cpmPlus
EXPERT OPTIMIZER 6.1

FUNCTIONAL DESCRIPTION

Use of DANGER, WARNING, CAUTION and NOTE

This publication includes DANGER, WARNING, CAUTION and NOTE information where appropriate to point out safety related or other important information.

DANGER Hazards which could result in severe personal injury or death
WARNING Hazards which could result in personal injury
CAUTION Hazards that could result in equipment or property damage
NOTE Alert users to pertinent facts and conditions

Although DANGER and WARNING hazards are related to personal injury, and CAUTION hazards are associated with equipment or property damage, it should be understood that operation of damaged equipment could, under certain operational conditions, result in degraded process performance leading to personal injury or death. Therefore, comply fully with all DANGER, WARNING and CAUTION notices.

TRADEMARKS

NOTICE

EXPERT OPTIMIZER FUNCTIONAL DESCRIPTION

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1. Executive Summary

1.1 ABB Collaborative Production Management Solutions

Most of the world's larger producers in all vertical industries (cement and minerals, metals, pulp and paper, oil and gas) are ABB clients. ABB CPM solutions enjoy market shares ranging to over 50% depending on the application.

ABB have best practices which have been proven & matured from experience with leading manufacturers; these practices are continually integrated into our Solution Portfolio.

Clients recognize quickly the potential, benefits and cost effectiveness of solutions developed and maintained by specialists with deep industry know/how.

1.2 Moving with Technology

cpmPlus Expert Optimizer is recognized as one of the best software platforms for real time implementation of advanced process control and scheduling solutions. cpmPlus Expert Optimizer, now in its 3rd Technology Generation, is based on the state-of-the-art Microsoft Windows operating systems with low cost of ownership – ABB keep and improve what works for our clients & remove or replaces what doesn't.

1.3 Helping our Customers to Do Business, More Effectively

ABB is a committed supplier to the worldwide vertical industries; it has partnerships with the most innovative corporations; ABB is the market leader in this area and is continuously working to deliver true customer value.

ABB provides fast consultative response to ensure optimal solution for your needs.

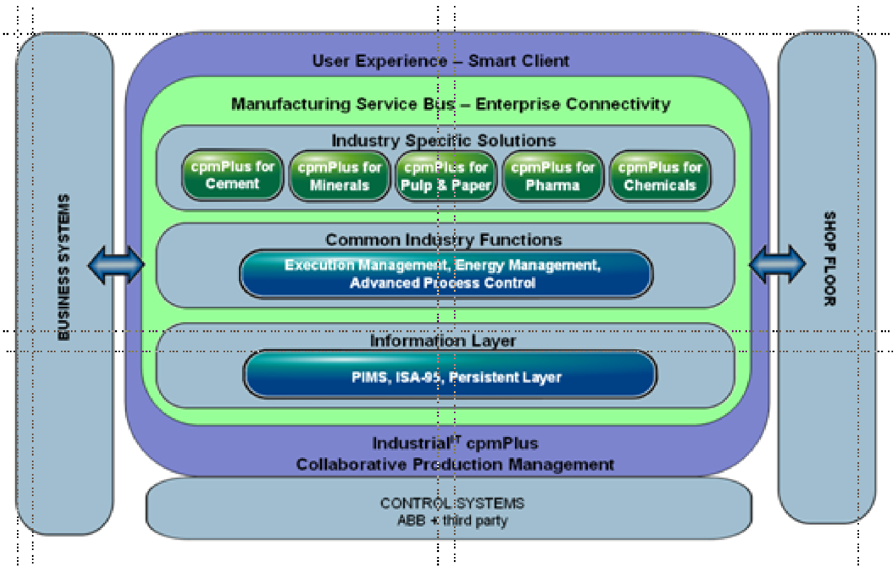

Figure 1: ABB's Industrial^{IT} cpmPlus

2. Introduction to Expert Optimizer

2.1 What Is Expert Optimizer?

Expert Optimizer is a hybrid intelligent system product developed at ABB, by engineers for engineers. It is primarily designed for closed-loop control, optimization and scheduling of industrial processes. Further, it can also be used for open loop decision support applications, although this is not its primary purpose. The product is shipped as a toolkit, on which users can build their own industry-specific application solutions.

Moreover, several strategies for control and optimization of key industrial processes have been developed and implemented in Expert Optimizer that can be customized at plant sites by ABB engineers. Among others, strategies for control and optimization of

1. raw materials blending
2. calciners
3. rotary kilns,
4. vertical, ball and SAG mills,
5. flotation,
6. digestion,
7. distillation columns, etc

have been successfully installed in more than a 300 sites with outstanding customer satisfaction.

Control of today's complex real world problems requires intelligent systems that form partnerships with different control techniques like rule based systems, fuzzy logic, neural networks, model based control, first principle models, etc. This is what Expert Optimizer has been designed for: it is open, flexible, versatile and able to comprise human-like knowledge within a specific domain. Moreover, it adapts and learns in changing environments, making decision and taking actions.

Figure 2 depicts details of the advanced control techniques available for strategy development in the Expert Optimizer Toolkit: complete integration of different control methodologies into a single environment has been fully achieved.

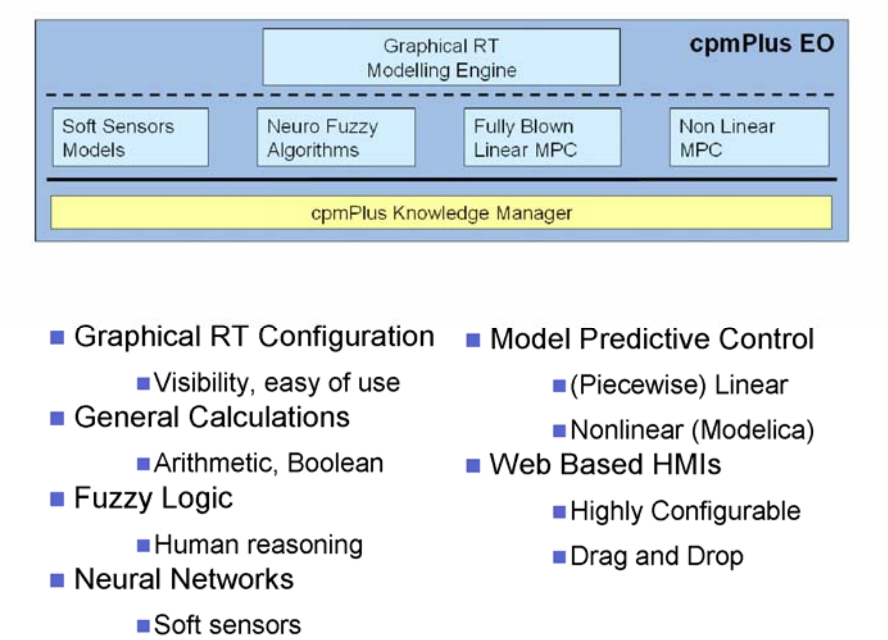

Figure 2: Expert Optimizer Technology

Note that Expert Optimizer is not a substitute for a plant DCS or PLC system. Rather, this software package is a high-level supervisor that supplies setpoints to the (PID) loops implemented at the lower level systems.

This document gives an overview of the functionality that is available to Expert Optimizer Toolkit users and outlines the system structure.

2.2 How Would Expert Optimizer Benefit your Plant?

The best possible control strategy is applied consistently at all times. This leads to strong reduction in process variability. Whereby the process can be brought to the optimal plant setpoints, which are usually the optimal ones in the economic sense, e.g. maximal feed rate, lowest possible burning zone temperature, exact flame oxygen levels, etc.

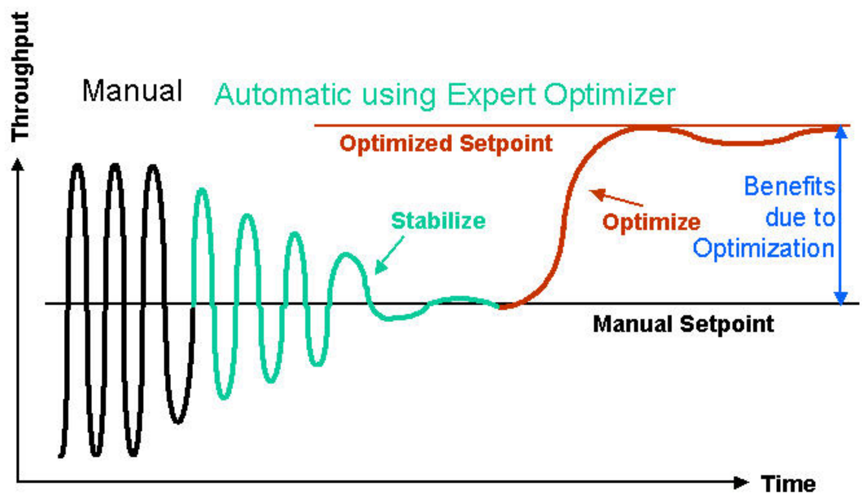

Figure 3: Expert Optimizer actions

Typical benefits of having Expert Optimizer controlling and optimizing your process are listed below. You can expect payback times of less than a year.

Direct Benefits for a typical plant

• Increased Output	**3 to 5%**
• Reduced Fuel Consumption	**3 to 5%**
• Reduced Emission Levels	**varies upon plant conditions**
• Reduced Power Consumption	**3 to 5%**
• Reduced Refractory Consumption	**10 to 20%**
• Reduced Quality Variability	**10 to 20%**

Indirect Benefits

- Enforcement of best operating practices
- Enhancement of process-specific knowledge
- Staff effectiveness

2.3 How Is Expert Optimizer Used?

Typically, the user starts with an industrial process problem where a hybrid intelligent system solution is possible. Then the Expert Optimizer Toolkit is used to implement the rules and mathematical models that provide the control solution to the process. These rules and models are known as the “Knowledge Base”. The control strategy may involve any combination of Fuzzy Logic, mathematical functions, Boolean logic, Neuro-Fuzzy and Model Predictive Control.

The decisions over what tool functions are necessary in developing a solution are dependent on the amount of process knowledge and understanding available. As a rule, the first step is to analyze the process knowledge available. Having done that, the next stage is to use Expert Optimizer Toolkit functions to build the core parts of the solution or a control strategy. In particular, the strategy

1. pre-processes the input variables,
2. combines the various control techniques,
3. and provides calculated outputs in the form of changes to the setpoints of the regulatory control.

In other cases the system simply provides advice to the operational staff for their action.

