AVEVA

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WHITEPAPER

Improving process economics of ammonia plant operations with Advanced Process Control

How ammonia producers can turn economic uncertainty into competitive advantage

Authored by:

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Executive summary:

The ammonia industry as well as the general chemical industry has always dealt with fluctuations in supply and demand as well as volatile feedstock and energy costs. The unexpected global pandemic that started in 2020 has injected a higher degree of uncertainty for ammonia manufacturers' operating costs and product demand for fertilizer. From the supply side, ammonia global production capacity is expected to expand through 2030 thereby increasing competition. The basic plant control systems have limitations that prevent ammonia plants from operating at their optimum state and maintain profitability in a competitive scenario. Advanced Process Control (APC) systems can address complex operational challenges extracting improved process performance. APC systems improve production rates and yield, and reduce energy consumption while maintaining product quality, helping ammonia manufacturers adjust nimbly through the prevailing market conditions. Also, APC is a key technology for digital transformation and the path to autonomous plant operation.

The ammonia industry

In 2019, nearly 235 million metric tons of ammonia were produced worldwide with the fertilizer industry creating the greatest demand. The COVID-19 pandemic disrupted manufacturing activities and brought down the demand for ammonia. However, as economies are opening and the production of food and chemicals is rising, the demand for ammonia is expected to increase in the coming years[2]. Coupled with that; 107 new ammonia plants are announced to start up through 2030 to increase global production capacity to nearly 290 million metric tons by 2030[1]. As a result, ammonia producers will continue to face an uncertain and highly competitive market environment for the years to come. Older plants will be challenged to approach the efficiency of the new builds.

The widely adopted Haber-Bosch process for steam reforming relies heavily on natural gas as the source of hydrogen. Ammonia synthesis for the fertilizer industry is a process that demands significant energy to react the chemical species that form NH_3. Since nitrogen gas is strongly held together by triple bonded molecules, a large amount of energy is consumed to operate the system at the high temperatures and pressure required. The synthesis of nitrogen and hydrogen into ammonia is an energy intensive step in the ammonia production process that only realizes a 10 to 20 percent conversion of gas per cycle (1), thereby requiring considerable recycle of synthesis gas. Therefore, an ammonia plant generates the highest profitability when the hydrogen content of natural gas is converted most efficiently. As a result, the biggest impact on ammonia plant profitability is maximizing yield at the lowest possible energy consumption per ton of ammonia produced.

When existing fertilizer plants need to push operations to their maximum throughput, they are limited by the mechanical constraints and capabilities of process control systems. The target process parameters subject to multiple interactions, time delays, complex responses to changing conditions, sparse or unreliable measurements, and variable cost structures are often difficult to maintain while honoring the mechanical limits with typical control strategies.

To competitively meet market demand, ammonia plants must operate closer to the limits to maximize throughput and yield while minimizing energy consumption. Increased profitability of ammonia plants is achieved using Advanced Process Control (APC). APC reduces variability in the process, allowing the plant to run closer to constraints. Increased throughput at lower specific energy consumption and a consistent quality results in increased profit and competitive advantage.

Learn more about technology trends for the chemical industry at the basic chemical industry page

Advanced Process Control

A study conducted by the Automation Research Council found that only about 15% of available automation benefits for manufacturing plants are captured with basic control systems despite the basic control system accounting for about 75% of the cost of automation. There is typically an additional 85% of ultimate automation benefits available with high return on investment advanced process control and optimization applications. A multivariable model predictive control also known as MPC presents the best cost-benefit relationship among all the automation layers.

