# Using Digital Tools to Further Optimize Product Quality and Calcination Performance

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**Abstract**

Recent technology developments have targeted improving the alumina calcination process and aligning benchmarks closer to the theoretical minimum energy consumption. Significant efforts have also been made to better understand the impact of alumina quality parameters on the calcination process, with the outcomes considered in new designs. With a more comprehensive understanding of the overall process as well as the relevant quality parameters, it is also possible to optimize the operation of the calcination plant. By introducing a performance indicator that Outotec calls the *Perficiency* factor, plant performance based on technically achievable levels can now be measured. Improvement of the *Perficiency* factor is done via Outotec's Pretium Advisor. As a digital operational support, incorporating the plant manufacturer's process, material and equipment know-how, the tool provides operational assistance by continuously comparing optimized plant operation with measured data. By monitoring the progress of digitally supported plant operation up to fully automated production processes, plant operation is safer, cleaner and more efficient. The tool also allows a number of optimization strategies as well as drawing conclusions on the operation of other connected process units, such as hydrate filtration.

**Keywords:** Bayer process, product quality, alumina calcination, Perficiency, Outotec Pretium Advisor

## 1. Introduction

Since its invention in 1888, the Bayer process has been continuously improved in terms of energy efficiency, production capacities and product quality control. Alumina refineries also place a strong focus on becoming low-cost producers. With an existing alumina refinery location, production costs primarily result from [1]:

- Energy costs (electrical and thermal);
- Soda costs;
- Bauxite costs;
- Maintenance costs.

Naturally, the specific costs vary with the refinery location as well as with the bauxite mineralogy. Within this framework, alumina refineries are eager to improve the efficiency of energy, soda and bauxite use while also decreasing maintenance costs. This implies that availability needs to increase with unforeseen downtimes kept to a minimum. Overall equipment efficiency (OEE) or total effective equipment performance (TEEP) are metrics which provide indicators of a typical improvement journey.

How OEE is calculated:

$$OEE = availability \times performance \times quality \quad (1)$$

where: *availability = available time / scheduled time*
*performance = actual capacity / design capacity*
*quality = good product produced / total product produced*

How TEEP is calculated:

$$TEEP = loading \times OEE \quad (2)$$

where: *loading = scheduled time / calendar time*

The factors are defined as:

- Loading: the portion of the TEEP metric representing the percentage of total calendar time scheduled for operation.
- Availability: the portion of the OEE metric representing the percentage of scheduled time the operation is available to operate. Often referred to as 'uptime/running time'.
- Performance: The portion of the OEE metric representing the speed/production rate at which the plant runs as a percentage of its designed speed/production rate.
- Quality: The portion of the OEE metric representing good quality product produced as a percentage of the total production.

Using OEE and TEEP, a metric can be created to assess the effective or useful plant production time. An OEE score of 100% would represent perfect production at design capacity with no unscheduled downtime and no out-of-spec product produced. A TEEP score of 100% would also indicate that the plant requires no downtime and thus produces at design rate throughout the entire year.

Mainly, the metrics are used for assessment of production machines with non-continuous processes while not taking energy efficiency or environmental footprint into account. However, there is literature proposing such extensions and also the application to continuous production processes [2], [3].

However, OEE and TEEP do not measure the efficient use of energy, raw materials nor utility. Furthermore, emissions such as dust or particles are also missing. This paper takes a look at how availability, product quality, efficiency and emissions can be used in a new metric, *Perficiency* and how *Perficiency* is improved in the calcination process with the Outotec Pretium Advisor.

## 2. The Calcination Process as Part of a Bayer Refinery

In a Bayer refinery, alumina is produced from bauxite. Figure 1 shows the Bayer circuit and illustrates its process steps or 'plant units'. Each plant unit's availability, product quality fluctuation or efficiency can impact the next plant unit's performance and thus the performance of the entire alumina refinery. In an alumina refinery's final process step - alumina calcination - the focus is on production rate, specific thermal and electrical energy consumption, minimizing shutdown times as well as utilities usage and product quality.