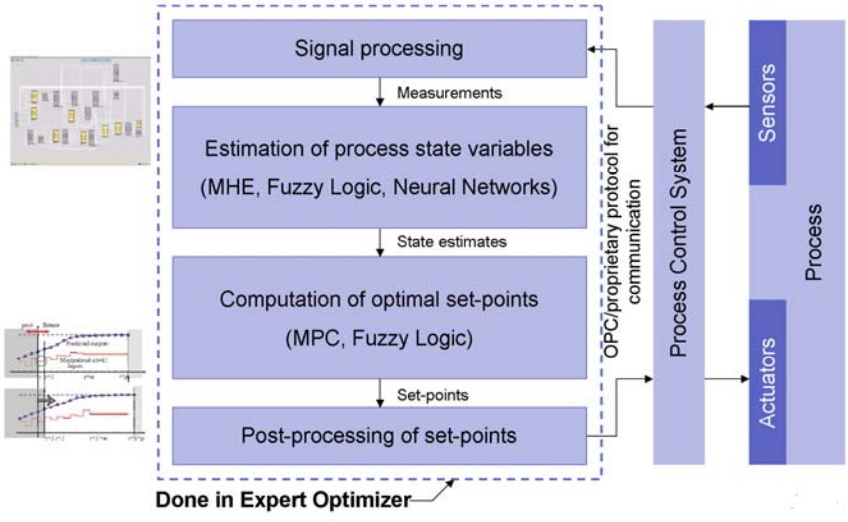

Figure 4. cpmPlus Expert Optimizer Strategy Layout

Clearly, our customers can tap the vast experience gathered by the ABB's process engineers by commissioning ABB to develop the strategy best suited to optimize their dynamic process. Otherwise, the second possible option for the end user is to bring the process knowledge into the control strategy by themselves.

ABB offers comprehensive toolkit training and application support for Expert Optimizer end users, helping them to develop and implement better process control and optimization strategies in a reliable and fast manner.

Throughout these processes, the activities of the Expert Optimizer Toolkit are clearly visible using graphical techniques in the form of operator displays, survey pages, or engineering displays. The transparency of the strategies developed in the Expert Optimizer Toolkit allows the engineer to focus on the quality of the process optimization solution

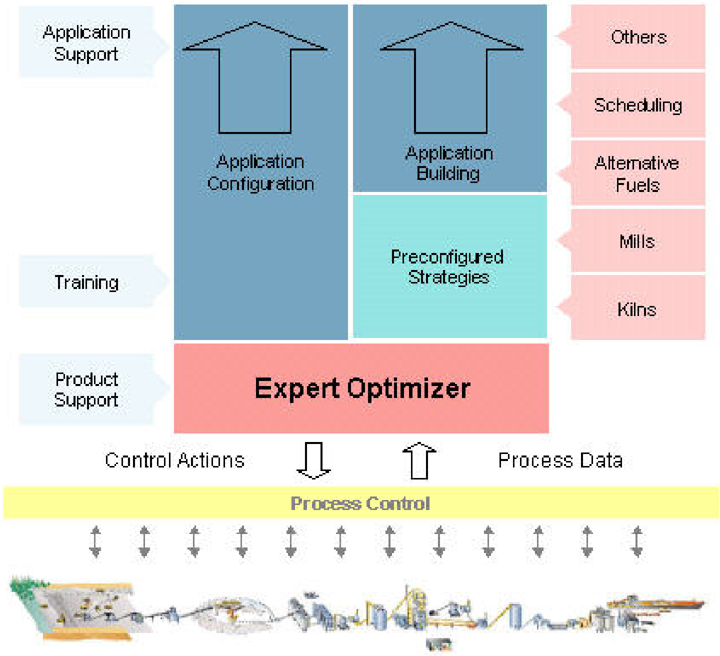

Figure 5: Expert Optimizer project

3. Architecture

The Expert Optimizer (EO) architecture is based on a 4-tier model with the following structure.

- EO Visualization Client: thin client user interface "Viewer"
- EO Application Server: business and control logic
- EO Database Server: persistent data storage
- EO Data Collector: data collection from analyzers, PLC's, historians, etc.

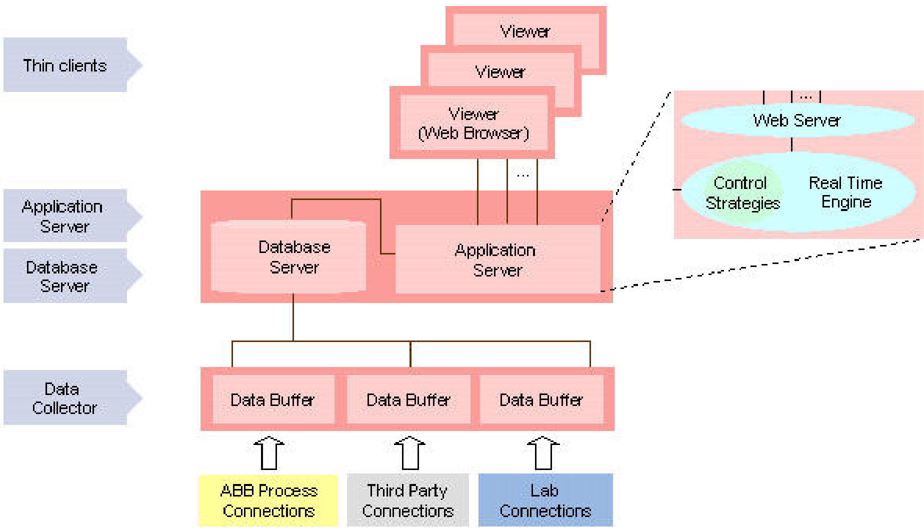

Figure 6: EO 4-tier software architecture

3.1 EO Visualization Client

Expert Optimizer Visualization Client brings all server functions to the MS-Windows® environment. Expert Optimizer Visualization Client provides comprehensive and easy to use graphical tools based on the latest web browser technology.

Expert Optimizer Visualization Client uses thin client technology and thus runs on standard web browser software. The user simply has to open a web browser and enter the address of the Expert Optimizer server. Easy swapping to other web-based applications, local or remote, is an inherent advantage of the web technology. Chapter 4 gives more details on this topic.

3.1.1 EO Application Server

The EO Application Server provides services such as data consolidation, user authorization, client data access, and scheduled report generation. The services are implemented as a set of objects and server processes.

The EO Application Server consists of:

- EO data consolidation that rolls up the primary log data to hourly, shift, daily, monthly and yearly values
- EO historical data recording, fetching the primary log information from the data collector nodes and storing them in the EO database.
- EO application modules (model predictive control, scheduling, etc.)
- Web Server for publishing HTML templates
- EO business objects providing access services to historical data and configuration information
- Client software installation support; the EO server includes the automatic installation kits for the EO Visualization Client client ActiveX controls.

3.1.2 EO Database Server

The EO Database Server provides continuous storage for historical logs, application configuration data, system error logs and system audit logs. It also supports basic statistical calculations as standard consolidation functions for the data (daily, weekly, monthly AVG, STD, MIN, MAX).

3.1.3 EO Data Collector

The EO Data Collector fetches the data from the process control systems and lab equipment and stores it in the historical log.

Expert Optimizer is control system independent. Information Exchange Software to most common process control systems, analyzers, laboratory equipment, etc. is available.

For small and medium size systems the data collector typically resides on the same server machine as database server.

Separate Data Collector nodes can be used when:

1. there is a requirement to have data collected remotely from the EO server (e.g. when the EO server is to be located in an IT center as opposed to close to the control system)
2. there is a requirement for raw data buffering outside the EO server.
3. increased collection and processing load needs to be distributed

4. Expert Optimizer Visualization Engine

Expert Optimizer's visualization engine (VE) brings the Expert Optimizer server functions to the MS-Windows® environment. Expert Optimizer VE provides comprehensive and easy to use tools based on the latest web browser technology to create rich graphical user interfaces.

4.1 Thin Client Capability

Expert Optimizer VEs run on standard web browser software and thus there is no need to install any additional software on the client PC in the operator stations. With lower installation and maintenance cost, it also benefits user flexibility: the user can work from any workplace. Moreover, in companies with centralized IT, there is no need to involve IT support to start using Expert Optimizer. The user simply has to open a web browser and enter the address of the Expert Optimizer server. Easy swapping to other web-based applications, local or remote, is an inherent advantage to the web technology.

Figure 7: Expert Optimizer visualization engine

The system is divided into a maximum of eight sections, which map to the eight control areas supported in Knowledge Base Server, see Section 5. The user can select which area to deal with by initially using the object tree in the left. Having selected an area of the plant, the user can then use all the standard displays provided for that area. The user can navigate using the area keys, the menu bar, the toolbar and the hotkeys at the bottom of the window, as well as previous and next display keys.

4.2 Trending Package

VEs support integration of all modern methods of process data display and can be customized to exact user requirements. Current features include trending from historical logs, trending with events marked up, historical and current reports, specialist graphical displays such as control charts and Pareto charts, and operator current values displays.

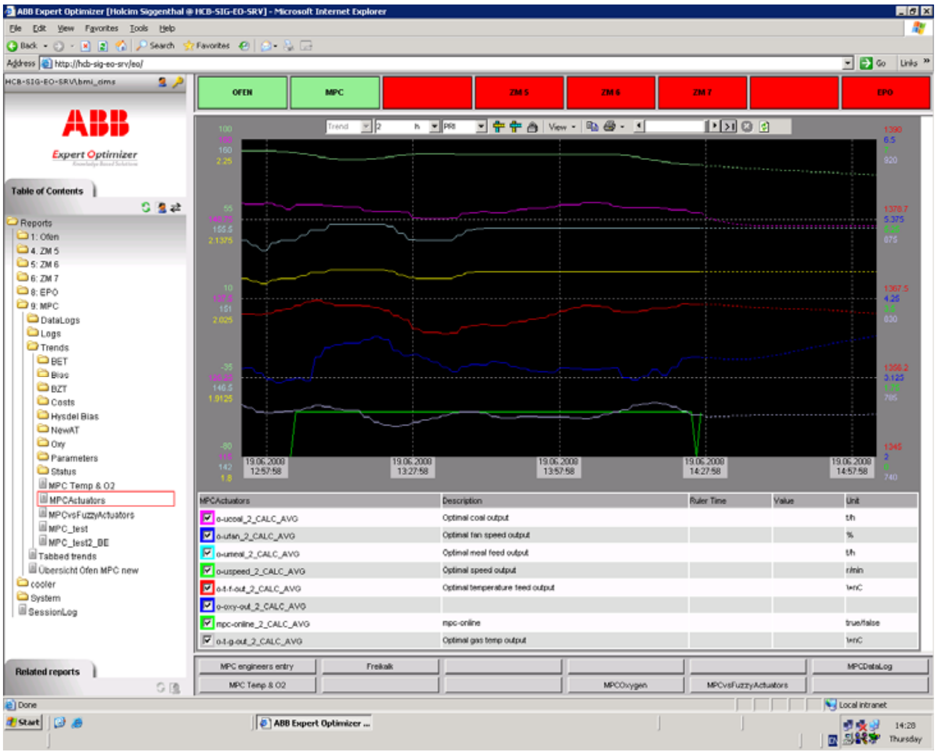

Figure 8: Expert Optimizer's trending package

Further, VEs allow the use of industry standard components to produce application specific operator displays to view and enter data. The VE connects to KBS to display operator and engineering information. In addition, the operator or engineer can use the VE to manually input values or targets into the strategy. The VE not only contains display layouts, but also supports the facility to build display applications in run time by dynamically loading pre-built forms. These forms can contain any Windows or ActiveX control that may be necessary for the application.

