7 Years After: Revisiting Advanced Process Control on a Delayed Coking Unit

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Abstract

The paper aims to revisit and discuss an application of advanced process control completed 7 years ago at a Delayed Coking Unit at the Agip Petroli Gela refinery.
The application had some remarkable features, including:

- Multi-layered strategy featuring different technologies working in synergy (MPC, Neural networks, SPC, etc.)
- Completely DCS-embedded solution
- Ad-hoc logics to build "virtual" feedforward variables able to detect process disturbances

The number of years of continued operation allows examining the actual benefits that applying high-tech control strategies deliver to a complex unit like a delayed coking. It represents also an useful opportunity to re-think and assess which lessons have been learnt and how a similar project could be realized today, with latest generation tools and methodologies. composite

After a quick overview about the implementation details, the paper will assess the results and the performance on a pretty long time-span (7 years!). A final section will discuss how the same application could be done in 2004, focusing on new technologies economic benefits and on the improvements they can allow in project workflow and execution.

1. Process Description

Gela refinery mostly treats heavy crude and residual products. In order to maximize coking production (and related light distillates) it is equipped with two delayed coking units. Refinery overhead plants management aims at saturating both coking units, by adapting other units downstream and upstream to reach this goal. The coking plant (identified as Coking-2) object of the work is composed of the following main units (see figure 1):

- a main fractionator column (designated by C-1)
- a column divided into two independent sections for the steam stripping of light and heavy gas oil (C-2)
- a furnace (F-1) for reaching cracking triggering temperatures
- two coke drums (V-1 and V-2).

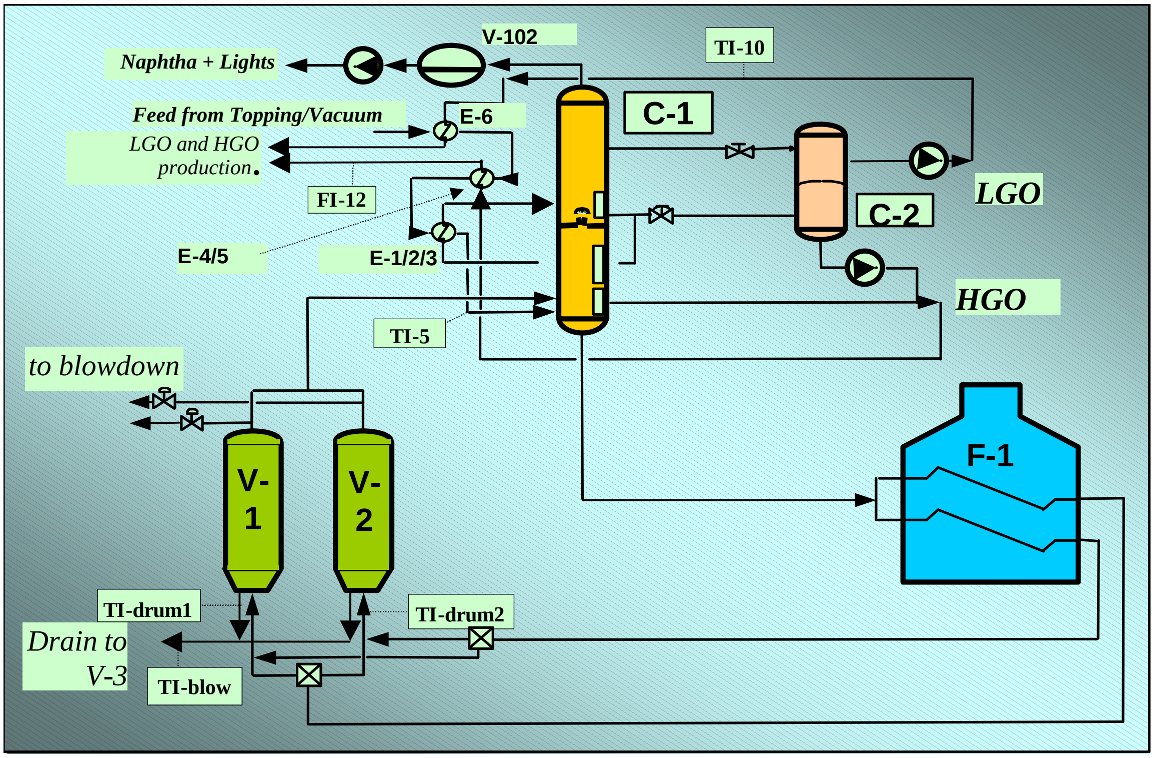

Figure 1 - Coking Plant Layout

After having been preheated by a series of heat exchangers (E-1, E-2, etc.) the charge coming from Topping and Vacuum units in variable percentages passes through the bottom of the column (where prospective light elements are removed) and reaches the furnace and from here the coke drums, producing the vapors which return to the column to be distilled.

The furnace is subdivided into two sections that can operate independently, so as to allow the unit operation even when one of the two sections is out of order, e.g for maintenance. Each section contains two pipe coils in which the residual product flows and is heated.

The fractionating column C-1 produces 3 different products: Heavy Gasoline (identified from now with BP), controlled at 95% ASTM for temperatures fluctuating from 150°C to 175°C, Light Gas Oil (GOL) controlled seasonally at 95% ASTM for temperatures fluctuating from 360°C to 370°C and Heavy Gas Oil (GOP). Two pumparound circuits contribute to remove heat from the column and their management represents an important control/stabilization gear. Unit typical throughput has been recently increased from 3000 up to 3500 ton/day.

The periodical switching between the coke drums causes a series of disturbances to the fractionating column, such as considerable temperature drops, with respect to optimum values.

When a drum is switched off, it immediately undergoes a steam stripping procedures. After the coke drilling and removal, the drum must be preheated so to be ready to replace the operating one. During the preheating phase, a fraction of vapors is deducted from the column and sent to the idle coke drum where it condenses and is drained.

