfer between the different production sites. Getting on line support for application development and tuning is quite easy by the combined use of the TCP/IP-connected GUI and the mail system.

The R&D corporate group is seen as a stable and well qualified service vendor, and this also holds with regard to the role as a software vendor. A certain advantage is the quick and appropriate response to desired tool developments. The small

efforts needed for vendor evaluation is also regarded to be a clear advantage.

Overall, the enthusiasm within the company is stimulated, which founds a good basis for successful MPC projects.

5. CONCLUSION

The last years R&D focus on advanced process control and specifically MPC technology has contributed significantly to the implementation rate and success within Statoil. Such a corporate competence unit within this application-oriented area can only be successful if there are interesting and challenging projects provided by the end user clients.

The tight integration of product development and application project experiences stimulates accumulation of knowledge and good solutions, so that the basis for doing good projects improves continuously.

REFERENCES

- Zhu, Y.C. (2000). Tai-Ji ID: Automatic closed-loop identification package for model based process control. *Proceedings of IFAC Symposium on System Identification*, June 2000, Santa Barbara, California, USA.
- Skoftealand, G., S. Strand and K. Lohne (1998). Successful use of a Model Predictive Control system at the Staffjord A platform. Paper presented at *IIR Conference on Offshore Separation Processes*, Aberdeen, February 1998.
- Strand, S. (1991). Dynamic optimization in state-space predictive control schemes. *Dr. Ing. thesis*. Report 91-11-W, Division of Engineering Cybernetics, NTH, Trondheim.