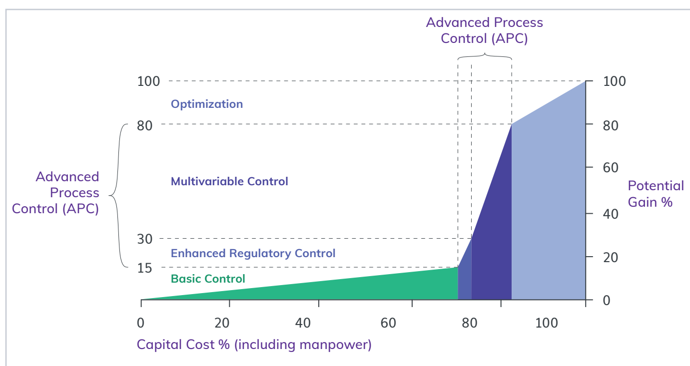

Figure 1: Automation return on investment

Multivariable model predictive control achieves benefits by reducing variability in the outputs of an operation such as quality, production volumes and operating costs by identifying the sources of variability and responding to these disturbances. This technology predicts the movement of the process and considers the operating targets and constraints as well as equipment limits that must be honored for safe and reliable operation. With these predictions the technology can continually push the plant towards optimal targets with reduced variability and higher reliability.

When operators try to push the plant towards constraints, they may encounter instability or exceed the constraint. To avoid that, they will back off to a comfortable operating point away from that constraint and typically keep the process there for the remainder of their shift. The algorithms of MPC allow more elegant handling of constraints. When the predictive models anticipate that a constraint will be encountered, it will take action to move right up to the constraint without exceeding. The advanced controller will back off the constraint as conditions change, but only as much as necessary, and for as long as necessary. Then it will move right back up against the constraint.

By recognizing and understanding the effect of different disturbances and setpoints on constraints, the widest range of stable process operations can be accessed, quality is improved, and operating profit is increased.

Benefits of multivariable model predictive control:

- Allows operation to be closer to limits by reducing variations
- Moves the process closer to multiple constraints (limits) simultaneously
- Provides access to a wide range of process operations
- Improves quality
- Increases operating profit by improving key metrics such as production rates and specific energy consumption

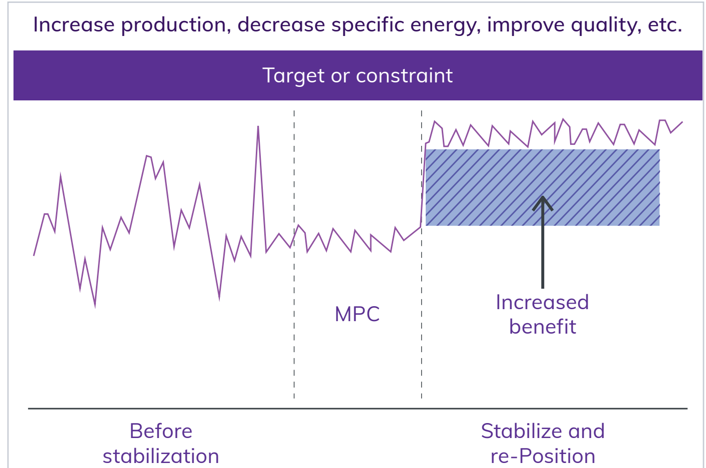

Figure 2: Multivariable Model Predictive Control

Another way to look at the impact of model predictive control is in relation to multiple constraints. Optimum operating conditions are typically at the intersection of constraints. With the process variability experienced with basic proportional-integral-derivative controllers, operators must select setpoints that keep the plant within the boundaries of multiple constraints and therefore a wide operating envelope. With the reduced variability of model predictive control, the operating envelope is reduced, and the process can be pushed closer to the optimal operating point.

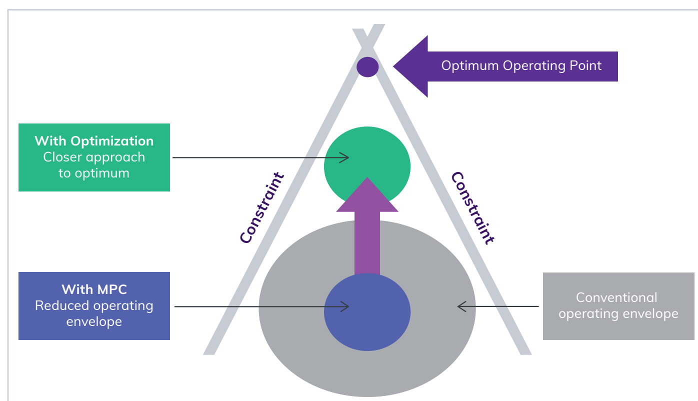

Figure 3: Motivation for optimization

The model predictive controller contains dynamic models that describe the process responses, including time delays, interactions between inputs and outputs, and complex responses (inverse, integrating, etc.). Statistical methods are used to develop the predictive model relating input variables (disturbances and PID setpoints) and output variables (targets and constraints). As a result, the model can predict the future trajectory of the process outputs for any variation in the process inputs.

