ABB Dynamic Solutions

The best available technology for advanced optimization applications

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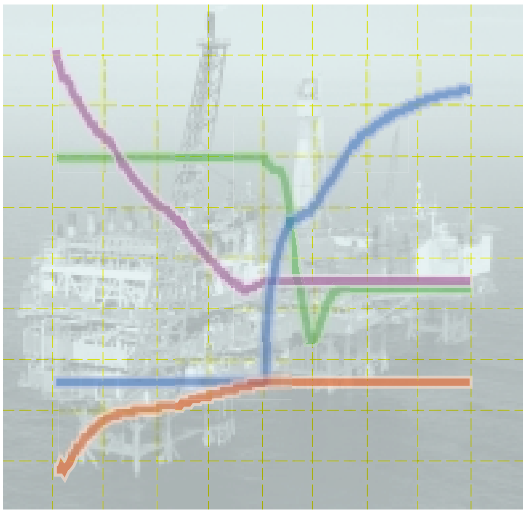
Integrated process modeling, control and optimization are emerging as the next product trends in the automation industry. ABB is setting new industry standards with solutions it builds on top of a high-fidelity modeling and simulation package. The solutions are part of the Optimize^{IT} product line in ABB's Industrial^{IT} portfolio.

ABB Dynamic Solutions offers the best available technology for advanced optimization applications in the process industries. The return on investment is enormous. In refining, for example, savings in excess of $ 6 million can be achieved annually by a 100,000 barrels/day plant simply by introducing ABB's new Optimize^{IT} in-line gasoline blending.



What industry needs to improve production quality and throughput is clear enough: better models and model-based solutions for optimizing the processes. Just as clearly, when the process has changing operational targets, these models need to be dynamic rather than steady-state. ABB has responded to this need with a software platform that permits advanced optimization for a wide range of industrial segments.

Dynamic Solutions

As their name suggests, ABB Dynamic Solutions applications are based on dynamic models. In effect, this means that ABB technology

- operates during transients (unlike steady-state applications, which have to be paused) and
- exploits process dynamics to reduce costs and improve production.

To gain technology leadership, ABB has launched a strategic partnership with Process Systems Enterprise Ltd (PSE) in London. PSE is a technology company that offers a process modeling and simulation solution environment, named 'gPROMS', regarded as the best available technology for process industry applications. gPROMS is further improved through ABB's automation knowledge and a developing process model library.

ABB Dynamic Solutions provides the platform 1 for managing and configuring models and applications as well as for the graphic display of results. The gPROMS dynamic simulation engine is offered with a graphic model builder, an extensive dynamic rigorous model library and an open-thermodynamics server allowing several types of physical property models to be solved in parallel with the process model. XML (Extensible Markup Language) has been selected as the data exchange format for application configuration. XML is a widely accepted standard for data exchange and is regarded as *the* 'language' evolving for the web and eCommerce applications. During run-time, the execution of application sequences can be scheduled. Dynamic data is exchanged between the functions in the suite and the control system via open communications protocols standardized by the OLE for Process Control (OPC) organization.

