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Experiences with a digital process monitoring system at Nutrien Borger

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1. ABSTRACT

First-principles models have been used to support process operations in the chemical and petrochemical industries for over 40 years but hitherto only to a very limited extent in urea plants. The limited application to urea is mainly attributable to the steep rise in complexity, execution time, and other difficulties that must be addressed as the model size increases if it is to have the necessary accuracy and scope to give a reliable indication of overall economic impact on the business. Nevertheless, urea plant models can encapsulate a large amount of process knowledge, and plant owners can benefit significantly from their use in both off-line and on-line applications. Such applications include data reconciliation, virtual (soft) sensors, and process performance monitoring like KPIs (Key Performance Indicators) and KVs (Key Variables), to name a few. These applications enable plant operators to stay up to date with real-time information even when they are off-site.

This paper describes the implementation of the SDPM (Stami Digital Process Monitor) system at the Nutrien Borger urea plant. The Process Monitor delivers a premium usability experience by optimizing views of KPIs and KVs for mobile screens, allowing to monitor dashboards and trends for further analysis.

2. AN OVERVIEW OF PLANT MODELLING

Depending on the level of prior knowledge, three different classes of model can be developed:

- knowledge-driven
- data-driven
- gray-box models

Knowledge-driven models, also called first-principle models, are developed on the basis of full and detailed theoretical knowledge of the underlying physical and chemical principles. For cases in which the principles are not well understood, recourse may be had to data-driven or ‘black-box’ models. These empirical models are based on simple equations developed from experimental data. In between these two extremes, there are many possible combinations of knowledge-driven and data-driven models. The theoretical knowledge offered by the simplified first-principles analysis forms the core of a so-called ‘gray-box’ model, while data-driven methods can compensate for those portions for which there is no adequate theoretical basis. The Stamicarbon model is purely knowledge-driven and is consequently quite precise. The mathematical model developed includes mass and heat transfer equations, reaction kinetics, vapour-liquid equilibria, and hydrodynamic aspects, and it covers the entire plant. In total, the Nutrien Borger urea plant model consists of more than 7,000 linear and nonlinear equations. An equation-oriented flow sheeting program developed in house is used to ensure fast solutions (typically 1 to 5 sec.) of the large and complex problems.

3. DIFFICULTIES IN UREA PLANT MODELLING

In contrast with the simple chemistry involved in urea plants, the underlying physics of mixtures containing urea and ammonium carbamate is complex. First, the feedstock to the synthesis is in supercritical state. Above the critical points, distinct liquid and gas phases do not exist, which gives rise to serious deviations in liquid to vapor descriptions. Secondly, urea/carbamate/water solutions show large negative deviations from Raoult's law and form a maximum boiling azeotrope at a specific composition. Inflection points caused by strong non-linearity are often the source for numerical instability, as the solver algorithm cannot distinguish from which side to climb the hill. For on-line application, the model has to meet a set of performance requirements, in particular with respect to speed, robustness and flexibility; already a challenge in itself!

4. THE CONCEPT OF KEY VARIABLES

Key variables (KVs) characterize the technical and economic performance of the urea process. Once KVs are fixed, the operating points are fixed. KVs are normally determined by off-line sample analysis in the laboratory. One of the drivers of process modelling was to give operators and process engineers reliable and accurate estimates of key variables. This would allow them to arrive at the optimum operational point and assist them in trouble-shooting activities. As an example, the urea yield in a reactor is fully characterized by its key variables molar NH_3/CO_2 ratio (N/C), molar H_2O/CO_2 ratio (H/C), retention time, and system pressure. Only N/C can be measured in real-time, whereas H/C and system pressure are determined by off-line sample analysis in the laboratory. Calculation of retention time would require a total mass balance calculation over the reactor. Specifically, real-time analysis of key variables constitutes an essential prerequisite for SPDM and control of urea plants.