By predicting the future variations, these models can continuously determine the setpoint adjustments required now to maintain targets and honor constraints. The underlying mathematics are quite complex. Even more complex if nonlinear relationships are included with neural networks. Predictive models are either determined from plant tests or from data captured by the plant historian.

A powerful aspect of these models is their ability to understand the impact that a change in set point of any controller will have on other outputs not under its direct control. Also, as constraints change the controller reacts instantly to the situation.

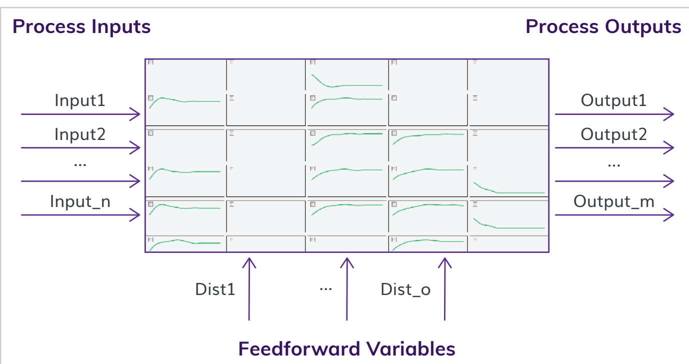

Figure 4: Model prediction for future trajectory of process outputs

To learn more, **download** the APC datasheet

MPC applied to ammonia plants

The ammonia synthesis process lends itself nicely to Model Predictive Control. The process has multiple reaction steps, high energy usage, interactions - especially in the synthesis loop with pressure, inerts, purge rate, large recycle and complex dynamics such as introduction of hydrogen at the primary reformer and nitrogen at the secondary reformer to control ratio at synthesis converter inlet. A percent increase in production or decrease in specific energy consumption can improve the profitability of the operation. Typically, MPC applications for ammonia plants will result in 1% to 2% improvement in specific energy, and 1% to 4% production improvements.

Model predictive control can be implemented for several ammonia applications, as follows. The primary and secondary reformers, synthesis gas loop and ammonia synthesis reactor typically have the greatest value. Depending on individual plant operation and bottlenecks, the other units may have a good return on investment as well.

- Primary and secondary reformers
- Carbon dioxide removal facilities
- Hydrogen (purge gas) recovery facilities
- Methanation system
- Synthesis gas loop
- Ammonia synthesis reactor
- Shift converters
- Steam system

Many of the typical advanced process control or model predictive control objectives for ammonia plants are listed below. The first two are overall objectives of the plant that are key metrics for the value that is generated with advanced process control. The next few are some of the key drivers to improve the overall key metrics. The final three are more qualitative outcomes. Note that any application should obey the process equipment operating constraints and certainly not compromise safety.

- Key Performance Indicators (KPIs)
  - Maximize unit throughput
  - Minimize specific fuel gas and steam consumption
- Drivers for KPIs
  - Control methane slip and balance primary reformer outlet temperatures
  - Control converter inlet H/N ratio and total inerts concentrations within pressure constraints and hydrogen (purge) recovery constraints
  - Control synthesis converter temperatures
  - Control refrigeration capacity
- Qualitative benefits
  - Enforce all specified operating and safety constraints
  - Stabilize the unit operation in the presence of unmeasured disturbances
  - Reduce operator workload

Stabilizing the unit in the presence of unmeasured or seldom measured disturbances such as ambient temperature and pressure, feedstock changes and others help the controllability of the entire complex. It has also been proven to assist in faster unit start-up. Plant operators have many assigned tasks, including continually tweak basic control setpoints values. This type of activity adds tension to the operators´ daily work as many of the required adjustments are counter intuitive or need action much faster than the human brain can understand and execute. This type of solution helps the operators to better understand process behaviours, improving their effectiveness, leading to higher job satisfaction.