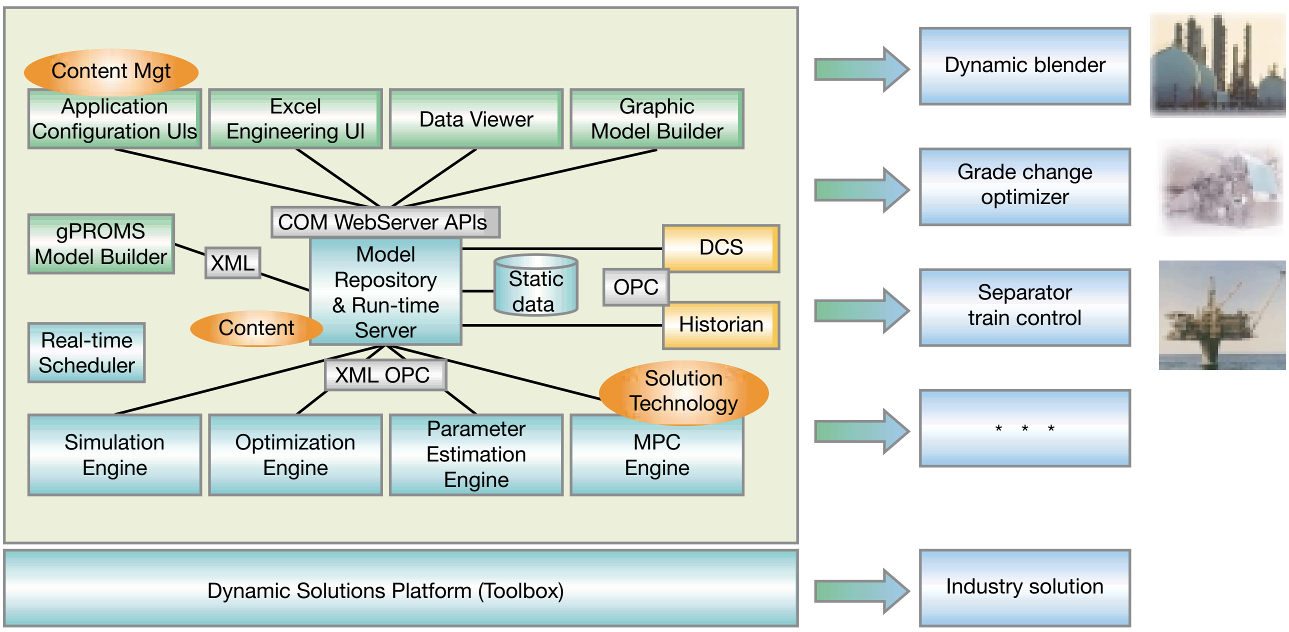
The platform is used to develop advanced applications involving high-fidelity simulation, real-time optimization, dynamic optimization, model-based predictive control, data reconciliation, parameter estimation, inferential measurements and blending. It can be applied within the process industries, including oil and gas, refining, petrochemicals, chemicals, pulp and paper, pharmaceuticals, metals and minerals.

Rigorous dynamic modeling meets model quality demands

As already mentioned, better operating performance calls for better models. Processes are generally non-linear and dynamic in operation, yet steady-state optimization ignores the dynamics and linear model-based control ignores non-linearities. While these assumptions can be sufficient where requirements are low, in many processes the non-linear effects and transients are so significant that linear dynamics and/or steady-state models are inadequate. Typical operational situations in which non-linearities and transients are important are process start-ups and shutdowns, load changes, major plant disturbances and recipe changes in batch or semi-batch processes.

Non-linear rigorous dynamic models can provide the precision required. However, the development costs for rigorous dynamic models were often prohibitive in the past. There were a number of reasons for this: modeling and application islands permitted little

1 ABB Dynamic Solutions platform for developing advanced process optimization applications for the process industries



model re-use; there were no commercial computer-aided tools with model libraries available, nor the computational power required to run demanding solutions. While progress in computer power has resolved the computation issue, ABB Dynamic Solutions overcomes the first two bottlenecks through the use of a graphic model builder for flowsheeting in conjunction with an extensive unit model library that enables even medium skilled users to effectively assemble rigorous, dynamic process models.

Model building

The models are built up from smaller unit models with ports for the connections. These ports are simply connections, not directed inputs and outputs as in common block-oriented modeling. In equation-based modeling, the models are transparent in the sense that the equations are visible outside the model, and they are therefore often referred to as open equation-based models. This is in contrast to sequential and block-oriented modeling, where each block must have an assumed causality. The equation-based modeling thereby allows a model of a process unit to remain the same, no matter how it is connected to other units. This allows unit model re-use even in different domains.

Modeling and simulation capability might include both differential algebraic equations describing lumped parameter systems, and partial differential algebraic systems for models where spatial variations are considered as well as time variation. The library includes unit models that are applicable throughout different industries. A Model Builder tool is provided to enable the user to design his own unit models and add them to the library.

Data model

A common data model is provided to ensure *consistent* data organization for the different tools in the suite, allowing them to be applied across different process industry segments. This overcomes the limitations of the modeling-island type of solution that prohibits model exchange, re-use, etc. The common data model includes equations for describing the behavior of the physical unit, as well as information about the physical design of the unit and applications.