Hiltunen et al. provides an analysis of the impact of assorted equipment failures within a calcination plant and its economics [4]. Since an alumina calciner is an integrated plant unit within the Bayer refinery, it is influenced by disturbances beyond its battery limits. Thus, Hiltunen et al. were able to adjust the available operation time by several factors beyond the plant units' influence. Since the product quality parameters in an alumina calcination plant are normally met, the quality factor for an alumina calcination plant in Equation 1 can be set to, or close to, 100%.

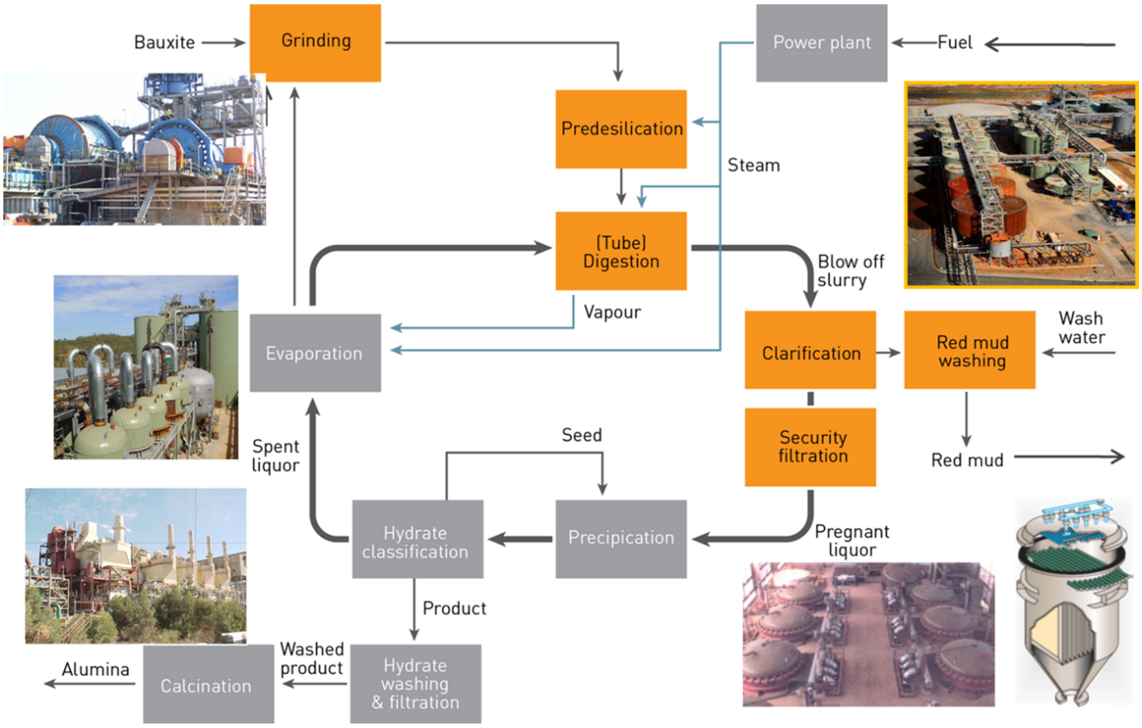


**Figure 1. Bayer process, producing alumina from bauxite.**

A good overview of alumina calcination technology and its benchmarks for industrially achievable efficiencies for thermal and electrical specific consumptions is given in a description by Klett et al. [5].

## 3. *Perficiency* – a Metric to Assess Process Plant Operation

The *Perficiency* rating can be considered as a metric to assess a process plant's operation. As a first step, OEE and TEEP are modified slightly and based on [4] production losses just within the plant.

### 3.1. OEE and TEEP modification

Figure 2 illustrates OEE and TEEP for a hypothetical alumina calcination plant using artificial data. Modifications are made and summarized by the indicator *additional production losses*. This indicator includes production outages caused beyond battery limits of the plant. The outage might be due to production stoppages in upstream or downstream process units, or from planned production stoppages for commercial reasons. While these production outages do not impact OEE, they will affect TEEP.