At the end of these operations, the coke drum is ready to start. The drum change takes place generally each 24-26 hours and depends on quantity and quality of residual product processed. The overall effect of these procedures on the fractionating column is a periodic reduction of heat available in the column C-1 with a consequent sharp reduction of distillate flow rate. Besides, a decrease of the temperature at the bottom of the column occurs, with consequent cooling of the charge entering the furnace and increase of its duty. Conventional control system tries to compensate these reductions by closing pumparound circuits, but this action is limited by flow rate low constraints and, sometimes, operators are compelled to control some variables manually.

2. Advanced Control Strategy

Plant basic control is performed and managed by means of a Network90 Distributed Control System (DCS) commissioned in 1989. Capability of the main fractionator to face the above-mentioned disturbances was increased later on, thanks to the implementation of a few cascade-control schemes, able to speed-up system response, realized by plant control engineers. Although these activities have been profitable from the point of view of the management of out-of-specification times (decreased of about 50%) they emphasised the presence of further efficiency recovery edges, justifying the application of modern control technologies.

From the middle of 1996 authors began studying some possible control configurations for the column C-101, which could allow a more stable operation, resulting into better economic performances. The resulting Advanced Control Strategy consists of the integration of several APC tools, to reach the specified goals [1]. The core of this strategy is the multivariable controller IDCOM-B, a version of the identification and control technology SMCA-IDCOM of Setpoint Inc. (now Aspen Tech. Inc.), integrated into the Infi90 DCS [2].

This product was one of the most widespread implementations of Model-based Predictive Control technology (MPC), the only one which has proved itself able to really optimize multivariable processes.

The main economic targets of the column C-101 are related to the capability of keeping the most valuable outputs (Heavy Gasoline and Light Gas Oil) as close as possible to pre-defined quality targets. Actually, these qualities that are expressed in terms of point value of 95% ASTM, were available only once a day, by means of specific analyses carried out at the plant laboratory, so that the control goals had to be turned empirically into maintaining of reference tray temperatures. Clearly the lack of timely and reliable information on product qualities introduces further uncertainty margins, harmful to the whole performance. Therefore it was decided to enhance the APC project scope adding to the multivariable controller an inferential measurement layer to estimate on-line product qualities. The software sensors were implemented using neural technology, which has proved to be particularly effective for this purposes ([3], [4]), through a proprietary product named Infi Neural Net.

Figure 2 shows a schematic view of the implemented control strategy. The inferential measurement software estimates the values of the product qualities, whose accuracy is increased correcting neural net predictions with a bias factor. The bias values are calculated on the ground of the discrepancy between inferred and lab-measured values analysis through a sophisticated SPC-based methodology. The estimated product qualities are controlled as standard process variables by moving the setpoint of the related pilot tray temperature controller by means of Inferential Smith Controller (ISC), a control algorithm alternative to the classic controller PID, available as a standard functional block in the system Infi90.

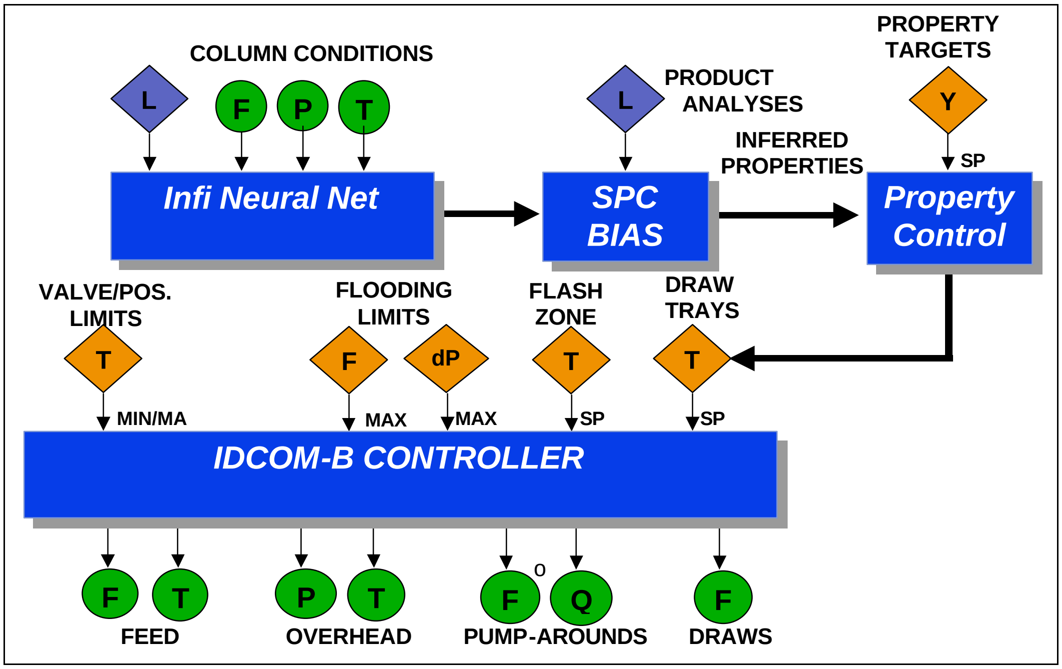

Figure 2 - Advanced Control Strategy

The controller IDCOM-B, in turn, manages the loops set-points controlling feeding flow rate, distillate extraction flow rate and pumparounds flow rate, so as to control temperatures and to apply constraints imposed by the physical operative limits of the unit. Special treatment was needed to identify the two “discrete” disturbance variables related to Warm-Up and Drum Switch and build related models. In fact, they are not linked to variables measured by DCS and for their definition it was necessary to create ad-hoc external logics.