Model library

A basic process model library has been developed as part of the strategic alliance between PSE and ABB. It includes unit operations, controls and basic system models such as pumps and pipes. Special domain unit models are also developed for certain industry domains such as pulp and paper. In addition to the predefined models, the gPROMS model builder tool permits the user to develop his own unit models and add them to the library.

[1] Jacobian – a determinant defined for a finite number of functions of the same number of variables in which each row consists of the first partial derivatives of the same function with respect to each of the variables.

Multiple model usage for consistency and reduced costs

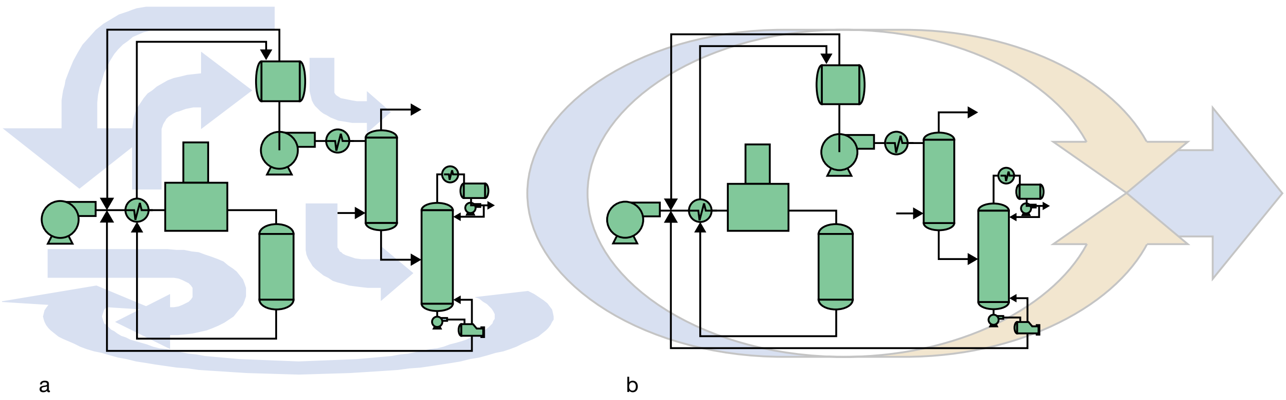
Open equation solution technology is used to solve the model. In equation-based technology there is no solver code incorporated directly in the models. The models consist of pure equations, variables and data in terms of parameters. This permits the process model to be used directly for different purposes (simulation, optimization, estimation, etc) so that the modeling cost can be distributed among several tools from the ABB Dynamic Solutions suite. Moreover, the model can be integrated with the most appropriate solution technology for each particular purpose. For simulation, for example, the solution technology is trimmed to optimally solve initial value simulation tasks. Solvers for dynamic optimization are trimmed to solve problems with additional degrees of freedom.

To achieve this multiple usage of the models, the Jacobian[1] of the system has to be available. In open equation-based systems, the Jacobian is obtained by finding the sensitivities of all equations with respect to all variables analytically before any simulation or optimization is performed. This significantly reduces the computational task compared with implementations where the Jacobian is obtained by numerical calculations.

Process simulation

In the case of classical sequential-modular simulators, the equipment/unit operation models are combined with the

2 Sequential-modular solution (a) versus ABB's simultaneous solution approach (b)



solver for the module. Each module is solved one after another, sequentially.

Taking a chemical process with a recycle loop as example, the sequential-modular solution technique requires several iterations in each simulation step in order to achieve convergence (if it can be achieved at all!). The sequential-modular solution approach was introduced several decades ago and is still prevalent in the majority of simulation tools on the market. Gradual improvements in the technology include simultaneously solved pressure flow networks, with the remainder of the model solved in sequential-modular fashion.

ABB Dynamic Solutions incorporates the modern simultaneous, equation-based solution technology. When performing simulations, the solver can treat the equations from all contained model objects as a single large set of equations for the entire process. The set of equations is solved simultaneously for the entire model. Systems exhibiting spatial distribution represented by partial differential equations are first automatically discretized by the solver, then the resulting set of differential algebraic equations is solved. This approach can be applied to all kinds of simulation, including engineering and training simulation. The two different solution approaches are illustrated in **2**.