The OEE evaluation shown in Figure 2 closely follows the definition as per other studies [6, 7, 8]. The calculation for this hypothetical plant gives an OEE of 80.8%. In addition, an OEE target value has been added to the graph. A performance target may be reduced as indicated in the example (to 95%), if a known bottleneck limits the plant production rate.

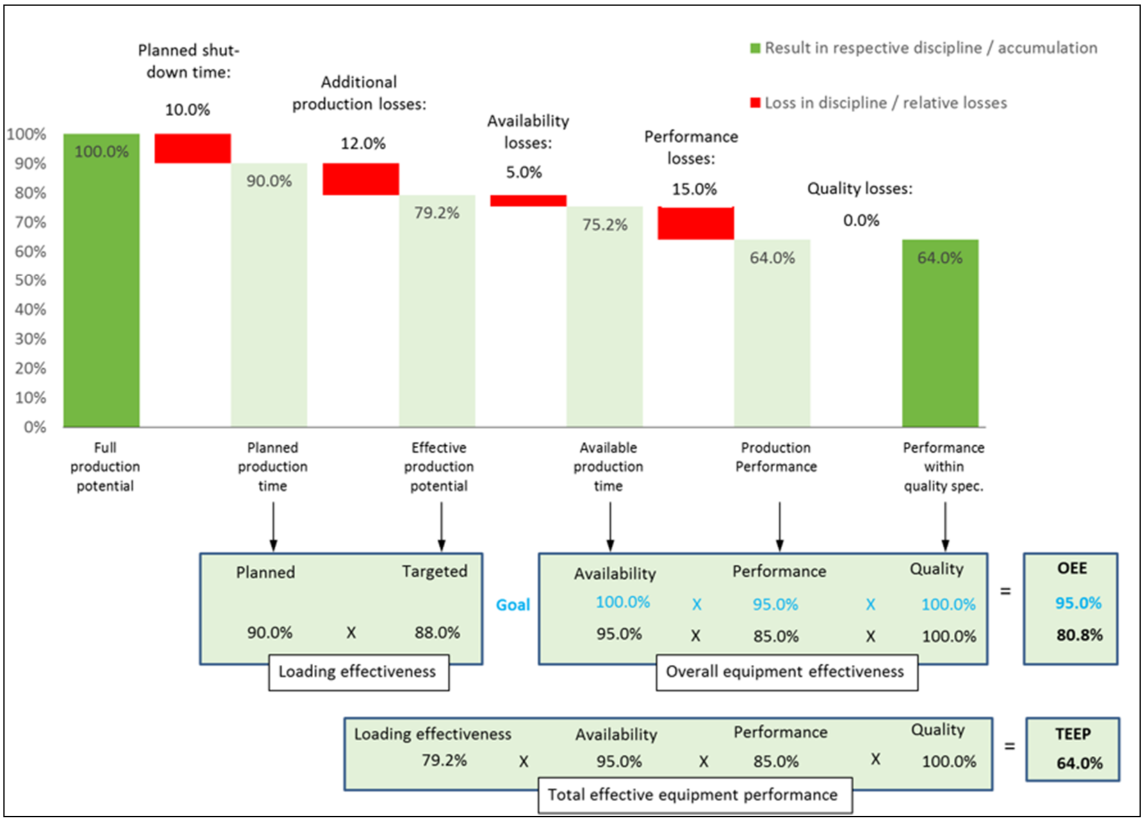


**Figure 2. OEE and TEEP for a hypothetical alumina calcination facility.**

The example in Figure 2 is with a correction suggested by Hiltunen et al [4]. Losses in the OEE and loading effectiveness are indicated in red, while the plant's performance is indicated by the green bars, based on the impact of the respective losses. These losses might be due to:

- **Planned shutdown time**: the accumulated time when a plant is not producing;
- **Additional production losses** not due to technical reasons in the plant, e.g. upstream/downstream issues or reduced production for commercial reasons;
- **Availability losses**: plant stoppages due to operational or equipment failures;
- **Performance losses**: reduced production/slow cycles due to operational or equipment failures;
- **Quality losses**: rejection of production due to unacceptable product quality.