Note that all display layouts and configuration information are stored in the database so no use is made of the local PC disk. In addition, the real-time clock is obtained from the server.

The system also has its own trending package that can read directly from the database in real-time and implements specialist process controls such as control charts or time series graphs. Amongst others, VE supports the following features:

- Trending - normal time series graphs, control charts, CUSUM and EWMA charts
- Tabular displays
- Rolling action lists

- Entry buttons for text, real and logical values
- Check boxes for logical data
- Text displays
- HTML browser

4.3 Miscellaneous Functions

Printing facilities are all routed to the server for printing. The VE display layout supports the standard Windows Menu bar at the top of the display and a fixed toolbar underneath. The tool bar allows the user to access previous and next displays, print the whole display, access message logs, etc.

The VE supports a security model based on role requirements with passwords that differentiate between operator, site engineer and engineer. In addition, on-line help is provided.

The VE supports both dynamic and static explanations of how the strategy is controlling the plant. Static explanations are read in as Rich Text Files (RTF) or be displayed standard text about current strategy activity. Alternatively, the strategy can generate dynamic text with comprehensive explanations on actions being carried out.

The last 100 message board messages can be displayed by the VE. System messages are also displayed in the bottom right corner as well as in the Toolkit displays. System messages have a time stamp allocated by the Toolkit.

In the VE, navigation between displays is possible in three different ways:

1. Selecting an area by the appropriate area button, a folder by selecting the appropriate folder button, and by selecting the display from the drop-down list.
2. Via hotlinks between displays. Certain displays can be set-up so that by clicking in a specific area of a display, the user navigates to another display related to the first. This method is most often used for the strategy explanation pages.
3. Dynamic Keys. The twelve dynamic keys are located along the bottom of the screen corresponding to the function keys F1 to F12. The user can move to the linked display either by clicking on the button or by pressing the function key.

5. Core Application Development and Configuration Tools

Expert Optimizer control applications and visualization engine pages are developed with the help of the Knowledge Based Solutions Toolkit (KBST). KBST is executed on smart clients (Engineering Stations) but the data is saved and maintained in the server only. This means that only one (and consistent) copy of the structures created is kept at all times. Another advantage is that only KBST needs to be installed in the engineering station; no other special software is needed. Clearly, if desired, KBST can also be installed in the server. This section introduces the main features of KBST.

5.1 Visualization Engine Configuration

Visualization Engine pages are configured inside KBST using dedicated functions with the following capabilities and properties:

- Rich client application
- All-in-one configuration and administration of server application
- Only basic IT skills required for application development, modifications, maintenance, etc.
- Drag&Drop, Copy&Paste, fill-in-the-blanks configuration
- Property sheets, style sheets
- Graphical toolbox with pre-configured elements for easy configuration
- Inline scripting
- Cross referencing
- On-line help
- National Language Support

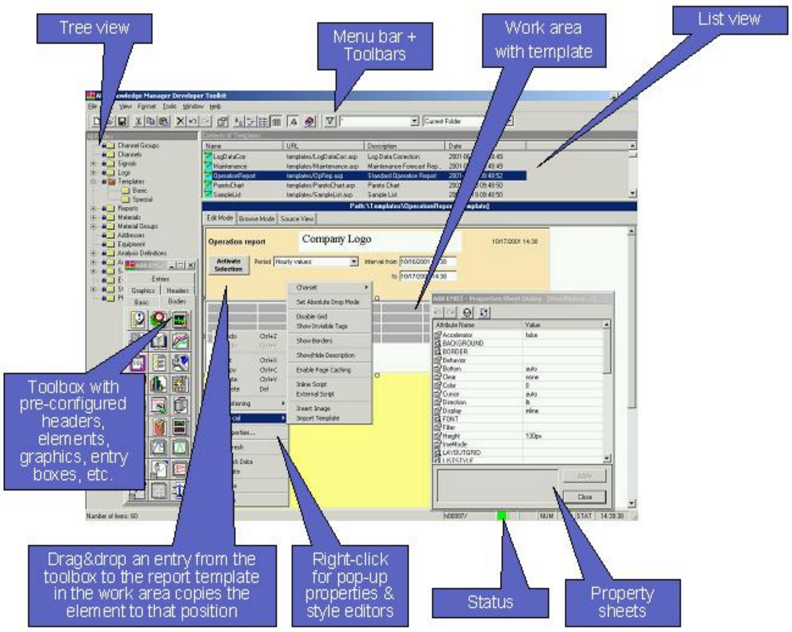

Figure 9: Engineering Toolkit view

5.2 Expert Optimizer Builder

Expert Optimizer Builder (EO Builder), which also resides in KBST, is the environment for building the Control Strategies. EO Builder capabilities allow the development of detailed and complex control strategies, which are then able to tie the input process to its outputs.

The toolkit provides a comprehensive variety of advanced control techniques. This ensures that the control strategy can be developed to the particular application needs. It comprises

- Mathematical Operations
- Boolean Logic
- Ruleblocks and Fuzzy Logic
- Neuro-Fuzzy Techniques
- Linear Model Predictive Control
- Nonlinear Model Predictive Control

Extensive palettes are available for process engineers to build their application solutions by picking standard components. When using the palette components the programming is done using data flow diagrams. These diagrams impose a structure on the strategy and thus make maintenance easier. They also allow the intermediate values in any calculation to be viewed, and therefore make debugging of the strategy possible. The calculation objects can be linked to plant inputs, plant outputs, to other objects, to operator messages or to historical logs. This process builds up the full application.

Typically, the process engineer will break up the strategy into various solution components with links showing data flow. Such solution components may be hierarchically arranged. This logical layout is presented to the engineer as graphical displays or workspaces that can be navigated. Flow lines carrying analogue or digital data can be examined, and data flows from the input of the strategy to the output by the next component, ‘pulling’ data from each source. These functionalities allow an efficient strategy development phase.

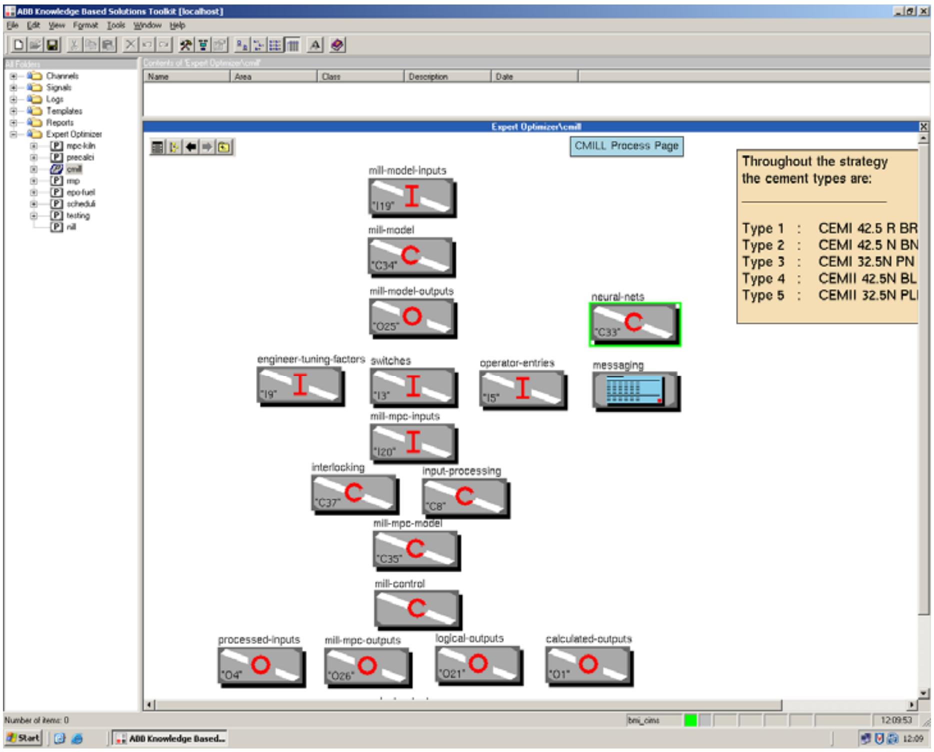

Figure 10: Expert Optimizer KBS Toolkit

5.2.1 Control Application

Control applications can be broken up into various independent modules, or areas, that may, or may not, be sharing the same IO source. Each area contains a complete strategy, which can be turned on and off independent of the other areas. Areas may be separate parts of the process that have different strategies or may be the same strategy repeated for multiple production lines. Each KBST has up to eight control areas. However, computer resource availability influences both the size of the control strategies and the number and frequency of IO point processing.

5.2.2 Strategy Objects

At the top level, a strategy consists of (see Figure 10):

- Input Modules, which define the analog and digital inputs from the process. Operator inputs are also defined in Input Modules. Data is acquired at rates of up to 1 second
- Control modules, which can be scheduled to run periodically up to a maximum of every 5 seconds. The control modules are the part of the Toolkit where the calculations are made. The modules take values from input modules or other control modules, execute mathematical calculations, and write outputs to other control modules or to the process.
- Output Modules, which define the outputs to the process and also the calculated outputs that are used for passing data between the different control modules contained in an area. Data is delivered at rates of up to 1 second.