Read the blog improving process economics with Advanced Process Control to find out more

Case studies

Case study 1

Case study 1 is based on an application deployed in an ammonia plant operated by a major producer in North America. This plant started the journey on using APC with successful pilot projects on a Urea Desorber plant and a sister plant for the entire ammonia plant. After conducting a study to determine the potential benefits and cost, a project was initiated focusing on the front end of the plant for feed maximization and energy savings. The project yielded saving of about 750 thousand dollars per year due to ammonia production improvements and specific energy reduction. Payout was less than six months. The application has been in operation since 2005 and it´s currently working towards expanding the application to the synthesis loop and the urea plant.

Challenge

- Improve utilization and sustainability of Urea Desorber and Ammonia Units that produce 535K tons of ammonia and 680K tons of urea annually

Solution

Use Model Predictive Control (MPC) for:

- Steam to gas ratio control
- Excess oxygen control
- Feed maximization strategy

Benefits

- ~$750K per year in energy savings at industry average gas prices and energy consumption
- 0.75% improvement in energy on a MMBTU/ton basis
- > 2% improvement in ammonia production
- In operation since 2005

Case study 2

The case study 2 is based on an application deployed in an ammonia plant from another major producer in North America. It pertains to a site that desired to maximize ammonia production while enforcing operating and safety constraints. There were secondary objectives to reduce operator workload and specific energy consumption. A study was conducted at this site, that included the cost and benefits of upgrade to a distributed control system and the identification of advanced process control benefits to justify the distributed control system installation. This study led to the installation of a distributed control system along with an extensive ammonia plant application that yielded 3-4% increase in ammonia production. The application was shortly thereafter expanded to all areas of the urea plant. In 2015 the plant capacity was expanded with a Kellogg Reforming Exchange System and the ammonia plant application modified accordingly. Advanced process control for the nitric acid plant is underway and they are also exploring opportunities for first principles-based optimization.

Challenge

- Maximize ammonia plant throughput and enforce specified operating/safety constraints
- Reduce operator workload and specific fuel gas and steam consumption

Solution

- Use Model Predictive Control (MPC) to control:
- Hydrogen to nitrogen ratio
- Syngas suction pressure
- Air compressor speed
- Ammonia synthesis reactor temperature
- Steam to carbon ratio
- Feed flow control

Benefits

- 3-4% increase in ammonia production
- In operation since 2006
- Expanded to urea plant, modified with KRES addition and now installing on nitric acid plant.

Improving benefits beyond the MPC

As mentioned before, the MPC is the main contributor to benefits related to plant automation. The MPC is also an important foundation to further optimize the ammonia plant. Once the process is stable through MPC, complementary models can be used to further optimize operations.

While the predictive models used for advanced process control are empirical dynamic models, first principles-based models can be added to the automation architecture. The most common first principles-based models used for online applications are process performance monitoring including adaptive reactor models and real-time optimization models. They are continuously tuned to close the mass, energy and equilibrium balance, optimizing operations according to the desired objective function, while keeping variables within the physical, operating and economical constraints. Typical objective functions for real time optimization are minimizing energy consumption or directly maximizing plant profitability.

Click here to learn more about Real Time Optimization

Another modelling approach that can be used is predictive analytics for equipment reliability with machine learning. In this case, the model is built based on historical data and can include process variables so as mechanical variables.

The latest advancement in models for online applications is Artificial Intelligence (AI) driven predictive analytics, that combines AI such as machine learning, deep learning with artificial neural networks and rigorous first-principles models, and real-time optimization. AI-driven predictive analytics is infused with results from the rigorous process simulation and optimization algorithms, creating a sophisticated model capable of providing advice about the most cost-effective choices for operations and maintenance based on a 360° view of risk.