The TEEP is calculated to be 64%. In the classic TEEP definition, loading effectiveness includes both unplanned production time and scheduled downtime [8]. However, process plant management usually aims to keep production up for an entire year, excluding planned annual shutdowns. In the example, the annual downtime (see "planned shutdown time") is assumed to be 10%.

In the alumina calcination example, a shortage of hydrate feed may cause the plant to stop or to lower the production rate. In the proposed TEEP rating, this outage is captured in the additional production losses previously described. Both planned shutdown times and additional production losses are summarized as loading effectiveness to comply with the TEEP definition from Hiltunen et al [4]. In doing so, it is possible to measure the potential for improvements not only in terms of the plant itself, but also with regard to external conditions.

The values provide a representative and comparable indicator of how well the plant is being utilized with respect to production potential. In the given example, a TEEP of 64% indicates the plant is losing 36% of yearly production potential for various reasons. A loading effectiveness of 79.2% indicates the potential from reducing planned shutdown time and by minimizing factors outside the battery limits of the calcination plant. The latter is generally possible since several process steps, such as filtration, precipitation and calcination, are often operated by the same company. Yet, an OEE and a TEEP of 100% indicate the technologically achievable values related to this technology.

### 3.2. Perficiency

However, OEE and TEEP do not give a clear indication of how efficient the process actually is. Performance losses might be based on operational shortcomings, but can also be due to equipment deficits. For this reason, further factors to measure and compare energy efficiency, raw material utilization, utilities use and environmental footprint have been defined. The combination of these measures can be regarded as *process efficiency*, including the technological and operational levels of a plant. Four proposed indicators to evaluate process efficiency are:

- Energy efficiency – a high value indicates a low level of energy used, both thermal and electrical;
- Raw material utilization efficiency – a high value indicates a process plant with a high percentage recovery of product out of the feed;
- Utility efficiency – a high percentage indicates a plant using a low amount of utilities, such as water, soda, nitrogen or start-up fuel;
- Environmental footprint – a high value indicates a low environmental footprint, and a low negative impact on the environment.

Summarizing these indicators into a single *process efficiency* factor and then multiplying it by the TEEP value leads to a new definition of a plant’s performance and efficiency rating – *Perficiency* – which is calculated as:

*Perficiency* = TEEP x process efficiency

Thus, *Perficiency* combines loading effectiveness, overall equipment effectiveness (OEE) and process efficiency in terms of the indicators mentioned. The *Perficiency* rating not only includes plant production time and production output, but also how efficient production actually is. From a commercial viewpoint, energy and raw material costs, product recovery, utilities and penalties from violating environmental regulations are considerable cost drivers. The *Perficiency* factor includes these drivers and offers a comparable rating for different production lines and sites.

The *Perficiency* evaluation for the hypothetical alumina calcination plant is given in Figure 3. In the example, the process efficiency rating is 86.2%. Energy losses are usually due to both operational issues and for technological reasons. Utility losses in the alumina calcination example are usually low. Soda and water are used in upstream and downstream process steps and not in the calcination plant itself. The rating in this example is therefore 98% and shows only minor losses due to use of start-up diesel after plant-trips. Raw material losses are also not relevant for an alumina calcination plant, since no hydrate product is lost. Further, environmental conditions and stack emissions are fulfilled at all times.