5.2.3 Control Application Modules

Inside control modules, standard objects can be selected from a palette and dragged into position on a workspace. There, they can be graphically connected to other such objects, to IO values, or calculated outputs to perform a specific part of the strategy. Such objects include the following:

- Algorithms - Objects for processing raw data and for controlling the output of setpoints to the plant.
- Arithmetic - Trigonometric, ranges, random number, exponential, logarithmic and common mathematical operators.
- Counters - Count-up and count-down timers as well as timers that give a true output after a fixed period of time and timers that give a true output for a fixed period.
- Complex Data Flow Diagrams (DFD) – Secondary workspaces providing additional working areas for strategy design.
- Display objects - Objects for writing data from the strategy to display pages and allows comments to be added to the strategy.
- Filters - First-order filter, last-iteration value, decayed value, running average, gradient.
- Miscellaneous - Linking terminals, constants values.
- Logical - ISO logical AND, OR, NAND etc. truth tables, and latch.
- Moderators - special complex DFD’s that can be turned on or off according to the value of some control logic. This allows parts of the strategy to be activated or disabled as appropriate.
- States - State transition diagrams and conditions for state change. States are used to determine how the data should flow through the strategy according to the process conditions.
- Switching - Divert data flow depending on conditions.
- Symbolic - Allows basic text handling.
- Tests - Variety of objects that can be used for testing the value of data.
- Variables - Where appropriate, allows data to be read from and written to plant inputs, plant outputs, calculated outputs, and local variables
- Neuro-Fuzzy - An implementation of single layer neural networks that is suitable for on-line process control purposes.
- Ruleblocks - The Expert Optimizer Toolkit version of a set of fuzzy rules, gives continuously variable outputs across a state space depending on the value of the inputs.
- Model Predictive Control and Mixed Logical Dynamical Systems– allows the definition of mathematical models in the Mixed Logical Dynamical form that can be used for model predictive control, scheduling and/or to predict the future values of critical process parameters.
- Model Predictive Control with Black Box Models – allows working with models generated from raw data. These models can be incorporated into MLD framework to form a model of larger complexity.

- Nonlinear Model Predictive Control with Modelica Models – allows importing Modelica models into the Expert Optimizer framework for its subsequent use in nonlinear model predictive control iterations. Parameter estimation can also be carried out.

Graphical editing techniques are available to link the above objects and functions to build the control strategy. In order to assist the engineer, each object has extensive on-line help, and the connections are color-coded and position-coded to provide visual clues to the type of connection that is required for all data flow connections. This color coding also aids in the debugging of the strategy. For instance, connections that are not active have white data-flow lines. True logical data-flow lines are red, while false ones are black. Lines carrying quantitative data are always blue, and in any engineering mode, the value can be obtained simply by clicking on the line.

5.2.4 Statistical Process Control

Using the features available in KBST, additional statistical and monitoring control modules can be built to enhance specific Expert Optimizer application strategies. The statistical output from these can be viewed in the VE. Functions that have been built using the scripting language include:

- Pareto charts
- Analysis of violations of control limits
- Variance and F Tests to analyze process stability

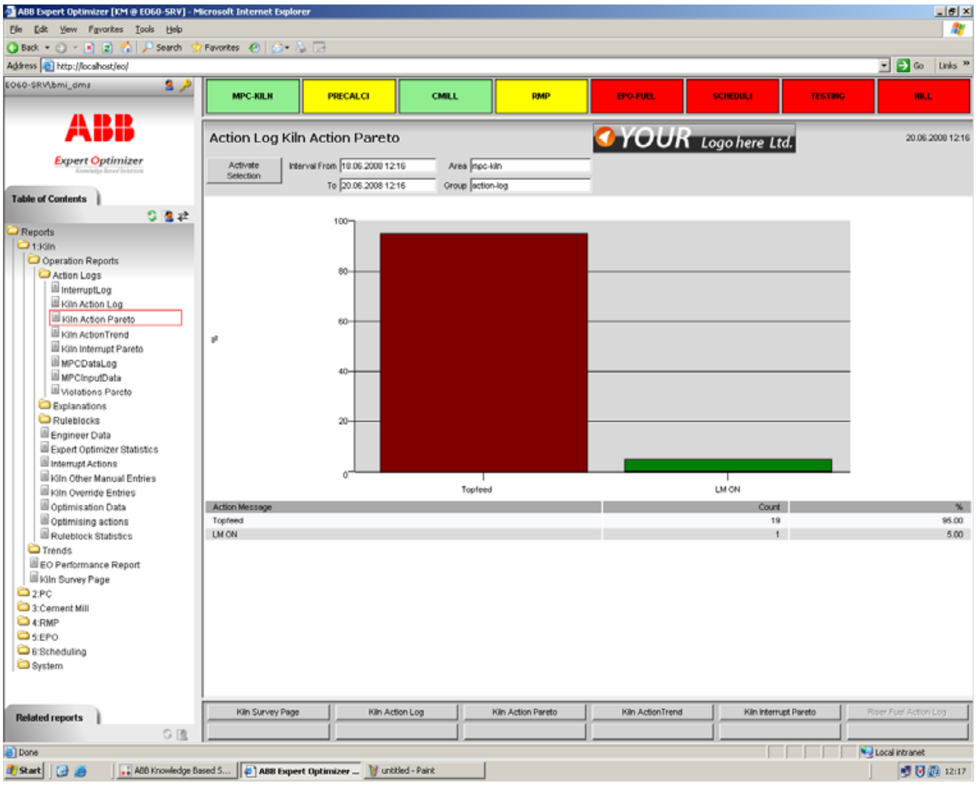

Figure 11: A strategy Pareto Chart display in Expert Optimizer

6. Fuzzy Logic and Neuro-Fuzzy Technology

One of the main strengths of Expert Optimizer Toolkit is that it offers Fuzzy Logic and Neuro-Fuzzy tools for the development of the application solution. Indeed, on the one hand, fuzzy logic inference systems incorporate human knowledge to make and implement effective decisions during the process. On the second hand, Neuro-Fuzzy networks are used to learn relationships between key process variables. Moreover, they adapt themselves to cope with changing process conditions.

The integration of all these complementary control techniques, coupled with ABB's extensive process experience and expertise, allows the engineering of powerful robust solutions, which provide substantial financial benefits to the factory for extended periods of time.

6.1 Neuro-Fuzzy Objects as Predicting Tools

The ability of Neuro-Fuzzy objects to learn relationships is an extremely powerful method of predicting important process variables. By using process variables that have a relationship with a desired output, a Neuro-Fuzzy object can be used to determine a predicted output.

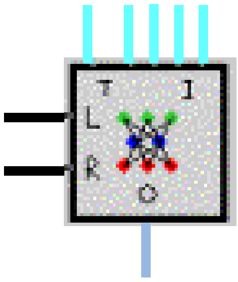

Figure 12: Basic Expert Optimizer neural network block

This technique is extremely useful when it is not possible to physically measure a process variable that is important to the control and optimization of the process. For instance, in mineral processing, an obvious example to be used in grinding is predicting particle size average as a function of the mill state and history. Another case would be the construction of free lime soft sensors as for cement kiln control.

Another important use of soft sensors is to provide a backup for critical process measurement devices. In case of failure of critical process measurements, a soft sensor can provide the control strategy with a usable estimate of the missing measurement. This allows for the control and optimizing system to continue to work to its objectives while the failed device is repaired. A typical case would be creating soft sensors to backup the burning zone oxygen measurement.

In principle, it is possible to develop numerous Neuro-Fuzzy applications to predict the same magnitude, but using different process variables. This allows for a situation where the different Neuro-Fuzzy predictions compete for the right to be used in the developed control and optimizing strategy. This ensures that the best prediction is always used.

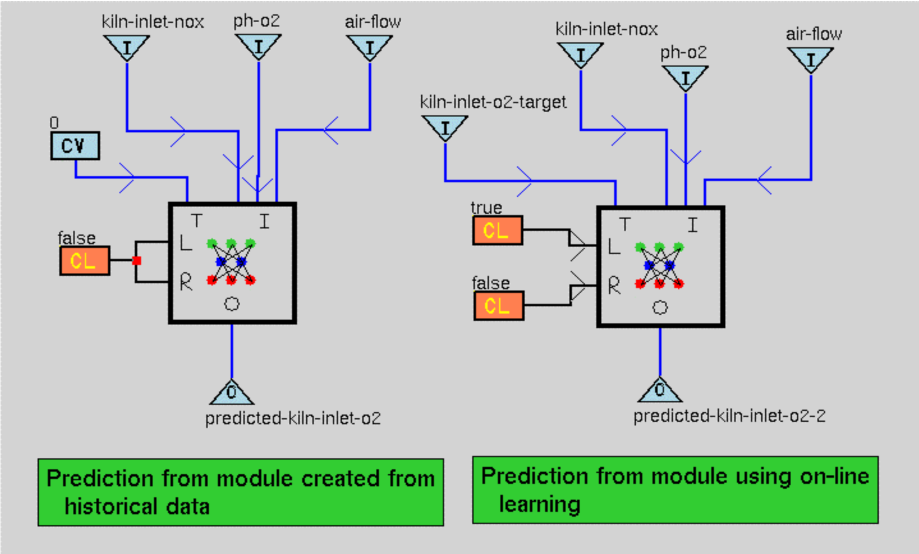

Figure 13: Concurrent soft sensors

As the process conditions change, the Neuro-Fuzzy applications are able to adapt. This ability ensures that the prediction is relevant to the changing process conditions. This ensures that only sensible changes are fed through to the process.

6.2 Neuro-Fuzzy Excel Tools

Neuro-Fuzzy networks are used to learn relationships between key process variables and adapt themselves to changing conditions.

In order to provide off-line learning capabilities the Neuro-Fuzzy Excel add-in has been developed. In this way, engineers can work in an environment that they are already familiar with, which increases their productivity. A custom Excel Toolbar allows access to the Neuro-Fuzzy Excel Tools.

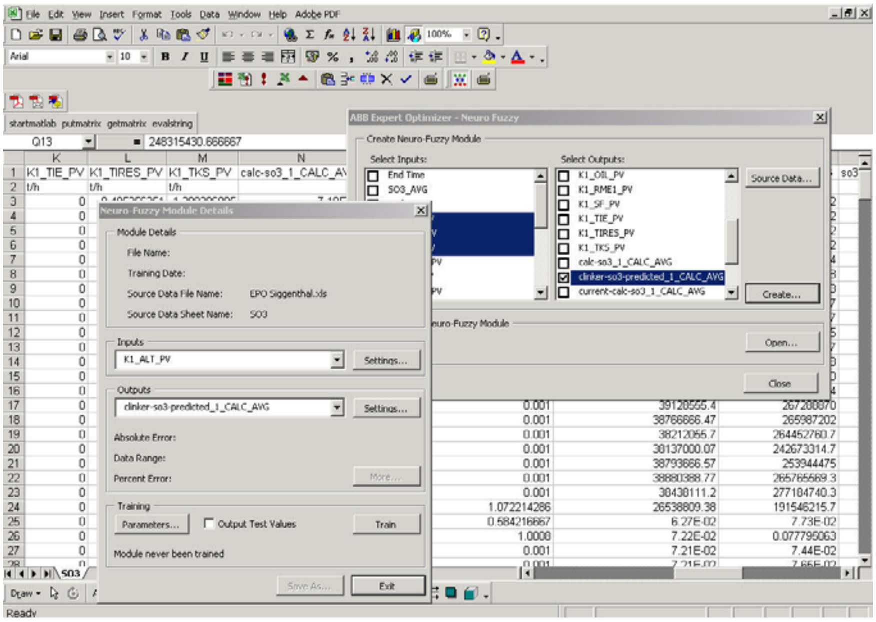

Figure 14: Expert Optimizer Excel Neuro Fuzzy Toolkit

The Neuro-Fuzzy Excel Tools provide tools to achieve a number of important functions. The main ones are mentioned below.