Parameter estimation

Semi-rigorous and rigorous models have to address the following challenges:

- The model has to be tuned to reflect actual operational behavior.
- The model has to be adjusted to accommodate unavoidable changes in process behavior.

Models always contain a set of uncertain parameters (eg, heat-exchange coefficients, reaction activation energies, order of reaction) that cannot be directly measured. Therefore, models must be tuned to match the actual plant operation by using experimental and/or operational data. Traditional manual tuning is lengthy, costly and prone to error.

ABB Dynamic Solutions offers a parameter estimation capability that is tightly bound to a developed process model. Uncertain or unmeasured parameters can automatically be estimated from experimental or operational data in both dynamic and steady-state models. The estimated parameters are optimal in the sense that they minimize the quadratic cost of model mismatch from actual behavior.

Parameter estimation is not only applicable in off-line mode. A different challenge is raised by changes in process characteristics due to equipment aging, and by changes in feedstock and operation philosophy during the plant's life cycle. Parameter estimation can additionally be used on-line to estimate model parameters. In this way, a model can be kept updated to reflect reality and ensure the superior operational performance of the applications built upon it.

Data reconciliation

Because of measurement error, sensor faults and sensor drift, measured values are rarely consistent in a plant context. This means that material and energy balances are commonly found to be not consistent when based upon the raw measurement values. This causes problems in several areas. For example, yield accounting is not accurate and simulation and optimization start from inconsistent values, making true results unlikely. Significant financial losses are accumulated if process heat or product streams are billed based on wrong measurements or if process leaks go undetected.

ABB Dynamic Solutions include data reconciliation functionality. The process model is used to correct measurements: a bias term is added to each measured value such that all corrected measurements are consistent in plant context and minimize a cost function which punishes inconsistencies as well as corrections. The measured data are cleaned of gross errors before the data reconciliation step is executed. Data reconciliation works both in on-line and off-line mode, and has the advantage that it operates on all real-time sampled data available and not just steady-state 'snapshots'. The procedure also includes rectified material balances and leak detection capability.

Process optimization

ABB Dynamic Solutions offers scalable solutions for optimizing plant operations.

Model predictive control is the solution technology offered in the event that the process is approximately linear in the operating regimes under consideration. Should the process be strongly non-linear and operated in a way that makes this apparent (such as during load changes or disturbances), dynamic, constraint-based non-linear optimization will be offered as the solution technology.

Dynamic and steady-state non-linear constrained optimization

Dynamic constrained non-linear optimization technology is utilized for the calculation of optimal transients of a process under constraints imposed by finite inventories, finite control ranges and limits on variables along a trajectory. Examples include grade changes in paper mills or recipe changes in blending or other batch and semi-batch processes. The optimizer can run in either on-line or off-line mode.

Non-linear constraint optimization can be applied in both dynamic and steady-state cases. Sparse matrix numerics are used for best performance by exploiting the process model's structural information. The optimizer operates on the rigorous process model to identify actual process responses to changes that may be imposed upon it. Unlike model predictive control, the non-linear optimizer allows an economic cost function to be specified.

ABB's 3dMPC multivariable predictive controller

ABB's 3dMPC multivariable predictive controller offers leading-edge optimized technology. The underlying control model is based on modern linear state-space technology, thereby enabling it to estimate the present state and predict the future behavior of the process. When optimizing process operation (eg, increasing throughput and reducing variability of key process variables) the controller considers couplings between the controlled variables. Both soft and hard constraints can be handled. Remaining degrees of freedom can be used for further economic optimization of the process.