5. OFF-LINE BASED MODELLING AND DATA RECONCILIATION

To ensure that the model represents the process accurately, historical distributed control system (DCS) data are collected from the operation and are subsequently used to validate the model. The measured data typically contain random errors and, less frequently, may also contain systematic errors. The role of the data reconciliation is to properly identify and correct deviations, and thus provide reliable information for updating the parameters of the model, or to spotlight systematic sensor errors. The major purpose of model validation is to evaluate the accuracy and reliability of the developed plant model. For process control engineers, off-line validation can be viewed as a feedback process, the aim being to bring the model predictions into agreement with actual process measurements, in much the same way as feedback is used in process control to adjust measured values to desired target values or to within a target range (see Fig. 1).

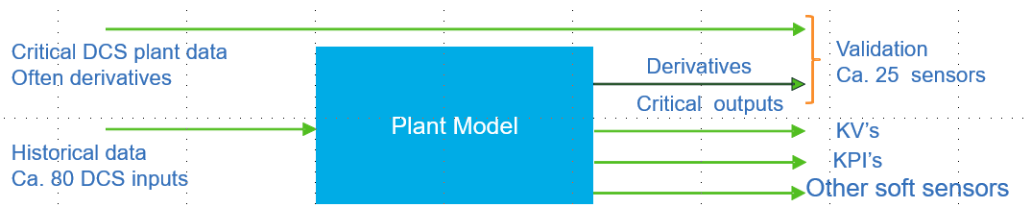

Figure 1. Principle of model validation

The operating conditions at key points in the Nutrien Borger urea plant can be set with about 80 sensor inputs, which generate about 25 meaningful feedbacks.
A validation example is illustrated in Fig. 2.

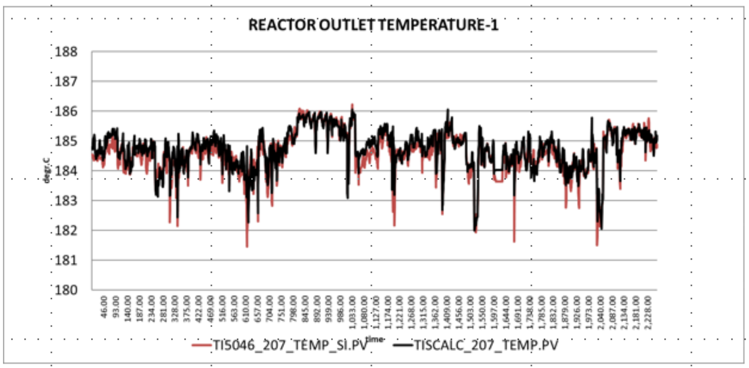

Figure 2. Validation reactor outlet temperature

The urea reactor outlet temperature is typically one of the critical variables in a urea plant closely observed by operators. To some extent, it represents urea conversion in the reactor, assuming other interacting variables like N/C, H/C, retention time and system pressure remain constant. As such, the reactor outlet temperature is not a KV, but a critical or derivative output and is not conclusive. The same temperature could have different meanings. The plot in Fig. 2 compares the temperature predicted by the model with the DCS reading over a period of more than 2000 operating hours. Accuracy is the level of agreement between the predicted and DCS values, while reliability is the degree to which the prediction errors vary. The accuracy of identification and reliability of validation procedures are sensitive to the size of the corresponding data sets. The required size of the historical data is typically 1-2 months; hourly averages suffice for analysis.

6. ADVANCE CONSULT™

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ADVANCE™ CONSULT is an off-line model-based service, offered by Stamicarbon. It all starts with conducting interviews with plant experts and operators, as they play a key role in fully exploiting the wealth of historical data. The experiences and expertise of those involved in day-to-day operation provide valuable insight into relevant process changes and performance of measuring devices, etc.
After introducing the Process Monitor on-site and receiving the data from Nutrien Borger, Stamicarbon regularly had virtual meetings with the client. These meetings aimed to help Nutrien Borger to better understand the meaning of the KPIs and KVs and how to use them to optimize plant performance. With a validated plant model and historical plant data, an in-depth analysis can be made from the plant operation.
Furthermore, in the discussions, suggestions for improving the operations in terms of capacity increase, emission reduction and energy efficiency were given. These suggestions were evaluated in the following sessions.