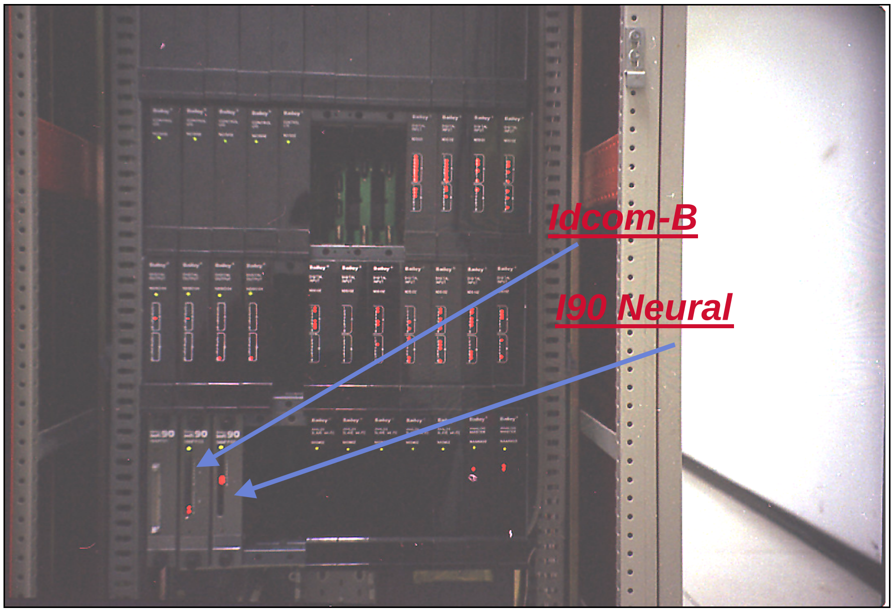

Fig. 3 – View of the APC Hosting DCS Cabinet

The whole advanced control strategy is implemented through two Multi Function Processor modules (see Fig. 3): one, a MFP03 equipped with a 32 MHz processor and a mathematical co-processor, includes Idcom-B and connection configurations with basic control and operator's console; the other, a MFP02 (16 MHz processor), includes 3 Neural Networks to evaluate the properties, a data reconciliation/sensor validation system, a bias updating mechanism and BP and LGO property control.
A number of auxiliary calculations (including logics to identify drum switching, inferential bias updating mechanism and application diagnostics) were implemented directly on the DCS, through function block configuration. All human interaction is managed through the standard DCS Consoles: Figures 4 shows the overall hardware architecture of the application.

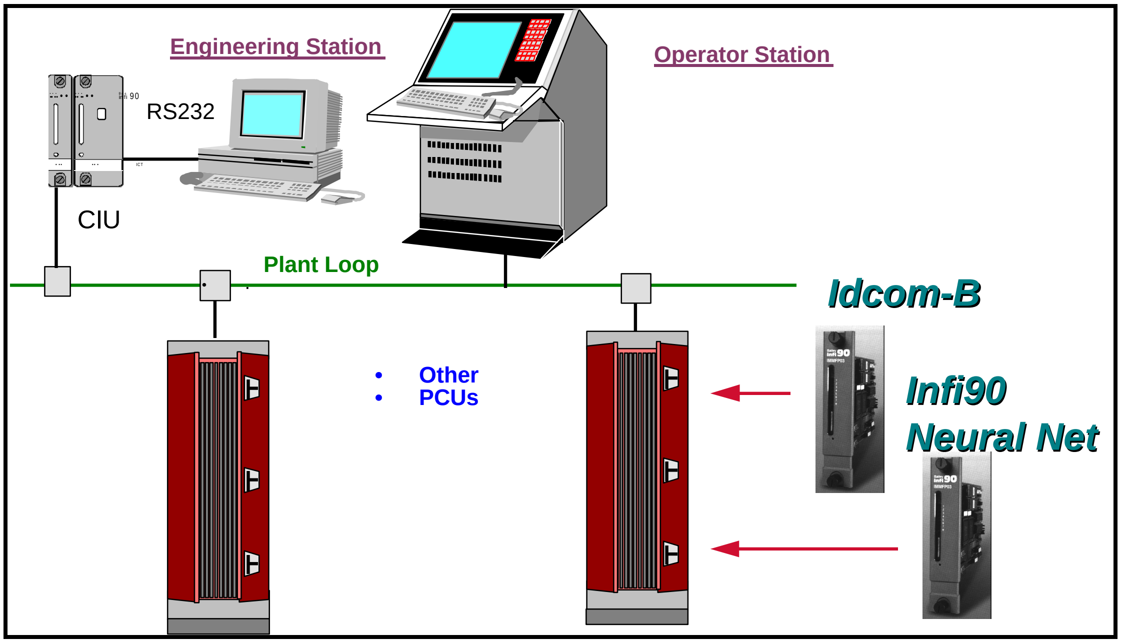

Fig. 4 - Hardware Architecture of the Application

3. APC Operation and Benefit Analysis

The whole advanced control strategy was fully commissioned in the late summer of 1997. Agip Petroli officially accepted it the following November. About 6 months later, the application underwent a meticulous economic and performance appraisal during a detailed and comprehensive assessment procedure investigating the first months of operation.

The analysis confirmed the project expectations from both qualitative and quantitative perspectives. During the 6 month-long test-run, the application had a service factor around 94%, showing a number of money-saving effects on plant operation.

Entering into details, the fractionator showed a greater stability, due to a dramatic reduction both in magnitude and time extension of the disturbance coming from drum switching and related procedures. Fig. 5 shows the evident reduction in the Integral Square Error[1] (going from 3.26 to 0.85 with a 70% drop) gained with the application of the multivariabile controller.