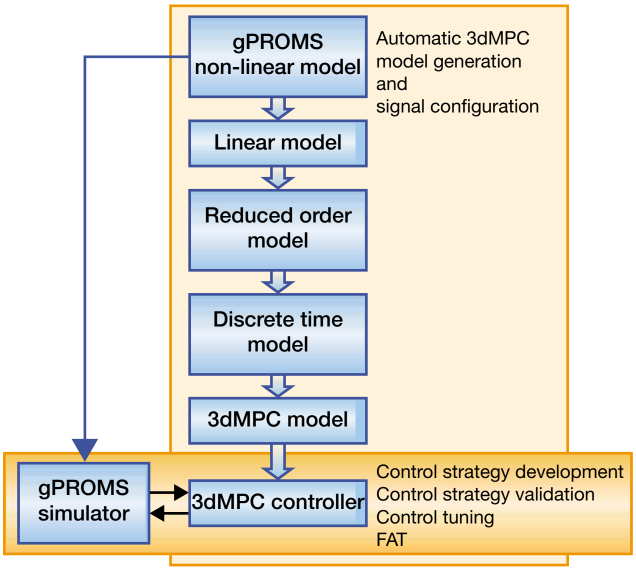
For non-linear processes operated in different operation regimes, 3dMPC can have different tuning sets. These may differ both in terms of the model and the tuning parameters. Static input/output non-linearities (typically originating from sensors and actuators) can also be included in the controller.

3dMPC consists of off-line engineering tools and an on-line controller package. The engineering tools include an identification module that utilizes state-of-the-art subspace and prediction error methods, a data preprocessing module and an internal simulator, as well as extensive tools for evaluating expected performance and robustness. The on-line controller package includes the controller, an operator interface, and features for performing identification experiments either in open or closed loop.

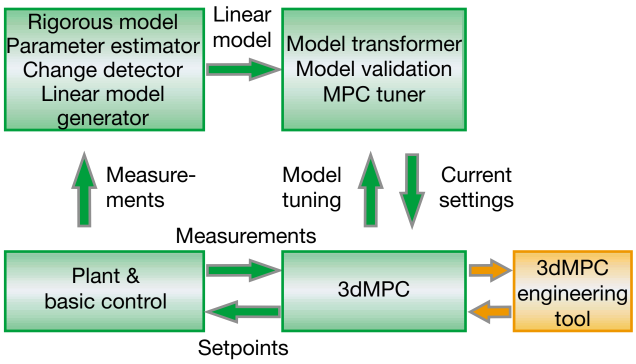
What sets 3dMPC apart from other commercial MPC controllers is a combination of certain features:

- Its control models are based upon state-space matrices, which means that extra measured variables can easily be used to support estimation of the present state of the process.
- It supports disturbance feedforward control.

3 Modules and functionality of the extended engineering tool for 3dMPC



4 Modules and functionality of the on-line tuner extension for 3dMPC



■ It can be extended to do indirect control.
■ It can be applied to unstable plants.

3dMPC extended engineering tools and on-line tuning extension

Standard 3dMPC engineering tools support modeling by identification. The *extended* engineering tools add functionality based on the use of a rigorous model, allowing direct generation of the linear model for the model predictive control. Multiple models can be generated for non-linear processes, which are operated at different working points.

The advantages are:

■ Commissioning work is reduced as plant experiments are used only for fine tuning, not for model generation.
■ The process model remains consistent in hierarchical control structures with real-time optimization and model predictive control.
■ Testing and tuning can be performed in the office, before shipping to a remote site where there is limited support.
■ Project costs are reduced as more of the engineering work is automated.
■ Control studies and controller design are possible during the plant design.

The extended engineering tools include linearization, optional order reduction (to further reduce model complexity), and conversion to discrete time, to obtain 3dMPC's state space models 3.