Experiences at Nutrien Borger have revealed that these meetings have been valued very highly. Measurement errors, equipment bottlenecks and inefficiencies were detected and seemingly deviating operating strategies developed from the model data proved to be very efficient. For example, such deviating operating strategy delivered 3% extra production capacity and a steam saving of about 3-4%.

Regular evaluation sessions as described above are part of the service called ADVANCE CONSULT™. The number of sessions in the first year of introduction will be higher than in the following years and will be reduced with time. Also, a few meetings between Stamicarbon and Nutrien Borger took place in the model development phase to discuss the unavoidable deviations between the process model and plant data. These meetings were scheduled on an ad-hoc basis.

7. THE CONCEPT OF STAMI DIGITAL PROCESS MONITOR

Once the model has been developed and validated for ADVANCE™ CONSULT, it can be adapted for online usage.

The Process Monitor is a total plant monitoring system, and successful implementation depends heavily on how closely the model represents the process as well as on the accuracy and reliability of input measurements. Specifically, real-time analysis of KPIs and KVs constitutes an essential prerequisite for advanced monitoring and perhaps later control of the urea plant. The requirements for a successful online performance monitoring include open connectivity (OPC) with DCS and other plant information systems. The plant model is OPC-compatible, securing machine-to-machine (M2M) communication.

After connecting the plant model to real-time plant data, the actual KPIs and KVs can be calculated with high accuracy. For this concept to work, there should be a connection between the Stamicarbon process model and the DCS of the plant. Since a Stamicarbon plant process model contains all proprietary Thermodynamics, Kinetics and V/L equilibria data, Stamicarbon requires complete control over the usage of such model. For security reasons, it is required to run this model in a secured Cloud environment, subject to the highest information security standards of ISO 27001.

Figure 3 illustrates the concept of the information chain for the Process Monitor. First, real-time process data from the DCS is transferred to the Cloud, where the process model uses the data to calculate the soft sensor values. Next, real-time plant data is transferred from the DCS to the plant model, running in the secured Cloud environment.

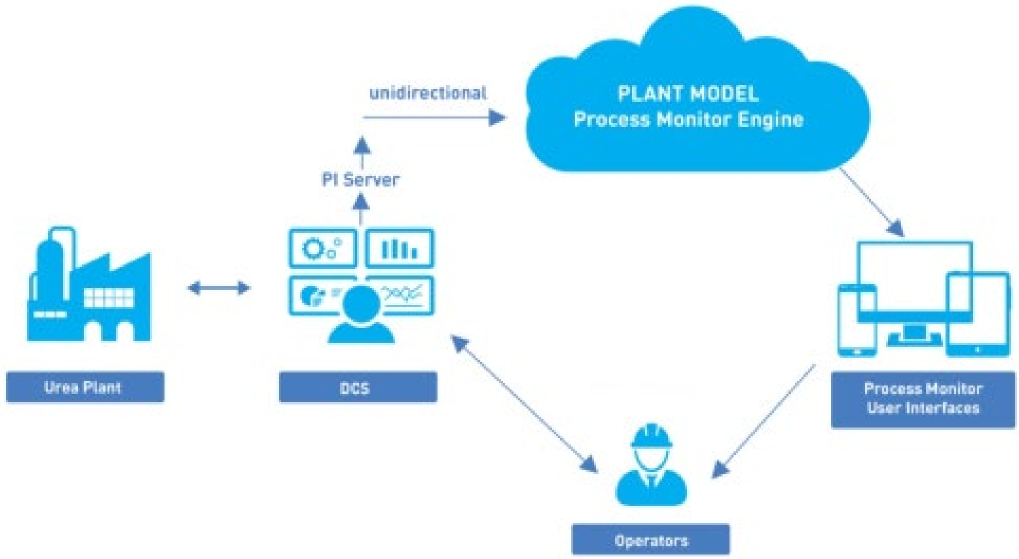

Figure 3. Hardware architecture for the Process Monitor

Please note that there is no closed-loop system-to-system communication. The arrows in Figure 3 indicate the direction of information flow. The plant DCS system is solely controlled by operators and only acts as a data source for the plant model. The concept is fully compliant with ISO 27001, the worldwide standard for Information Security Management.