- Data Collection: automatic downloads of data from
  - the Expert Optimizer database
  - a Knowledge Manager database
  - any other source in an Excel format
- Data Preparation
  - Automatic or manual removal of out-of-range data
  - Set time offsets to data
  - Automatic or manual data normalization
- Creation and training of Neuro-Fuzzy Modules
  - selection of Inputs / Outputs / Family and Learning Rate
  - Created module performance report (e.g. by means of %Error and %Spread)
- Remote Operation
  - The functions can be executed remotely from the Expert Optimizer Toolkit
- History
  - A table is generated with the all created Neuro-Fuzzy modules for storage
- Export To The Expert Optimizer Toolkit
  - Created Neuro-Fuzzy modules can be directly imported into the Expert Optimizer Toolkit

6.3 Summary of Neuro-Fuzzy Capabilities

- Predict key process parameters
- Develop soft sensors
- Integrate into an expert system and allow for prediction reasoning
- Influence solutions through hierarchical competitive solutions
- Learn relationships among key process variables for process optimization
- Learn relationships between key process variables and production
- Constraints for enhanced optimization
- Adapt to changing process conditions

Additionally, off line neural network training capabilities are provided via Excel import, export and training functions.

7. Model Predictive Control Based on Mixed Logical Dynamical Systems

Optimize[IT] Expert Optimizer uses the so called Mixed Logical Dynamical system approach for mathematical model creation. This decision is based on the fact that this approach allows considering both continuous and Boolean states, inputs and outputs along with linear constraints on them. This is especially useful for economic process optimization type of applications.

7.1 Model Predictive Control

Model Predictive Control (MPC) is based on the so called receding horizon philosophy, i.e., a sequence of future optimal control actions is chosen according to a prediction of the (short to medium term) evolution of the system during the interval $[t, t+T]$, where t is the current time and T is some application dependent prediction horizon length. The first term of the sequence is then applied to the plant. When measurements (or new information) becomes available a new sequence, which replaces the previous one, is determined. Each sequence is computed by means of an optimization procedure, which takes into account two objectives:

1. optimize the performance and
2. protect the system from constraint violations.

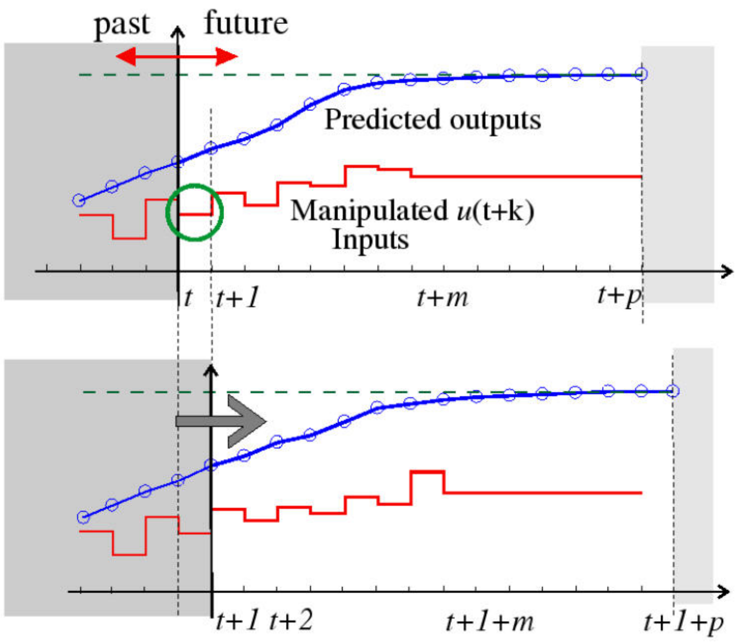

Figure 15: Model Predictive Control basic idea

There is extensive literature on the properties of controllers obtained via this procedure. In particular, stability, robustness and measurement feedback control under these conditions are well covered issues.

MPC is often used for control and optimization of industrial processes. For instance, in power generation these algorithms compute optimal setpoints for temperatures, pressures and fuel feed rates during the startups and shutdowns of large generating units. Similarly, model predictive control is one of the building blocks of today's state-of-the-art process industry.

Usually, the use of these techniques for real plants includes the development of (nonlinear) mathematical models describing the process, and the selection/design of a suitable cost functional, which takes into account the goals to achieve. For instance, the functional might penalize deviations from given desired operating points, or represent operating costs. The optimal inputs to the system are calculated via minimization of this functional, subjected to the constraints defined by the mathematical model. Clearly, to be successful the minimization algorithms must exploit the structure of the problem, as given by the model type and the optimization functional characteristics.

7.2 Mixed Logical Dynamic Systems

A mathematical model in MLD formulation has the form

$$x(t+1) = Ax(t) + B_1u(t) + B_2\delta(t) + B_3z(t)$$
$$y(t) = Cx(t) + D_1u(t) + D_2\delta(t) + D_3z(t)$$
$$E_2\delta(t) + E_3z(t) \le E_1u(t) + E_4x(t) + E_5$$

where $x(t) \in \Re^n$ are the continuous and binary states, $u(t) \in \Re^m$ are the continuous and binary inputs, $y(t) \in \Re^p$ are the continuous and binary outputs, while the vectors $\delta(t), z(t)$ represent auxiliary binary and continuous variables, respectively. The elements A, B_1, B_2, B_3, C, D_1, D_2, D_3 and E_1, E_2, E_3, E_4, E_5 are matrices of appropriate dimensions. Auxiliary constraints on the states, the inputs and the auxiliary variables are expressed via inequalities involving the matrices $E_i, i = 1 \ldots 5$.

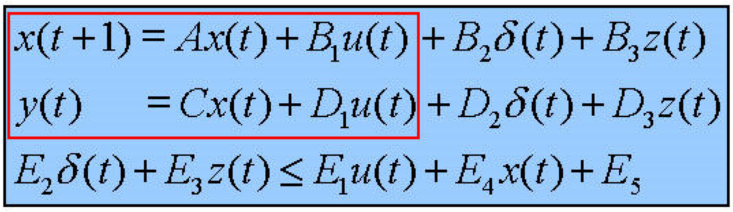

Figure 16: Mixed Logical Dynamical Systems

Using mathematical models in the Mixed Logical Dynamical system formulation is natural for several reasons. Firstly, it includes continuous and Boolean states, inputs and outputs. Secondly, it contains the description of all logical relationships of the process. Moreover, it allows the inclusion of piecewise linear relationships in the modeling with the sake of approximation of nonlinear relationships. Last but not least, there is a standardized way to treat model predictive control exploiting MLD models.

This approach to model generation increases dramatically the modeling possibilities. In particular, it allows for representation of processes as diverse as turning on/off parts of the plant, different types of start up and shutdown procedures, as well as the introduction of complex operating constraints like the switching between different operating conditions. Because of the presence of integer variables, the MPC scheme is formulated as a mixed integer linear or mixed integer quadratic program that can be solved efficiently.

It should be noted that Expert Optimizer's Neuro-Fuzzy blocks can be represented as an MLD system, which opens a whole variety of possibilities for black box model identification.

7.3 Graphical Model Building Toolkit

Model development is the crucial step in designing MPC based controllers. Not only they have a major impact on the performance, but they also are the major source of cost in the strategy development.

In order to address this issue the Expert Optimizer includes a revolutionary a graphical model development environment. This tool provides a palette of blocks that represent basic MLD models, which can be parameterized via drag and drop tools. These blocks can be dragged and dropped into the work area and linked graphically to represent the underlying physical phenomena and to design the desired cost function. Additional MLD blocks can be added by importing pre-compiled models into the workspace.

The general modus operandi is as follows.

- The process is decomposed in application dependent meaningful subsystems (e.g. feeders, mills, silos, belts, etc)
- Each subsystem is modeled independently by using a combination of blocks of the palette, and eventually, imported MLD blocks
- Subsystems are linked graphically. As a rule, the lines will represent mass and energy flows
- Apply drag and drop to parameterize the blocks
- Design and represent the objective function as MLD block

Generation of the overall process model, MPC problem solving and presentation of results is taken over by the software!

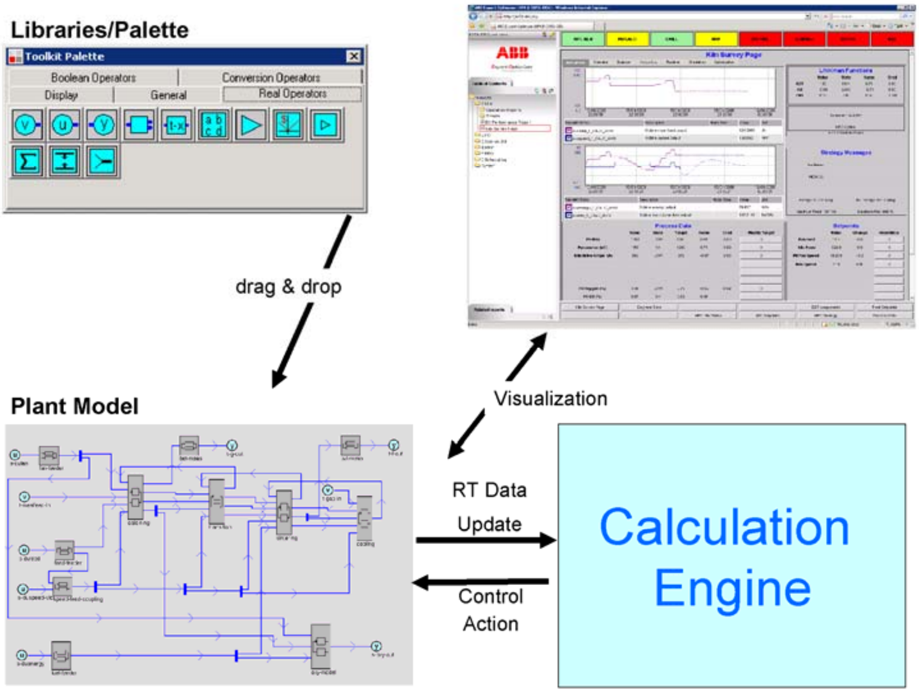

Figure 17: Graphical MLD Model Building Tool

7.4 Importing Linear Models

State space models of the form

$$x(t+1) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t)$$

with continuous variables u, x, y, can be generated from raw data, obtained for instance via step change experiments. This technique is known as system identification and there are well established methods for its application.