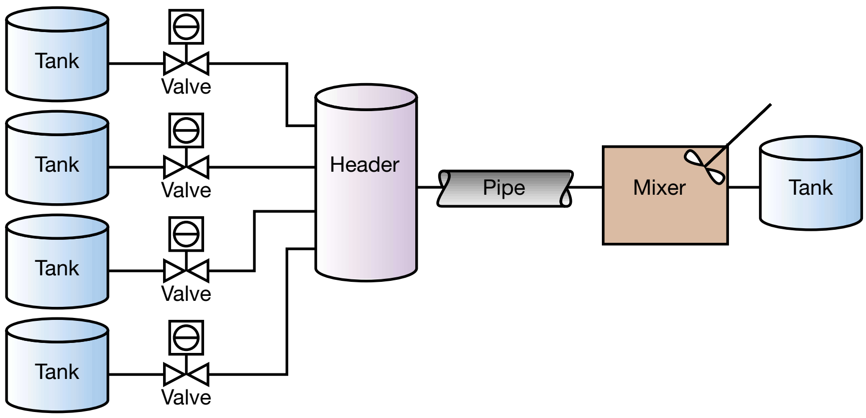
Process equipment aging, variations in feedstock, changes in operating philosophy and catalyst activity fluctuations are all possible reasons for a process response not fitting the model results. This often reduces the operational performance of model predictive control, so that it has to be taken out of operation until the underlying models are updated. With more conventional approaches this would entail a further series of expensive open-loop plant experiments and subsequent model fitting.

ABB Dynamic Solutions features an on-line tuner extension for 3dMPC 4. This has a rigorous simulator running in the background that automatically adapts the critical parameters by means of parameter estimation. In the event of significant changes, a new 3dMPC model is generated with MPC tuning recommendations. This is loaded as a standby controller into the 3dMPC run-time executable code and can be taken into operation on operator acknowledgement.

Examples of applications in the process industry

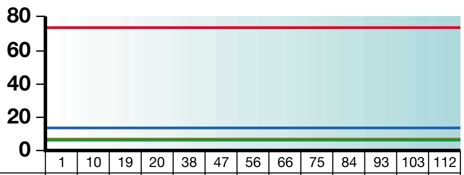
ABB Dynamic Solutions offers the best available technology for advanced

5 Blending scenario

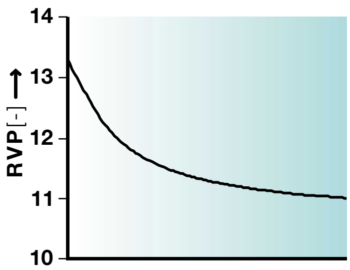


6 State of the art in blending: single recipe

RVP *Reid vapor pressure*



	1	10	19	20	38	47	56	66	75	84	93	103	112
Hvy ref	6.20	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55
Naphtha	13.5	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9
Cat gas	73.8	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6	72.6
Butane	6.50	6.83	6.83	6.83	6.83	6.83	6.83	6.83	6.83	6.83	6.83	6.83	6.83

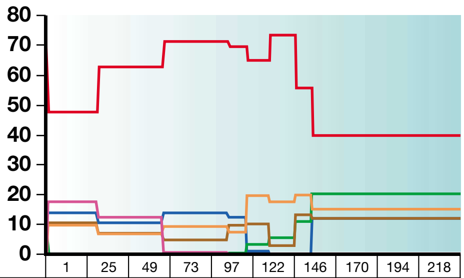


7 ABB's dynamic blender

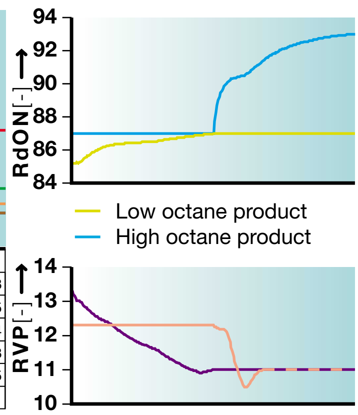
Multi-recipe dynamic optimization across two blends, taking into consideration the component availability and properties

RVP *Reid vapor pressure*

RdON *Road octane number*



	1	25	49	73	97	122	146	170	194	218
Hvy ref	6.20	0.01	0.01	0.00	0.00	3.54	11.02	20.48	20.48	20.48
Lt ref	0.00	9.77	6.74	9.28	9.28	19.68	19.88	15.15	15.15	15.15
Naphtha	13.50	13.78	10.74	13.79	13.79	1.03	0.07	12.04	12.04	12.04
Cat gas	73.80	48.04	63.11	71.36	71.36	65.39	55.81	40.18	40.18	40.18
Butane	6.50	10.75	7.14	4.73	4.73	10.36	13.22	12.15	12.15	12.15
Isomerate	0.00	17.65	12.26	0.84	0.84	0.00	0.00	0.00	0.00	0.00



optimization applications in the process industry. Two applications – one involving dynamic blend optimization and the other multivariable predictive control – are given in the following to illustrate where its benefits lie.