Finally, the plant model calculates the actual KPIs and KVs, which are available on any device connected to this secured, client-specific Cloud environment. This can be a dedicated computer in the control room, a laptop, a tablet, a smartphone, a smartwatch, or any of these devices simultaneously.

The GUI (Graphical User Interface) is designed as a number of dashboard screens. The term "dashboard "refers to tools for the graphical visualization of key performance indicators (KPIs) complemented by key variables (KVs) and reporting functions. They can be used to identify poor performance and the improvement potential. So, a dashboard is a visual display of the most important information needed to achieve one or more objectives; consolidated and arranged on screens so the information can be monitored at a glance. Figure 4 illustrates the main KPI dashboard screen at Nutrien Borger.

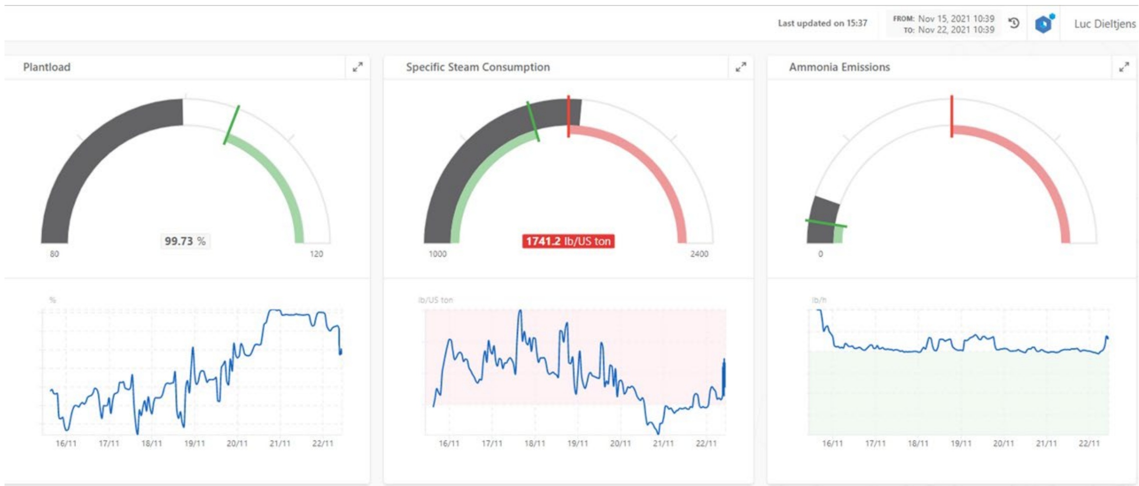

Figure 4. KPI dashboard

Provided that the Process Monitor is widely used within the organization, people have identical information from a centralized single data source. It would prevent typical discussions like what is the plant capacity or what is the specific steam consumption?

The Process Monitor has a purely advisory function; corrective actions are left at the discretion of the operators.

8. THE PROCESS MONITOR ADDITIONAL FUNCTIONALITY

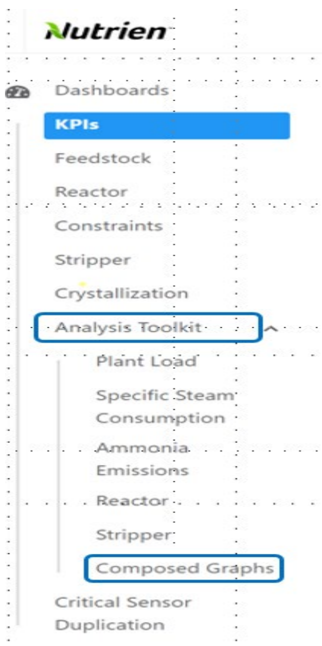

Figure 5. The Process Monitor

Next to monitoring KPIs, SDPM supports several other functions (see figure 5). Relevant KVs on the feedstock, reactor, stripper and carbamate compositions in several process sections can be monitored in dedicated dashboard screens.