Noting that these models are just special case of the MLD models introduced before, Expert Optimizer offers the possibility of importing them in its graphical environment. In other words, user defined models may then be combined with model sections and cost functions constructed explicitly with graphical tools. This feature offers uniquely powerful capabilities for structured modeling and controller design.

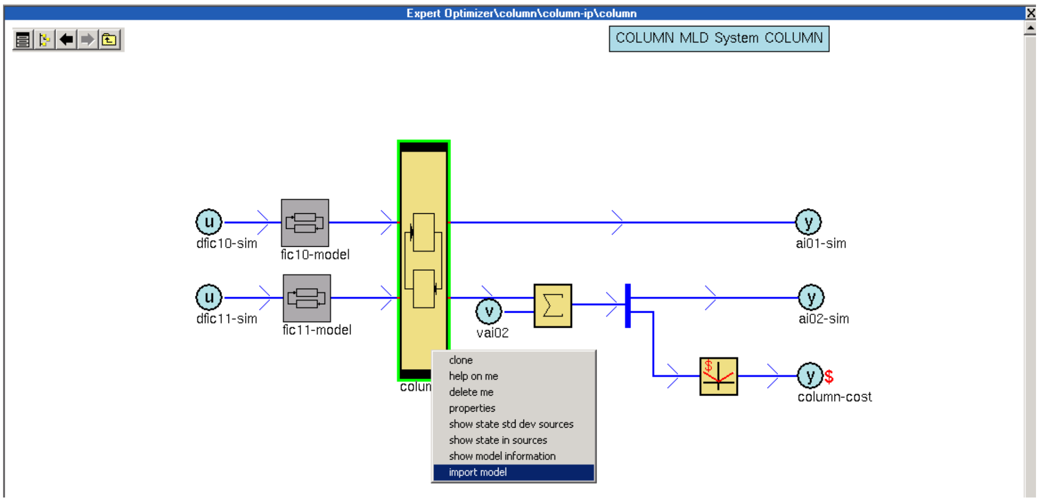

Figure 18. Context menu for model import in EO Builder

7.5 State Estimation in the Moving Horizon Approach

At every iteration an MPC controller needs a good estimation of the plant conditions. Mathematically, it means having a good set of values to initialize each and every state $x(t)$ in the model. Not only that it is often the case that the model contains states that are not directly measurable (e.g. mid kiln feed temperature), but also even direct measurements are often corrupted by noise and biases.

To deal with this problem observers or state estimators are constructed. This means given

1. the history of actuators moves and measurements $u(\tau), y(\tau), \tau \in [t-M:t]$,
2. and the plant model, including the constraints,

   the system calculates the trajectory of states $x(\tau), \tau \in [t-M:t]$ that better "explain" the given history and the model. Tuning parameters are the degree of trust on the existent measurements (so called measurement noise level) and in the model (process noise level).

Expert Optimizer implementation of this method hides all complexity from the user. All is required it is to attach to the model those variables containing the current values of the measurement and actuators. The system automatically collects the data needed, i.e. the values of actuators, measurements and model parameters, poses the associated mathematical programming problem and calculates the estimation of the states as required. Also automatically, these values will be passed to the MPC engine for calculation of the optimal moves.

This capability can also be used in standalone fashion for construction of (model based) soft sensors or even simply for noise filtering purposes. One example of this usage is the implementation of material balancing applications, where the values of certain magnitudes in the process (eg metal content oand/r reagent usage) are reconstructed by looking at magnitudes measured at other points of the circuit and a (simple) mathematical model of the installation.

7.6 Estimation of External Disturbances

Expert Optimizer graphical tools allow for inclusion of additive terms (disturbances) acting on the system. These were quantities that were known to the controller but out of its control. The capability was often used to model for instance the behavior of external sources of energy and/or material. So far, it was for the user to provide numerical values or trajectories for these magnitudes. Often that was a non trivial task.

Now though, using novel algorithms, Expert Optimizer is in the position to estimate best values for the additive disturbances acting on the model, releasing or at least supporting the user in that difficult task. It reaches this goal in ways closely related to the approach implemented for state estimation, see previous section. Again, mathematical complexity has been hidden at the maximum.

7.7 Constraint Prioritization

Hard constraints can easily lead to the optimization problem be unfeasible and thus to failure of the controller to produce reasonable values. In order to reduce the likelihood of this problem Expert Optimizer lets the user introduce a priority for each hard constraint. In case of unfeasibility, the Expert Optimizer engine will automatically substitute hard constraints in the lowest priority level with soft (if severely weighted) constraints and attempt to solve the optimal control problem again. If still not successful, Expert Optimizer will relax yet another set of constraints until priority level zero is reached. Actuator constraints always have priority zero. This is to avoid major violations of the controller specifications.

This feature is useful in conditions where conflicting objectives are present like when dealing with environmental constraints and performance specifications. It leads to increased robustness and predictability of results.

7.8 Linear Model Identification

cpmPlus Expert Optimizer includes an advanced graphical user interface for linear model identification from step change data. We will refer to this software as *Expert Optimizer Model Builder*. The tool is based on Industrial^{IT} Predict and Control. The main components of the EO Model Builder are:

- Configuration Tools
- Data Processing Tools
- Modeling Tools

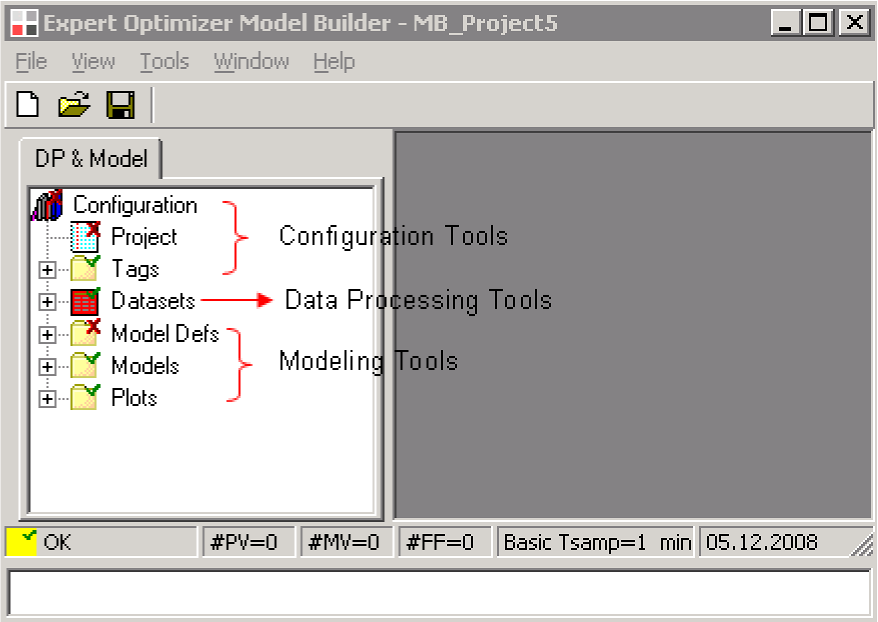

Figure 19 - Main components of EO Model Builder

7.8.1 Configuration tools

The Configuration Tools are used to create and modify a model. The configuration is a definition of the controller variables, which are classified as manipulated variables, process variables, and feedforward disturbance variables. The configuration also includes the definition of the basic sampling period and the names of the OPC tags (representing OCS/DCS tags).

7.8.2 Data processing tools

The Data Processing Tools provide functions for signal processing to generate datasets suitable for the model identification methods. Datasets can be created with the data import tool by importing log files containing recorded data or other acceptable file types containing data within Excel spreadsheets, comma-delimited text files, etc.

7.8.3 Modeling tools

Modeling tools are used for building models of the process from datasets. Modeling tools for model identification include

- methods based on subspace identification and prediction error techniques
- tools for editing, merging, and connecting models,
- capability for building user-defined transfer functions and state space models
- model evaluation tools, with various functions to assist the analysis

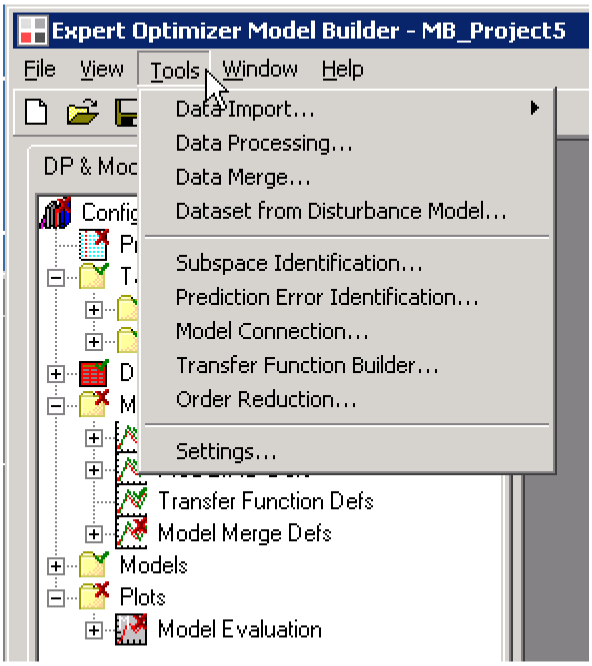

Figure 20 – Model Builder Tools

7.8.4 Model Export

Once the model has been identified, it can exported and then re-imported into the graphical run time environment of Expert Optimizer using capabilities described in Section 7.4.