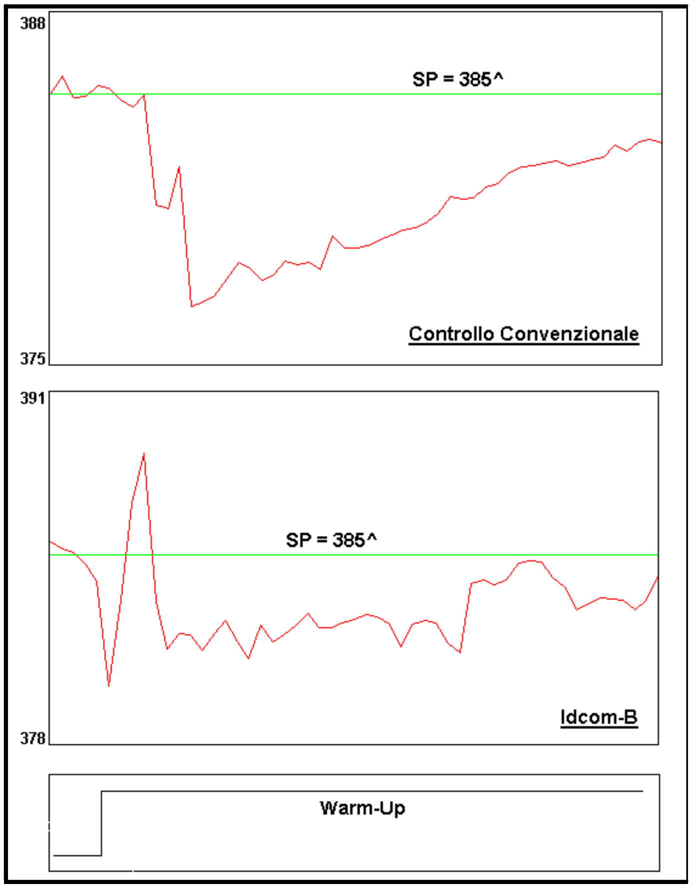

Fig. 5 - Comparison of HGO Temperature Trend During Drum Switch Without and With MPC

Moreover, better control allows keeping products qualities closer to targets. Figure 6, shows, as an example, the comparison between the 95% ASTM distribution for Light Gasoil in the two semesters January-June 1996 (without APC) and January-June 1998 (with APC). The clear variance reduction in the latter (around 25% for Heavy Gasoline and 40% for Light Gasoil) allowed to obtain products whose spec were closer to the objective given from the Planning department.
A further return went from the increase in the yield of more valuable light distillate: in the case of Light Gasoil, the amount lost in heavier streams was reduced by 36%.

Altogether the three factors above resulted in benefit able to completely pay-back the application in around 6 months of plant operation. Such an estimate did not include other benefits difficult to be translated into dollars, like the reduction in stresses during drum warm-up and switches.

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[1] Integrated Square Error, ISE, where: ISE = $\int_0^\infty [\mathbf{PV}(\mathbf{t}) - \mathbf{SP}(\mathbf{t})]^2 \mathbf{dt}$)

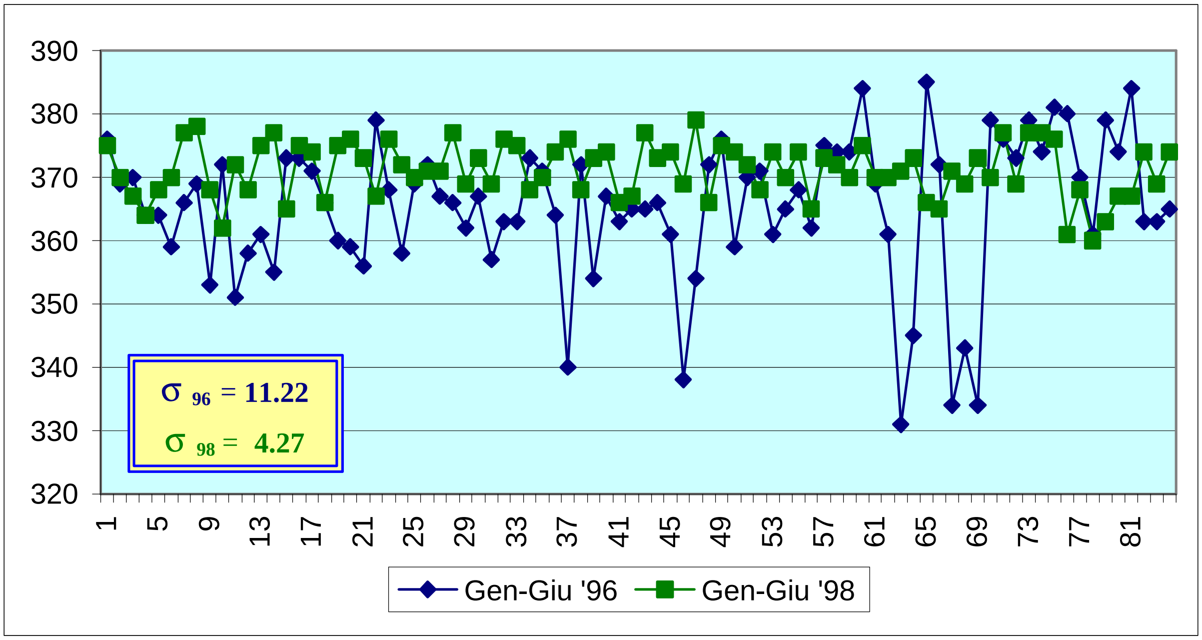


Fig. 6 – Comparison Between ASTM 95% For GOL Without (*blue*) And With (*green*) MPC

In the following 6 years (1998-2004) the APC application has remained constantly on-line and quite profitable. Service factor has increased further almost up to 100% of the time with both the furnace sections in operation. Inferential system prediction reliability has allowed to reduce of 50% the number of analysis performed manually in the lab each week, with an additional benefit in the production cost.

Seven years after the application commissioning, neural estimator performances exhibit no evident signal of degradation: Figure 7 shows the comparison between estimated and lab measured values for the Light Gasoil in the period June-July 2004. It is possible to appreciate the overall good behaviour of the predictive system: the average error is in fact of 1.43% with a standard deviation of 1.46%.

Quite remarkably the application has resulted so robust to need only one maintenance activity in 7 years from the supplier. In that case the maintenance resulted into a simple recalibration of one of the neural models.

From the beginning, application found good acceptance by control room operators, who soon became valuable partners during commissioning and start-up. This was certainly due by the fact that all the training and the application manuals and user guides were provided in Italian language. Today managing the plant through the APC strategy has become a comfortable and everyday practice for them: as a matter of fact operators are used to restart it after each and every plant shut-down without the need to involve control and/or maintenance engineers.

It is possible to state that the APC application has surely helped the plant to reach the actual excellent performances of the last years when it has been able to increase of 15% its annual throughput, thanks also to improvements to process instrumentation.