Dynamic in-line blending is set to become the future standard in blending

Blending is used in various industries. The objective is to blend multiple streams of various qualities in order to produce a specified product that meets certain quality specifications. Examples of blending applications are: gasoline (petrol) blending and distillate blending in refining, lube oil blending, crude oil blending in the upstream oil and gas industry, product blending in chemicals, dry blending in the food industry and raw material blending in pharmaceuticals. 5 shows a typical blending scenario.

The current state of the art is to use steady-state models of the in-line blending process to calculate a single recipe that is supposed to remain fixed throughout the entire blend. However, this neglects not only the process dynamics but also any deviation from the true blended product demand and longer-term planning objectives 6.

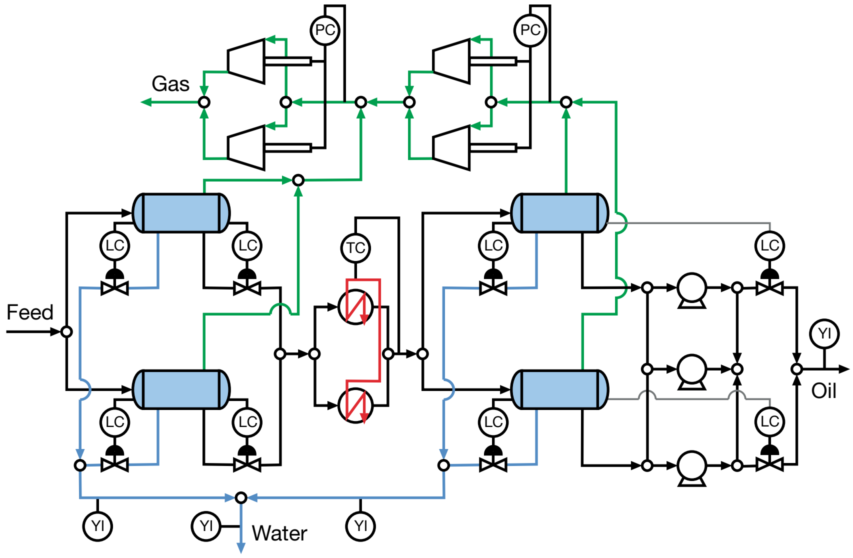
ABB's Dynamic Blend Optimization approach is to model the process with non-linear dynamic process models. These models are used to calculate optimal multiple-period recipes that reflect changes in the properties of the planned product (eg, from regular to

8 Separator train and compressor network on an oil and gas production platform, with four separators and four compressors

LC *Level control*

PC *Pressure control*

YI *Inferred value from model*



premium gasoline) as well as changes in component availability or properties due to upstream operational changes. The recipe is even re-adjusted during a single blend if, for example, the component availability or properties change as mentioned. The system also permits the user to specify a minimum blending duration as part of the overall objective. Dynamic parameter estimation and data reconciliation are used to improve the model fit, which further increases the economic benefits by reducing give-away 7.

Dynamic Blend Optimization opens up potential economic benefits of approximately 0.172 USD per barrel, adding up to a possible annual saving of $ 6 million (100,000 barrel /day plant) for gasoline blending [1]. The 0.172 USD/barrel benefit comes from potential benefits of 0.0893 USD for multi-period optimization, 0.0727 USD for blend optimization (taking into account changing component properties and availability), and 0.0100 USD for dynamic parameter estimation and data reconciliation.

Dynamic Blend Optimization can be applied to all types of blending tasks. It can be operated in either on- or off-line mode.

Oil & gas production enhancement by multivariable predictive control

Offshore oil production platforms use a network of separators and compressors to preprocess the feed stream received from the wells. The conventional technique is to utilize gravity to separate the oil, gas and water phases. To achieve the required degree of separation, it is common for several separators to be arranged in a separator train 8.