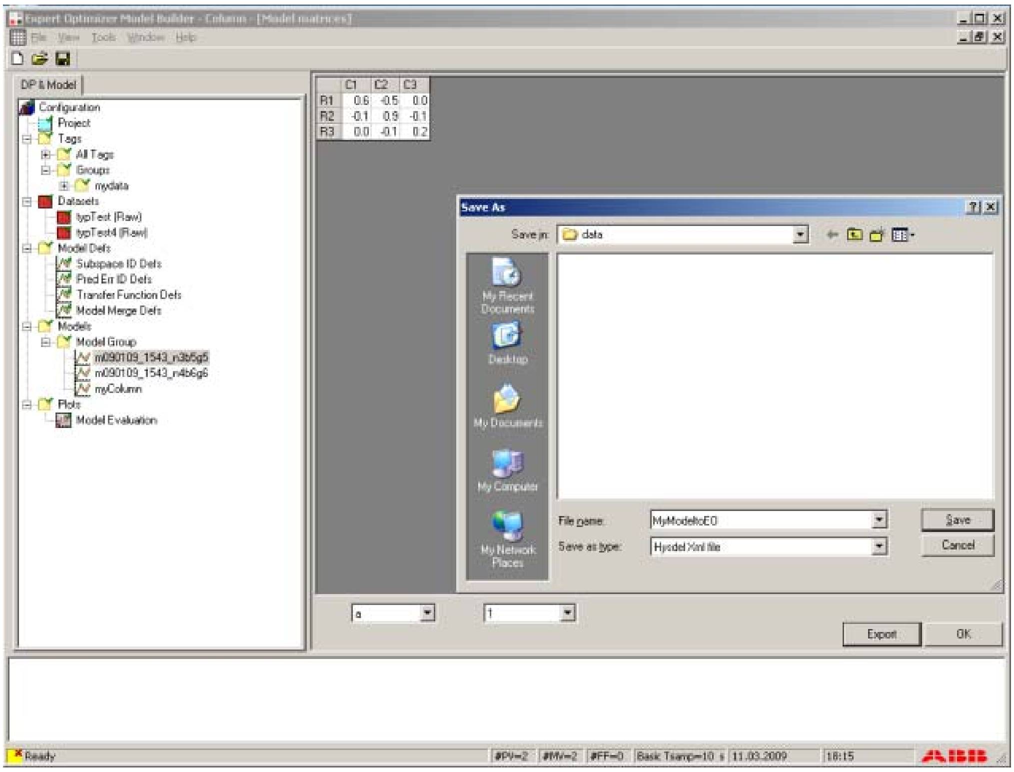

Figure 21. Exporting a model for usage in Expert Optimizer's real time engineering environment

8. Non-linear Model Predictive Control Based on Modelica Models

This section describes the implementation of solving non-linear dynamic optimization problems in the Expert Optimizer platform

8.1 Basics of Non-Linear Model Predictive Control

The general formulation of non-linear dynamic optimization problems is given by

$$\min \ \phi(x(T), z(T)) + \int_0^T f_0(x(t), z(t), u(t))\, dt$$

$$0 = F(\dot{x}(t), x(t), z(t), p, u(t))$$

$$u(t) \in U$$

$$x(t) \in X$$

$$z(t) \in Z$$

where, F defines a general system of differential algebraic equations (DAE). The variables x, z, u denote the differential, algebraic and manipulated variables, respectively.

The preferred choice of solving the above problem is to discretize the DAE into a finite difference equation using back-wards Euler. This results in a non-linear program (NLP). The resulting NLP is quite sparse and structured, which enables an effective solution when using modern software.

As measurements become available, a receding horizon approach can be implemented resulting in a powerful MPC controller. All concepts of the linear case (see Section 7.1) apply here.

8.2 Implementation of NLMPC in Expert Optimizer

Using the ABB Model Editor, a powerful software for model design and simulation that can licensed independently, the user can import his nonlinear models in the Expert Optimizer environment for immediate usage in NMPC fashion.

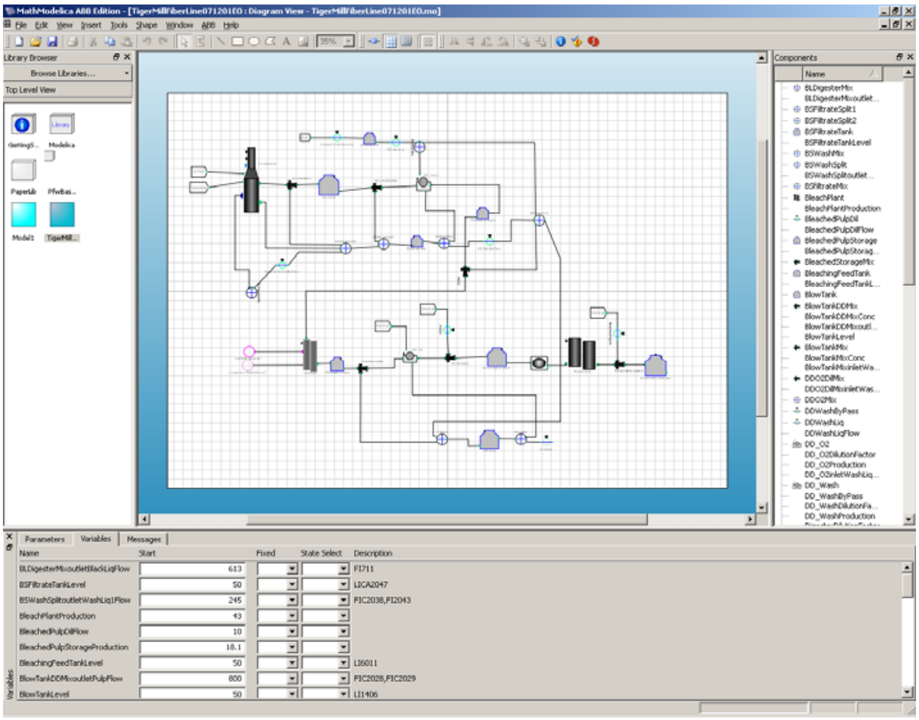

Figure 22: Nonlinear Model in ABB Model Editor

When one nonlinear model is imported in Expert Optimizer, the model is converted into a binary code, which provides interfaces to the state-of-the-art non-linear programming solver. The code is written in such a way that the number of discretization points and the grid-size can be changed without having to re-create the model.

Now these routines become linked to the Expert Optimizer graphical real time environment, where they are parameterized with drag and drop tools, and set ready for NMPC iterations. The comfortable look and feel of the linear MPC tool is maintained.

8.3 Nonlinear MPC Modes

In this section of Expert Optimizer, three working modes are provided; see the next three sections Disturbance estimation and constraint prioritization are not yet available in NMPC.

8.3.1 State Estimation

This mode also implements the so called Moving Horizon Estimation, where the model current states are estimated as the initial conditions that minimize a trade off (cost function) between sensor noise and process noise over a period of time where measurements are collected.

This capability can also be used for parameter estimation using the augmented state approach. The initial model should be modified accordingly.

8.3.2 Process Simulation

Giving an initial condition for the model states, this mode simulates the model into the future with the manipulated variables kept to their current values. This produces a representation of the system open loop behavior at the current conditions.

8.3.3 Process Optimization

Given an initial condition for the model states and a cost function defined as

- The sum of deviations from setpoints for selected model outputs plus
- the sum of selected outputs plus
- the sum of squares of selected outputs,

Expert Optimizer calculates the optimal values for the manipulated variables that minimize the cost function over a receding horizon. The associated trajectories for manipulated variables, model states and model outputs (controlled variables) are made available for display and further post-processing.

9. MPC Results Display Tools

9.1 Display of MPC Modes State Estimation, Simulation and Optimization in EO Builder

The models that are created in Expert Optimizer perform three tasks:

- Estimation of the states of the process model
- Simulation of the process model
- Optimization with the help of the process model

Estimation means that the states and all other variables of the model are estimated as part of an optimization problem that trades off the measured history of some key variables versus the relationships we know exist among them due to the process model.

Simulation of the model means that the current state of the process is given as inputs to the model. Then using MPC techniques, the evolution of the process can be predicted into the future.

Optimization of the model means that, using MPC, the model is evaluated into the future and will then give the optimal inputs. The optimal inputs are usually the setpoints that should be sent to the process to achieve the lowest "cost" within the constraints.

In the EO Builder the result of these three modes can be displayed for every single variable of the model.

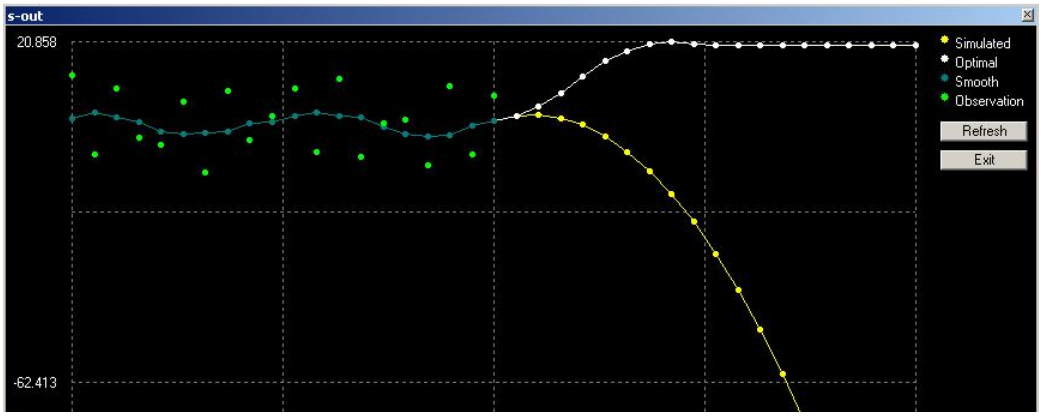

Figure 23: MPC modes results in EO Builder

9.2 Display of MPC Modes Simulation and Optimization in VE

When the Expert Optimizer is ***On-Line***, the process is controlled by Expert Optimizer periodically sending the optimal setpoints direct to the process.

When Expert Optimizer is ***Off-Line*** (supervisory mode) then the Plant operators can view a real time trend which shows the Simulated (Predicted) process values compared with the Optimal Process values as calculated by the MPC algorithm. This gives an indication of the direction the process will go if the setpoints are left at the current values, as opposed to the more preferable direction given by making the optimal setpoint changes.

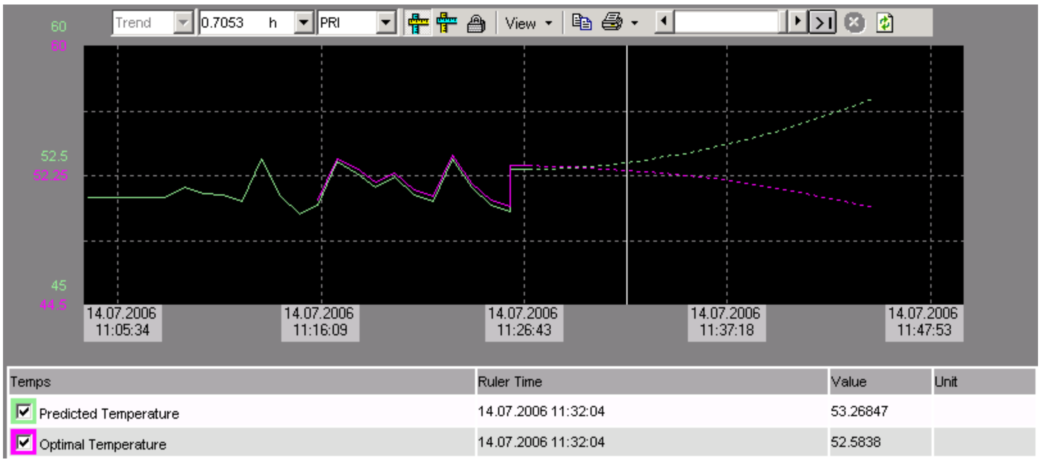

Figure 24: Trend displaying predicted vs. optimal

The trend display above is part of the Operator Interface in the visualization engine. It shows the history of process variables, alongside the future predictions (dotted lines) in simulation and optimization mode.