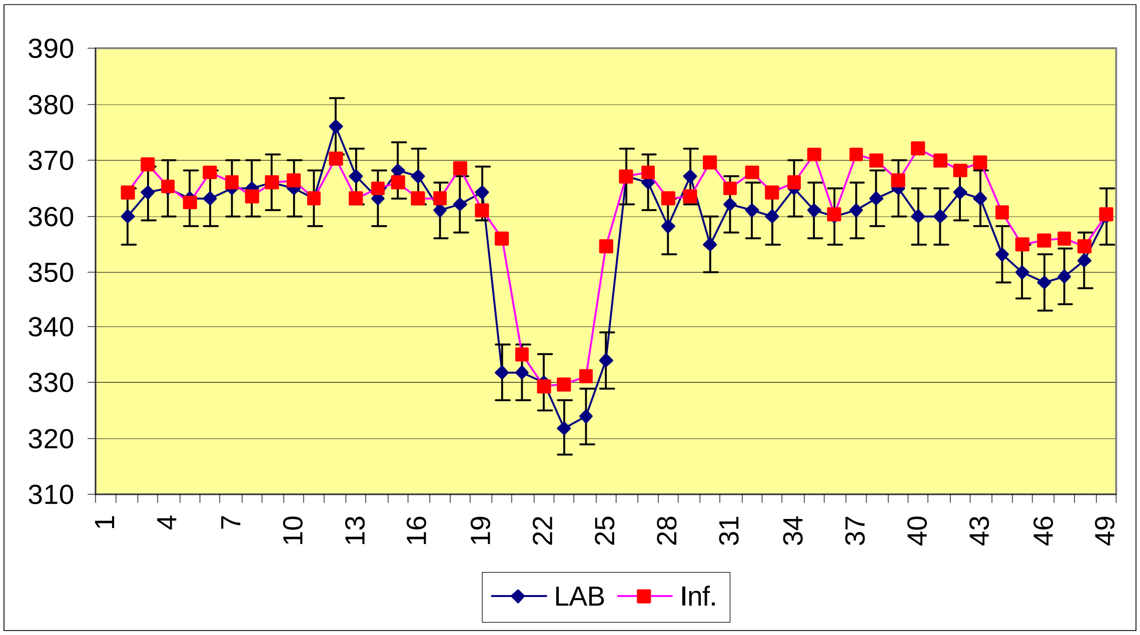


Fig 7 – Present Performances: Comparison Between Predicted and Lab Data for GOL 95% ASTM in the period June-July 2004

4. Seven Years Later: Would New Technologies Deliver Additional Benefits?

In the first sections of this paper we have tried to describe how combining different advanced technologies resulted, over the years, in a sustained and remarkable benefit for plant bottom line. Yet 7 years after commissioning (and even more from design) this could represent an useful test-case to re-think and assess which lessons have been learnt and how a similar project could be realized today, with latest generation tools and methodologies. As a contribution to a more general analysis, in the following a short discussion about how the same provider would implement a similar project today is given.

Probably the most striking feature of the application was the use of DCS-embedded APC products. Around mid-nineties there were some very specific reasons supporting such an approach [2]:

1. no need to have an expensive external computer linked to the DCS through a computer gateway
2. no need to write (or buy) the software able to interface your DCS database with an external computer
3. operators had all the control displays (both basic and MPC related) on the same GUI: no need to train operators with different equipment, keyboards, operating systems, etc.
4. on-site plant engineers could be rapidly trained to maintain and upgrade the multivariable controller, as well as the basic regulatory loops

Nowadays most of these rationales have disappeared. Personal Computers are more and more powerful, reliable and cheap. Connectivity problems have been successfully tackled by OPC client-server architecture, which is now a mature technology. PCs are pretty common devices into control rooms even as main operator consoles, so that software integration and information sharing among different CPUs have become straightforward. Furthermore Visual Basic clients are available and easy to be configured so that they are well accepted by operators. Interestingly Coking-2 plant is just an example of this trend, having moved in the last years from the old Bailey MCS consoles (based on VMS operating system and DEC Inc. hardware), to the Microsoft Windows™-based Tenore NT ones. Finally and above all, a new generation of young, computer-used (and computer-skilled) operators and engineers is around at refineries and petrochemical plants, quite comfortable and sometimes eager in exploiting Information Technology as an everyday production-boosting tool.

Moving from these considerations, ABB has developed in the last 3 years an innovative Advanced Process Control product suite designed to be hosted into external PCs. The suite is presently composed by three products (see [5] for more details):

- Optimize^{IT} Predict & Control, a new multivariable controller based on innovative modeling techniques;
- Optimize^{IT} Inferential Modeling Platform, a software package for development and deployment of empirical models;
- Optimize^{IT} Loop Performance Manager, a comprehensive solution for control loops tuning and performance assessment.

The choice to move from proprietary architecture to commercial PCs, has allowed to remove the main drawbacks characterizing the embedded-APC approach, including:

- Opportunity to apply APC strategies on proprietary DCSs only
- Need to maintain special tools for downloading and cross-compilers
- Limitation on application size and algorithm complexity due to the limited number-crunching power of DCS-card CPUs

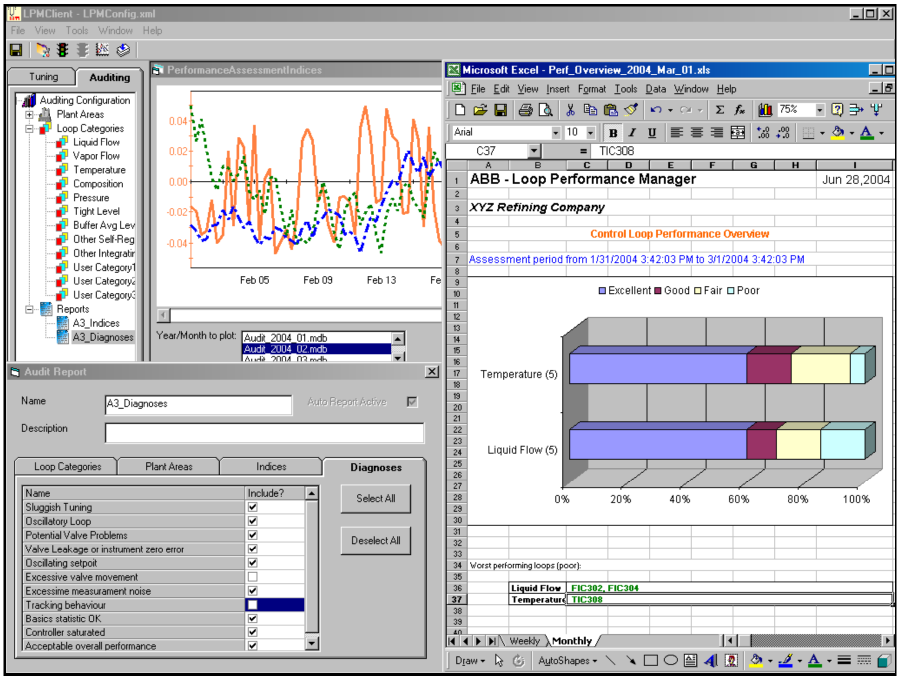
However, the biggest question is how these technology advancements could affect the control engineer and the plant operator, in their day-by-day activity. On a very general ground the answer can be divided in two parts:

1. The evolution in modeling technologies improves process control performance. As a direct consequence, this leads to better economic performance on existing applications and creates new opportunities for projects where the ROI was not adequate with the prior technology. Furthermore, the new technologies can make feasible problems that were previously considered technically too difficult or not worth the investment. So wider application and better performance are the first effect.
2. With easier to use software, prevalent availability of live and historical process data and with computer power no longer an issue, on-line modeling should proliferate for simpler, everyday applications. For instance, the control engineer will be able to quickly build, test an inferential model whenever he wants or needs one, with an easy-to-use toolkit, residing on his/her PC.

Coming to the Coking-2 application, these technologies would bring benefits in quite a few ways. In order to properly appreciate them a short description of each product is needed.

Optimize^{IT} Loop Performance Manager (LPM**)** is a product designed to optimize and properly maintain the base of any process automation system: the main regulatory control layer [8]. The loop tuning system improves control loop performance, while the auditing system insures that performance does not degrade. LPM provides a powerful, yet extremely easy-to-use, collection of software tools that control engineers and process operators will find useful to start-up, diagnose and maintain control loops. The package supports a wide variety of commercial PID control block

algorithms (both from ABB and our competitors), as well as various configuration options available for those PID algorithms. By combining data collection, model identification, feedback tuning, feedforward tuning and controller simulation in a single user interface, it delivers a complete tool and removes the barriers preventing optimization of DCS.
LPM contains two main components, a Loop Tuning tool and a Loop Auditing tool. Loop Tuning is performed following a model-based approach. A facility allows to collect data (both in auto and in manual mode) and to use them to build, test and assess models of different complexity. Once an adequate process model has been identified, this can be used for the actual tuning phase. Several tuning rules (lambda tuning, dominant pole placement, IMC) are available together with exhaustive assessment and simulation tools.



Year/Month to plot: Audit_2004_01.mdb, Audit_2004_02.mdb, Audit_2004_03.mdb

Name: A3_Diagnoses
Description:
Auto Report Active ☑

Name	Include?
Sluggish Tuning	☑
Oscillatory Loop	☑
Potential Valve Problems	☑
Valve Leakage or instrument zero error	☑
Oscillating setpoit	☑
Excessive valve movement	☐
Excessime measurament noise	☑
Tracking behaviour	☐
Basics statistic OK	☑
Controller saturated	☑
Acceptable overall performance	☑

C37 = TIC308

ABB - Loop Performance Manager Jun 28,2004

XYZ Refining Company

Control Loop Performance Overview

Assessment period from 1/31/2004 3:42:03 PM to 3/1/2004 3:42:03 PM

Worst performing loops (poor):

Liquid Flow	FIC302, FIC304
Temperature	TIC308

Fig. 12 - Example of Trend on evaluation KPI

The Loop Auditing section is designed to stay connected to DCS. At pre-defined time interval, a scheduler will access the selected PID, collecting data, which will be used to compute up to 41 different KPIs. These indices can be further elaborated in order to produce a number of diagnostic hypotheses. Both indices and diagnosis can be trended (see Fig. 12 for an example) and remain stored in weekly and monthly reports for maintenance analysis and/or investigation, providing a powerful tool to continuously monitor automation performance.

The availability of a reliable loop-tuning tool would speed-up the basic control tune-up, and provides a sound base for MPC in a much shorter time. Moreover applying the loop monitoring features facility would provide a timely, automatic assessment of control loop health allowing to promptly identify malfunctions or even performance degradation. This would be particularly interesting for furnace loops that are subject to relevant stresses and instrumentation failures.

Optimize^{IT} Predict & Control (P&C) is a multivariable, model predictive control software package, designed to exploit the benefit coming from a ground-breaking modeling approach. For a long time technical literature has described modern control algorithms based on a flexible type of multivariable model. The model was based on linear differential equations that mapped the relationships between process inputs and process outputs through use of intermediate variables, called the *state vector*. Models of this type are called *State Space* models. MPC algorithms came along after state space models were introduced, but did not use this type of model, for several reasons including the constraints placed by real-time execution in 1980 and 1990-vintage CPUs. The result was that state space models were ignored for a long time by the process industries, until recent enhancements in new algorithms and the increased computational power in modern computers has changed that [6], [7].

P&C includes a state estimation algorithm to dynamically estimate the state variables at each time step by applying the process input measurements (MVs and FFs) to the model and then defining corrections to the states based on the CV prediction errors (the difference between measured value and the value predicted by the model). New state estimates are generated and used to improve the current and future predictions for all the CVs (reducing CV prediction error). The effect of process input and output disturbances are considered in the state estimate. This is different than standard MPC algorithms that are based on step response models, as shown in Figure 8.