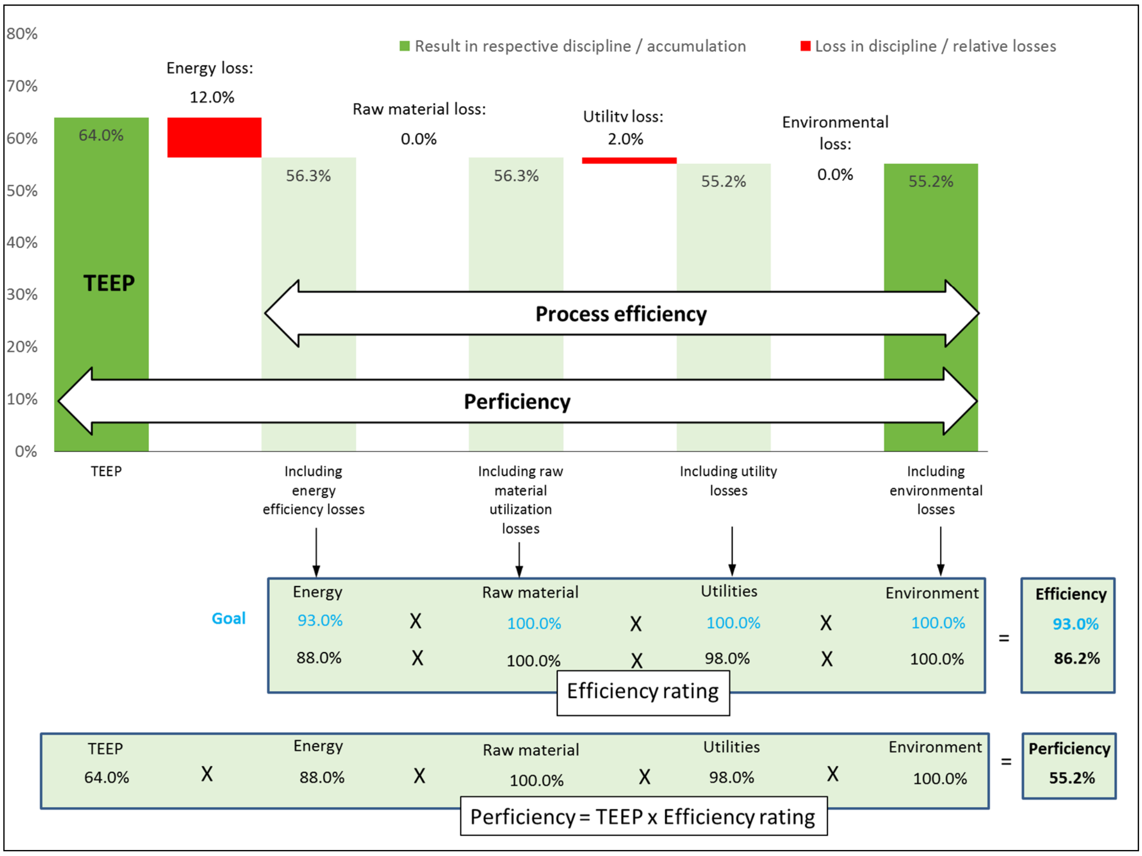


**Figure 3.** ***Perficiency*** **for a hypothetical alumina calcination plant.**

A *Perficiency* rating includes TEEP and a process efficiency rating as well as any or all of the following indicators which might lead to a loss in the rating:

- **Energy loss**: increased energy consumption leads to reduced process efficiency;
- **Raw material loss**: an insufficient recovery of the product from the feed material indicates a reduction in raw material utilization;
- **Utility loss**: increased consumption of utilities (such as water, nitrogen, soda, start-up diesel etc.) reduces process efficiency;
- **Environmental loss**: increased environmental footprint (such as dust emissions, SO2, etc.) reduces process efficiency.

By including a *Perficiency* target, analogous to the OEE/TEEP target, a plant's technological level is taken into account. An older plant with a less efficient energy recovery, and thus higher nominal energy consumption, might have a lower target rating in this indicator. In this way, the *Perficiency* rating itself indicates comparison to the technological optimum for a given process.

The individual indicators defining the *Perficiency* rating are related to the most current technological level possible. Consequently, a plant consuming more energy than a high-end alumina calcination plant in terms of energy consumption has a rating lower than 100% for this indicator.

Using the rating system, bottlenecks in the plant *Perficiency* can be clearly defined. The ratings might indicate which debottlenecking measures are the most beneficial or where plant operation needs to be improved. As an example, see Figure 4, where all of the indicators mentioned have been evaluated and compared to both the target and the technological reference. In this example, it becomes clear that the hypothetical plant lacks energy efficiency while achieving good availability compared to technological reference. Thus, operational performance could be a potential factor for increasing *Perficiency*.