9.3 Entering and Displaying Scheduling Results

In order to meet the requirement of scheduling problems, Expert Optimizer offer web based functionalities for

1. entering time data related to
   a. availability of resources
   b. time structure of prices and/or costs tariffs
2. display of scheduling results
   a. Gantt charts, useful for showing the status of equipment in form of color bars long the time axis
   b. Steps trends, useful for showing time series of discrete values like switching on/off commands

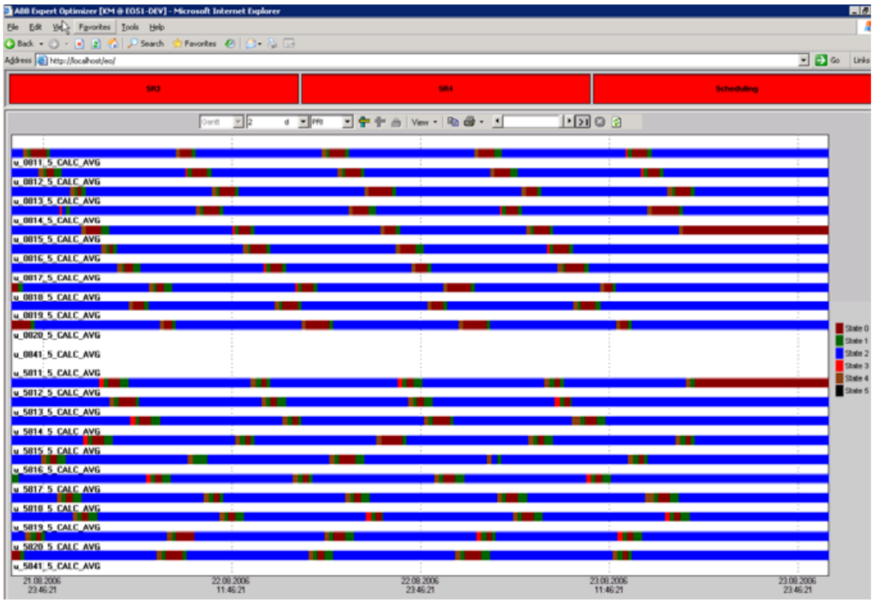

Figure 25: Gantt chart

10. Putting the Pieces Together

For control and optimization of a given plant we propose a control scheme, which

1. uses Neuro-Fuzzy techniques to filter and pre-process data and measurements creating reliable real time signals
2. uses Neuro-Fuzzy and/or standard MPC to stabilize the process on desired process targets and
3. uses MLD+MPC ideas to generate optimal reference trajectories or targets. This part of the algorithm is driven by optimization functional related to economic performance.
4. It might collaborate with other cpmPlus modules like cpmPlus Energy Manager in order to determine the modes in which the plant ought to run.

The solution architecture looks as follows:

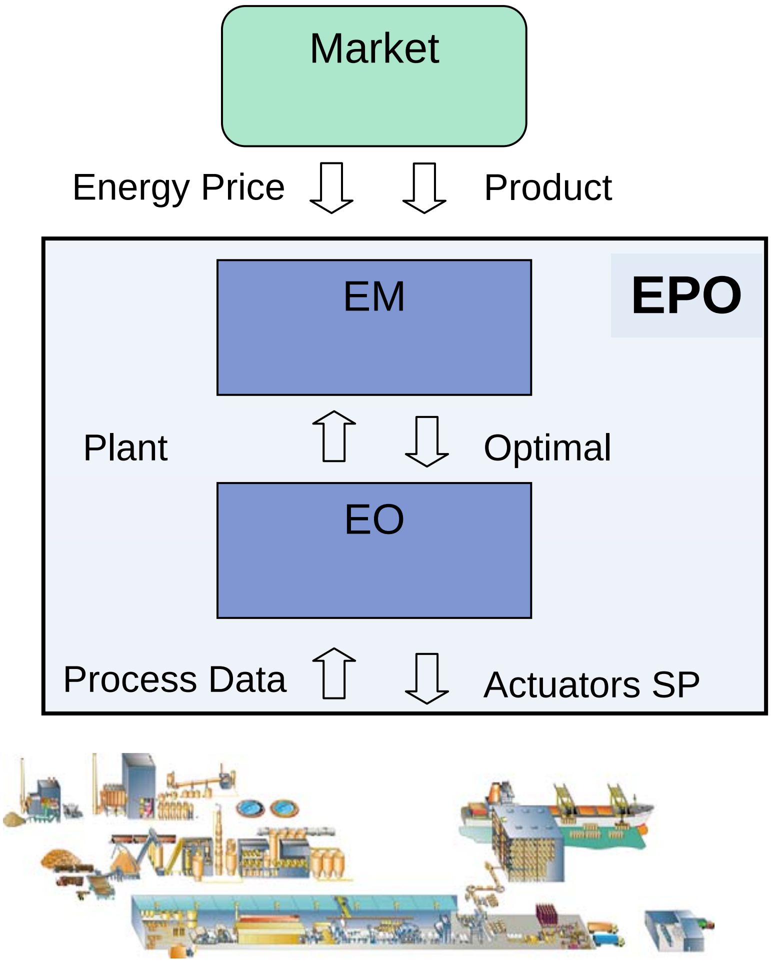

Figure 26: Economic Process Optimization

10.1 Typical Applications

Expert Optimizer Version 6.1 is extending the system well proven capabilities with model predictive control using models in the Mixed Logical Dynamical system form. We can foresee the following immediate applications to this technology

1. Industrial Steam Power Plant economic process optimization
2. Fuel mix optimization to reduce costs while meeting the process and environmental constraints
3. Production scheduling of grinding plant to reduce energy bills
4. Different kinds of model based soft sensors
5. Enhancements to kiln and grinding optimization
6. Flotation columns and banks
7. Plant wide flow management
8. Optimization of hybrid batch and continuous processes

11. I/O System & Drivers

The IO system allows the Expert Optimizer Toolkit to communicate with the plant via PLC and DCS Systems for input and output. An extensive range of I/O protocols is supported and additional custom drivers can be produced.

Input and Output data can be processed by the system at intervals of ten seconds or multiples of ten seconds.

12. Expert Optimizer Hardware Configuration

The basic configuration for the Expert Optimizer hardware is shown in Figure 27. The system uses PC technology.

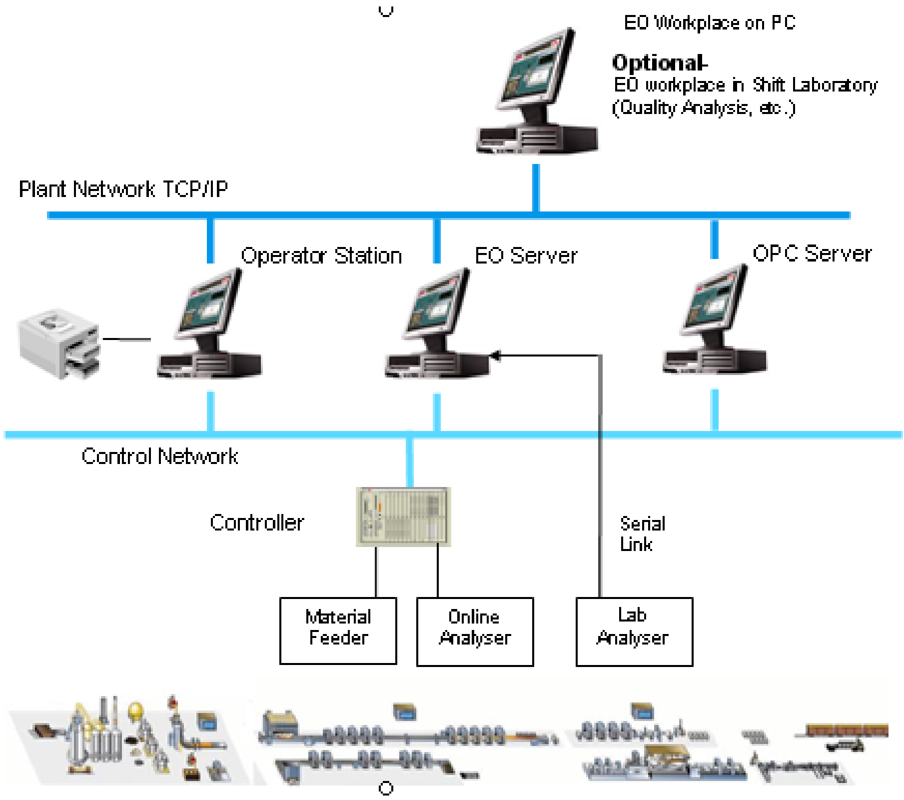

Figure 27: Hardware configuration

12.1 Expert Optimizer System Server

The purpose of the server is to run the expert system software, communicate with the plant PLC or DCS, and run the database.

The server is also used to run the network's services and output system error messages on a console. The power of the server determines the size of the expert system that can be run. Servers run under Windows Server 2003.

12.2 Expert Optimizer Engineering and Visualization Stations

The visualization stations are PC clients running on Windows OS. Each of them runs an operator interface as described in Section 4.

In addition, rich clients are used to display the expert system so that the engineer can work on the strategy. The use of the engineering stations is based on the use of floating licenses. Each system has a number of licenses that determine how many engineering interfaces can run at any one time. On experimental systems and on those controlling small number of plant areas, one engineering workplace is generally sufficient. On larger systems, two or more are generally best. One engineering license is normally supplied, and extras are available as an option.

13. Revision Table

Rev. ind.	Page (P) Chapt.(C)	Description	Date Dept./Init.
-		Original Issue, 3BHS212798	2005-04-18 ATBAM / EG
01	all	Update for version 5.0	2005-05-24 ATBAM / EG
02	P 22 C 7	Revision of MPC chapter	2006-09-18 ATBAM / EG
03	all	Revision to cover EO 5.0.1	2006-10-05 ATBAM / EG, SMcG
04	all	Update for version 6.0	2008-06-21 ATBAM / EG
05	all	Update for version 6.1	2009-03-31 ATBAM / EG