Another valuable feature is constraint detection. A constraint is anything that prevents the plant from achieving its goal, mostly producing the maximum amount of urea. All urea plants are subject to operational constraints such as restricted dimensions and limited control capacity. In most cases, constraints can be detected (measured by sensors are saturation of actuators) and consequently can be monitored. Constraints might change caused by external disturbances, e.g. the ambient temperature. Logging this constraints, and constraint swapping provides valuable insight to find ways to increase the total capacity of the plant.

The option "*composed graphs*" in the analysis toolkit menu is a powerful tool to do an in-depth plant analysis. It allows for combining several graphs containing KPIs, KVs and DCS sensor values.

The usage of composed graphs can be illustrated with a case study. In figure 4 a significant variation in specific steam consumption – order of magnitude +- 200 lb/US ton – may be observed. Using the *analysis toolkit*, the root cause of this variation can be further investigated.

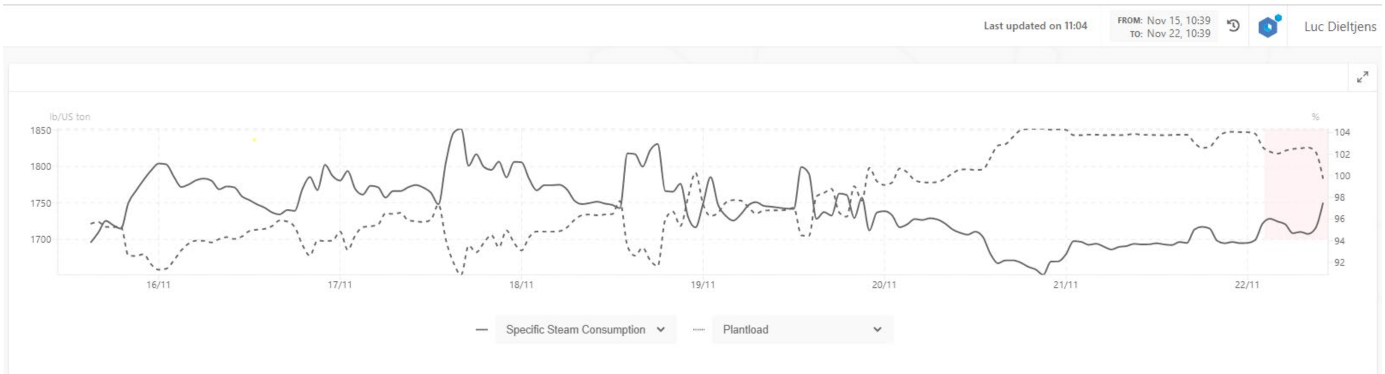

Figure 6. Specific steam consumption versus plant load [1)]

1) For all graphs, the solid line is on the primary Y-axis and the dashed line is on the secondary Y-axis

In figure 6, the specific steam consumption is plotted together with the plant load. A remarkable strong negative correlation can be seen.
During operation, the urea plant consumes more steam per ton of urea produced at lower capacities. However, from the thermodynamic point of view, the contrary would be expected. At higher plant capacities, the retention time in the pool reactor reduces, consequently lowering the yield in the reactor. A lower reactor yield would always result in higher steam consumption. Further analysis is required for better understanding of this reversed observation.

The next plot (Figure 7) shows the correlation between the specific steam consumption and the conversion in the reactor.