The dynamics of the different separators are strongly linked through the export compressor train and pump network. In addition, the gas and liquid dynamics in the separators are connected. The feed to the separators is often unstable by nature due to multiphase flow from wells, sub-sea manifolds and multiphase pipelines connecting remote wellhead platforms to the production facility. This makes optimal control of separator trains a multi-variable problem, and disturbance rejection an important issue. To design robust multi-variable controllers it is clearly important to have good, reliable dynamic models.

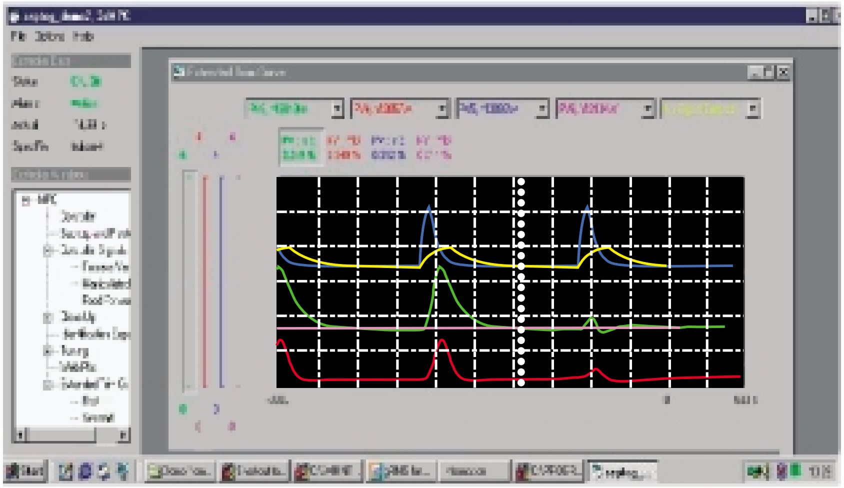
The major disturbance entering the separator train is a multiphase flow regime referred to as 'slug flow'. Slug flow represents large variations in the inlet flow rate and gas oil ratio. It often causes poor separation, widely varying compressor loads, and may in some cases lead to costly compressor and platform shutdowns [3].

The plant shown in 8 was modeled in gPROMS [2] and consists of two parallel separator trains, with two separators in series in each, a network of four compressors, a heat-exchanger, valves and piping.

The traditional control approach is to use decentralized PID controllers on each separator, ignoring the interaction between the different equipment and the three phases in each separator.

ABB's approach is to apply its 3dMPC multivariable control technology on top on the regulatory level control loops. The purpose of this is to:

- Reduce the effects of feed disturbances entering the first-stage



9 After activation of the 3dMPC controller (dotted line) the separation performance radically improves, with much smaller fluctuations in impurities, eg the percentage water-in-oil is controlled close to its setpoint and the percentage oil-in-water is maintained below its constraint level of 0.08%.

Blue	*Oil in feed stream*	Green	*% water in oil product stream*
Yellow	*Gas in feed stream*	Red	*% oil in combined water stream*

separator in order to prevent compressor trips and platform shutdowns.

- Increase throughput (ie, maximize production and maintain product quality).

This is achieved by taking the coupling between the four separators and the four compressors and the phases into consideration and by actively controlling and using the separator buffer capacity to realize the production improvement potential.

The model used in the 3dMPC controller is derived automatically from a rigorous non-linear dynamic simulation model of the separator train using the extended 3dMPC engineering tool. This approach significantly reduces the need for lengthy and costly experiments performed in the field. It also is in line with the authorities' preference not to have to disturb the oil production system in order to obtain data for model identification, which is a typical feature of competing products. In addition, it is possible to use closed-loop operational data to further tune the controller.

9 compares the production system performance achieved with PID control and with a multivariable predictive controller. The improved disturbance rejection achieved with the 3dMPC controller is clearly seen as smaller excursions of the impurities in the product and water streams (green and red) after activation, ie during the last slug disturbance shown in the diagram.

ABB Dynamic Solutions and Industrial^{IT}

ABB Dynamic Solutions is part of the Optimize^{IT} product line in ABB's Industrial^{IT} portfolio. This increases the standardization of products as 'building blocks' of larger solutions while building in functionality that will allow multiple products to interact seamlessly as components of real-time automation and information systems.

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