Watch the on-demand webinar AI-Driven analytics in chemicals

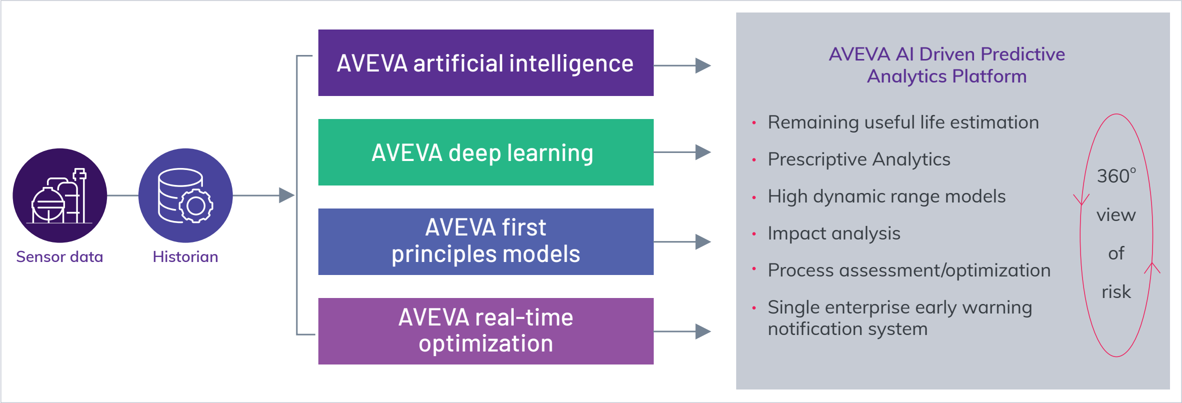

Figure 5: AI-driven predictive analytics

Take aways

In this whitepaper we have reviewed the costs and benefits of automation for chemical operations in general and ammonia plants specifically. Basic control systems capture about 15% of the potential automation benefits at about 75% of the total automation costs. Advanced Process Control captures the most automation benefits with a high Return on Investment, and MPC is the main contributor to automation benefits.

There are many cases on the proven, sustainable benefits for Ammonia Plant operations. The main measurable benefits are production improvements of 1% to 4%, and 1% to 2% reduction in specific energy.

Other automation opportunities for nitrous fertilizer plants include:

- First principles-based model for process performance monitoring
- First principles-based model for real time optimization
- Predictive analytics for equipment reliability with machine learning
- AI-driven predictive analytics, combining AI, deep learning, rigorous first-principles models, and real-time optimization

References

1. Frahm B., Lin R. and Poe W.: “Improved ammonia plant safety via advanced process control systems”. Nitrogen & Methanol No. 247, p. 25 (Sep-Oct 2000).
2. Lin R., de Boer R. and Poe W.: “Optimize ammonia plant operation”. Hydrocarbon Processing. Vol. 78, 6, p. 91 (Jun 1999).
3. Grasdal K., Barone P. and Poe W.: “Benefits of Advanced Control to Ammonia Plant Operations”.
4. AIChE Ammonia Safety Symposium
5. San Francisco, California, Paper Number 5E (Sep. 22-24, 1997).
6. Production capacity of ammonia worldwide in 2018 and 2030 – Statista, 2021
7. Worldwide Ammonia Industry to 2025 - Identify Drivers and Challenges – Business Wire, Aug 2020

About the author

Bill Poe is a Technical Advisor at AVEVA with over 35 years of experience in operations, project development, implementation and management of advanced process control, optimization and real-time performance monitoring projects in a variety of industries. His accomplishes include many successful projects in the nitrous fertilizer industry on primarily ammonia plants, but also methanol, hydrogen and carbon monoxide units. Current projects include nitric acid advanced process control as well as real-time performance monitoring and optimization of ammonia plants.

Prior to AVEVA, Bill held positions at Shell Oil Company, GE and Schneider Electric. He has several patents, achieved a President’s Award at Shell Oil, received the GE Innovators Award and attained the Invensys Circle of Excellence. Bill earned a bachelor’s degree from Georgia Institute of Technology and a Master of Science from Columbia University both in Chemical Engineering.