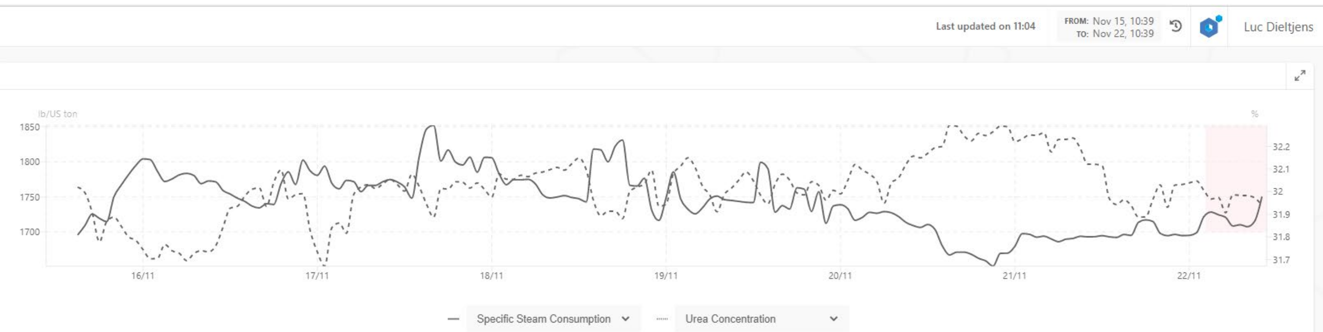

Figure 7. Specific steam consumption versus reactor yield

The variations in specific steam consumption are caused by variations in reactor yield. Further analysis reveals the root cause of the efficiency fluctuations in the reactor.

In Figure 8, the H/C-ratio is plotted together with the reactor yield.

[1] For all graphs, the solid line is on the primary Y-axis and the dashed line is on the secondary Y-axis.

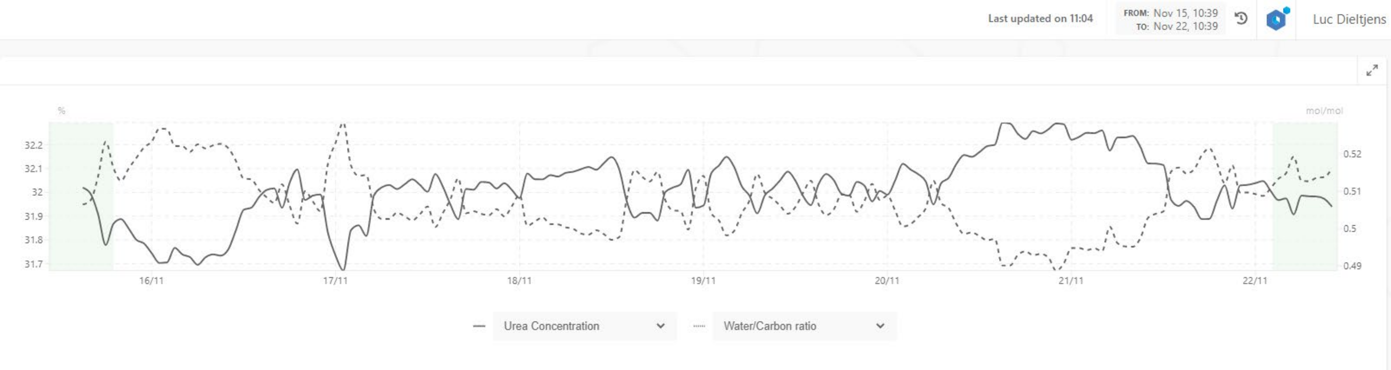

Figure 8. Urea concentration versus H/C-ratio reactor

The variation of urea concentration in the outlet of the reactor is caused by variations in water content in the same reactor. The majority of water in the reactor, besides the water produced with the urea reaction, originates from the Medium Pressure-carbamate recycle [2].

2) Nutrien Borger urea plant is designed with MP-flash technology downstream the stripper. As such, the carbamate recycled to the pool reactor comes from a medium pressure stage.