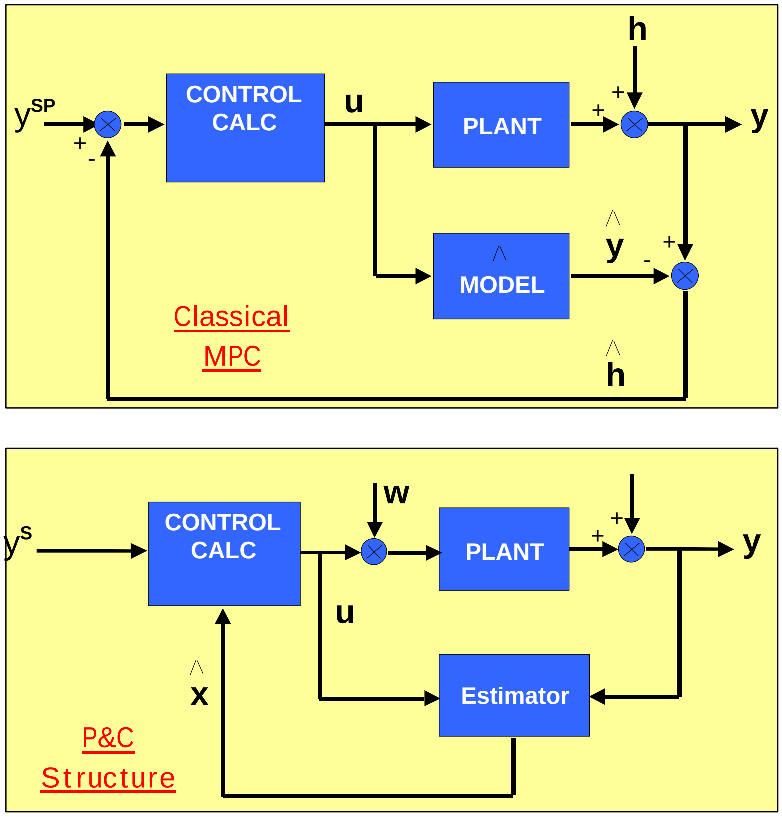


Fig 8 – Classical and P&C Structure

By considering process input disturbances, the state estimates will predict larger long term changes in the CVs than a simple bias calculation for output disturbance. The state space model allows for earlier detection and faster controller response to unmeasured disturbances, when compared to other competing MPC technologies. Figure 10 illustrates this improvement on a simple example, represented in Fig. 9.

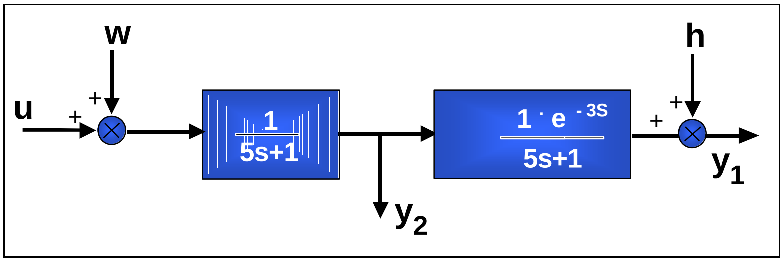


Fig 9 – Process with Intermediate PV

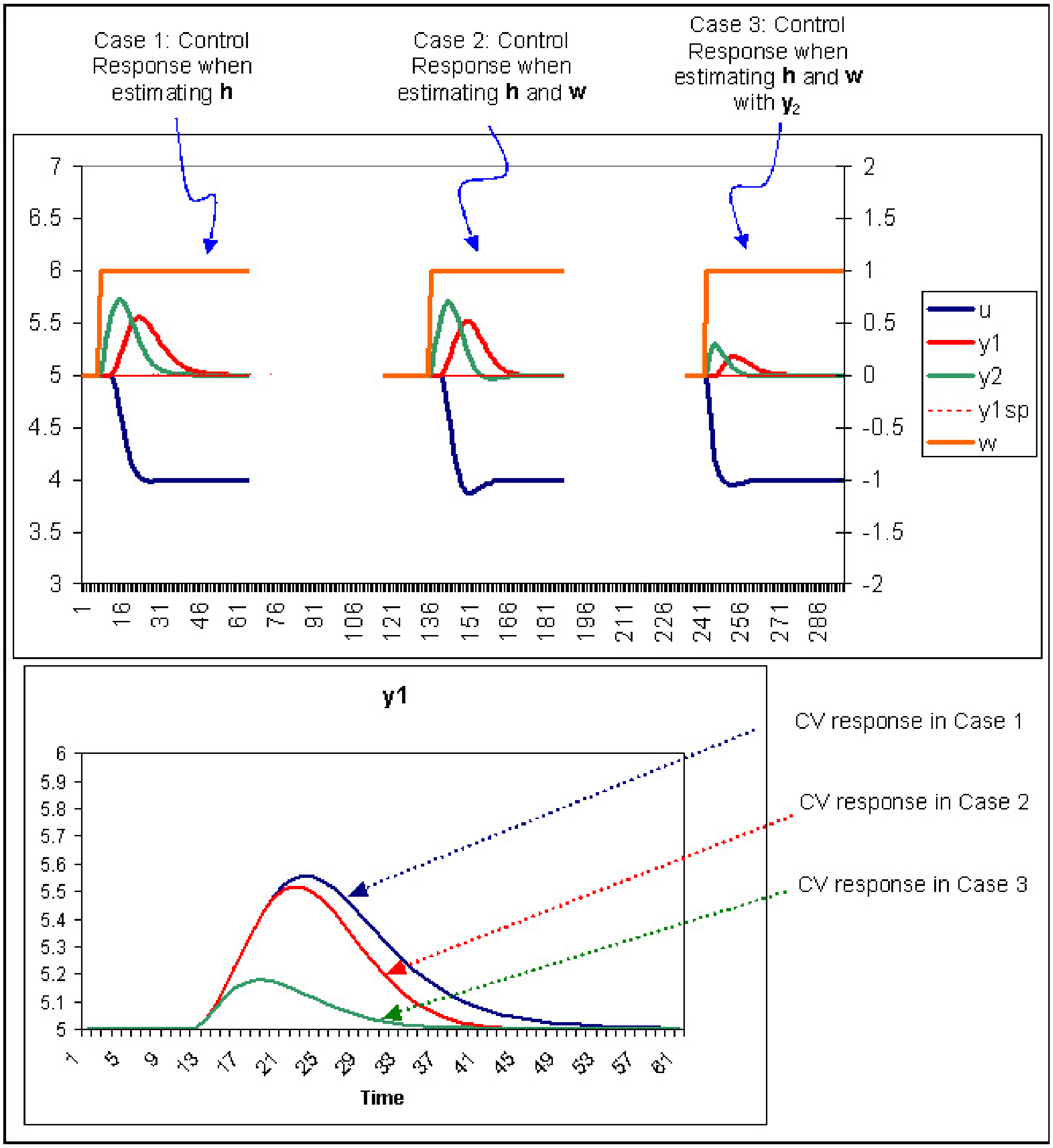


Fig. 10 – Effect of Intermediate PV

The three trends compare how an MPC compensate the disturbance **w** entering into the system by estimating:

a) an output disturbance **h**;
b) an input disturbance **w;**
c) an input disturbance **w** with feedback from the intermediate variable $\mathbf{y_2}$.