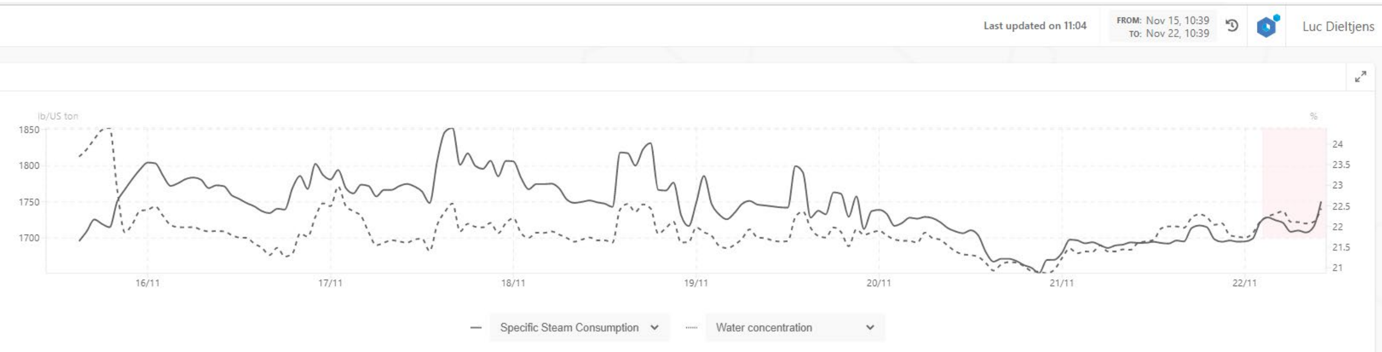

Figure 9. Specific energy consumption versus water concentration MP-stage carbamate

Figure 9 shows a confirming positive correlation between the specific steam consumption and the water concentration in the carbamate in the MP stage. It seems that the root cause has been identified; however, a good observer would notice that the water concentration in the MP carbamate is not the only reason for the variations in specific steam consumption.

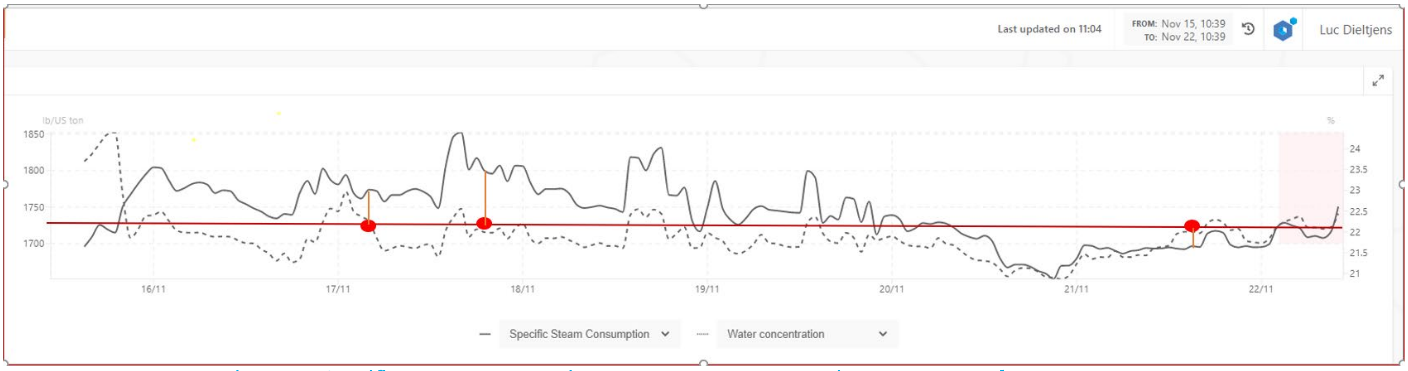

Figure 10. Specific energy consumption versus water concentration MP-stage carbamate

Imagine a virtual line with constant water concentration, say 22wt% water. Three bullet points are indicated on that line, all having a different specific energy consumption. The above implies there are other reasons, different from variations in water concentration in MP-carbamate, why the specific steam consumption would change.

The combined plot underneath answers the question for the presence of an additional disturbance acting on the process.