In Case 2, the MV response is stronger resulting in a lower deviation for y1. In Case 3, the MV responds much sooner, further improving the deviation for y1.

Inclusion of extra process variables that are not controlled is a unique feature offered by P&C because the state space methodology provides an integrated model representation. The state estimator utilizes all the current measurements (CVs and PVs) to detect unmeasured disturbances and predict their future effects on the CVs. Notice that the measurements are considered as "feedback" to the state estimator, but the new state estimates are also used in the controller calculations for the future, so the PVs provide a feedforward effect in the controller.

State space formulation also provides a better model representation of integrating systems, like levels, which results in stable control of these variables. Beyond the state space formulation, P&C uses a multi-objective, multi-step control algorithm that delivers prioritized constraint control and maximum decoupling. P&C treats setpoint variables and feedforward variables as true vectors, creating the ability tight control during scheduled grade changes, as opposed to treating a ramp like a series of step changes (see Figure 11). Clearly no DCS embedded CPU has the computing power to manage such a demanding numerical processing load on a typical industrial application.

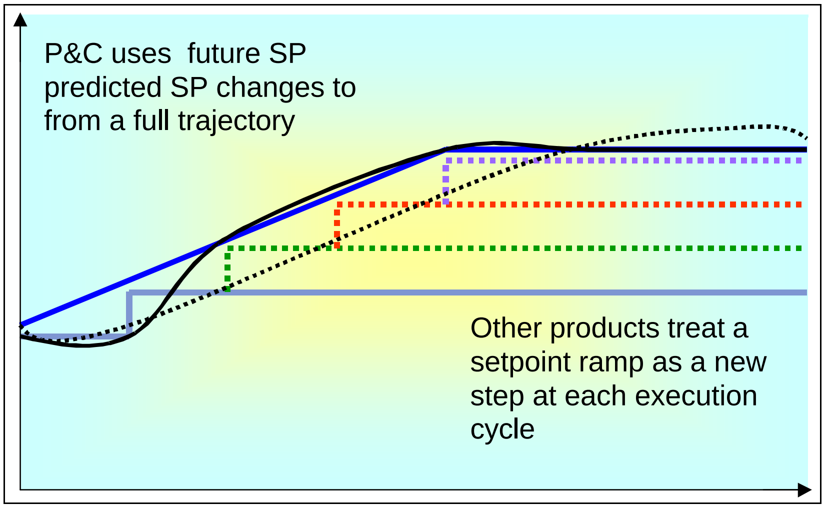


Fig. 11 – P&C SP Trajectory Capability

On a unit like Gela Refinery Coking-2, the innovative MPC algorithm could increase the return of investment basically in three ways:

- allowing a better management of drum switching, thanks to the additional information coming from extra state variables feedback;
- improving Coking-2 disturbance rejection and overall performance during upstream unit load changing operation exploiting the superior management of setpoint and disturbance ramps;

- including drum levels into the APC strategy because of the much better management of integrating variables.

Optimize^{IT} Inferential Modelling Platform (IMP) is an innovative software package for the development and deployment of data-driven advanced applications.
It is based on two separate environments:

- IMP Model Builder for application design and development
- IMP On-line for on-line project deployment and monitoring

IMP Model Builder features latest generation data analysis and modelling technologies developed in house or selected from technology leaders around the world, including:

- Neural Networks;
- Genetic Algorithms;
- Principal Component Analysis;
- Multiple Linear Regressions;
- Partial Least Squares;
- Statistical Process Control (both uni- and multivariate);
- Calculation Scripts.

All the different tools are embedded in an intuitive working environment based on the latest HMI concepts, which remove any hurdles for the inexperienced user.
IMP On-line is designed to quickly and efficiently deploy applications involving process models. The engineer only needs to physically connect his PC to the network, browse the OPC Servers available and select the tags he wants to read or write back to the DCS. With no need to write a single line of code, he may specify the preferred options concerning a large number of possible configuration details, including bad quality management, tag limits, engineering units/conversions and tag filtering. IMP features built-in routines to allow straightforward implementation of biasing. After connecting, through ODBC, to external repository of lab data (LIMS) for automatic collection of lab analysis, different equations and different timing for bias computation can be set up for any configured prediction. Several filtering and data validation strategies can be selected and customized to fit the specific client needs. Results can be easily written back to DCS for single-window interface and trending.

A delayed coking is quite a receptive unit for modeling applications so IMP would impact greatly the project in several ways. Empirical models could be quickly developed to help predicting drum status and optimizing foam prevention, or to estimate furnace emission levels. Thanks to the powerful Model Explorer facility, plant engineers could exploit the same models built for and actually executing on-line, in off-line-mode, for what-if or scenario analysis, allowing to predict which would be the effects of a unit input change on plant behavior. Additionally IMP statistical process control capability (both univariate and multivariate) would represent a valuable tool to extend LPM monitoring functions from control loops to the whole process unit.

Finally the whole project execution would also be streamlined thanks to the integrated (and more performing) tools and the possibility to implement calculations (from bias update for inferential up to the logics to identify discrete events) on the hosting PC, avoiding any DCS configuration.
Diagnostics-oriented, monitoring or simply ancillary calculations, which could be required and/or simply useful after commissioning, could be easily implemented at any time into IMP without interfering with DCS primary functions.

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