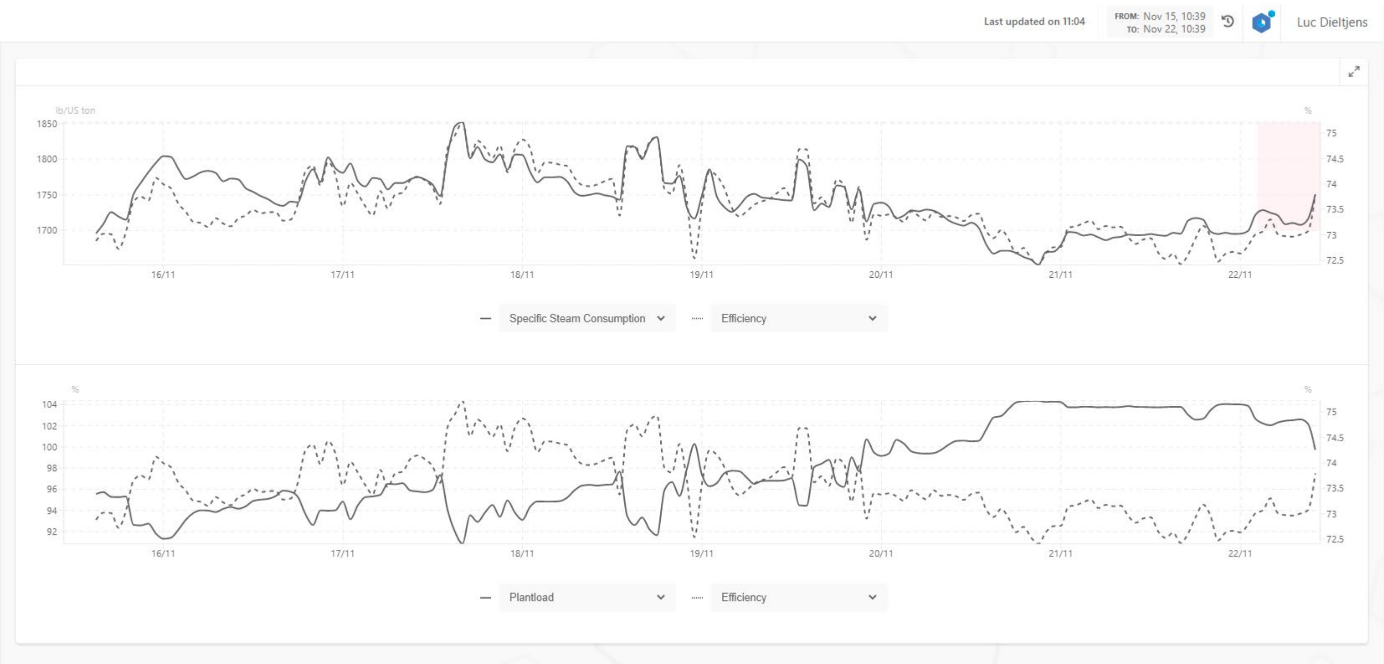

Figure 11. The combined plot, stripping efficiency versus plant load and specific steam consumption

The combined plot (Figure 11) takes the stripping efficiency into account. It correlates stripping efficiency with the plant load and specific steam consumption. The interpretation is straightforward; the higher the plant load, the lower the stripping efficiency — and the lower the stripping efficiency, the lower the specific energy consumption.

So far, this completes the analysis on the variations in specific steam consumption and can be summarized as follows:

- The process condensate inputs (typically flow controllers) to the carbamate systems (Medium Pressure, Low Pressure and reflux condenser) are kept constant irrespective of the plant load. This results in a high H/C-ratio in the reactor at low capacities.
- The shell pressure on the stripper is kept constant irrespective of the plant load. This results in high stripping efficiencies at low plant load capacities.
- Keeping the above-mentioned controller settings constant causes high specific energy consumptions at reduced plant load.

This way of identifying cause and effect at deviating operating conditions is new for Nutrien Borger's operating staff. Therefore, it requires guidance and training on using these new tools effectively.

9. CONCLUSIONS

The Stami Digital Process Monitor delivers a premium usability experience by optimizing views of Key Performance Indicators (KPIs) and Key Variables (KVs) for mobile screens allowing to monitor dashboards and trends for further analysis.
Next to KPIs, it also generates KVs, which can be monitored next to other variables for in-depth plant analysis. Operating strategies developed from the model data as part of the ADVANCE CONSULT™ service proved to be very efficient on the example of the Nutrien Borger plant – delivering 3% capacity increase and a steam saving equivalent to 3-4%.
Provided that the Process Monitor is widely used within the organization, people have identical information from a centralized single data source.
However, with the Process Monitor being a new tool, guidance and training on its effective usage are required for operating staff.
Nutrien Borger staff has direct access to Stamicarbon engineers for consultancy.

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