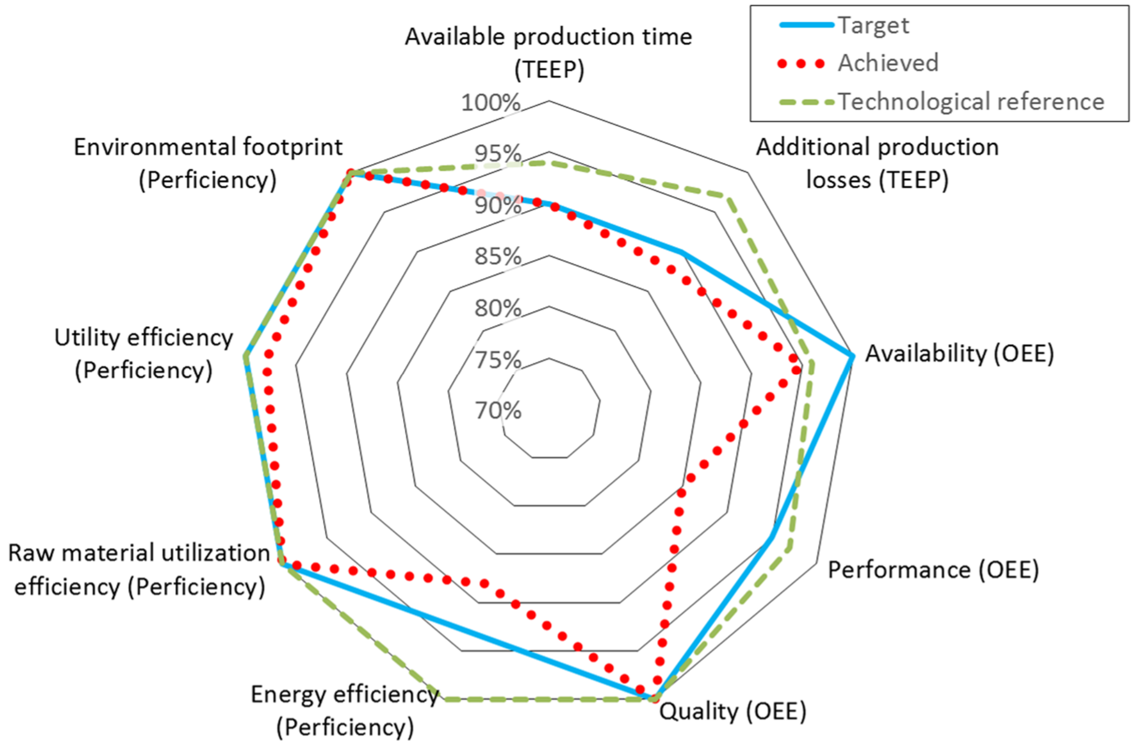


**Figure 4. Evaluation of the hypothetical alumina calcination plant, comparing its achieved *Perficiency* with target and technological reference in all indicators.**

Using the *Perficiency* metric, the technological and operational levels for the plant per indicator can be determined. When both the technological and operational levels are high, the plant, from both an operational and efficiency perspective, is performing at the top of its potential. Otherwise, the metric is used to identify room for improvement, both in terms of technology and operational measures. Note that a target value can be above the technological reference. In this example, the target availability, excluding the planned shut-down, is 100%. However, this value is not reached. Reaching this value would set the new technological reference.

Of course, improvements in energy efficiency as well as in raw material or utility use efficiency need stable operating conditions. Any instabilities will be detected not only in the efficiency factors, but also in OEE/TEEP, since production performance will fluctuate. Generally, fluctuation can be seen only after some time and the same is true of availability due to its uneven use of equipment.

This thinking is what motivated Outotec, with its process, material and equipment capabilities, as well as decades of experience and in-depth theoretical know-how, to develop a 24/7 expert system which can monitor and advise plant operations teams.

## 4. Digital Solutions - Outotec Pretium Advisor

As a designer and manufacturer of large-scale plants, Outotec has the process know-how needed to calculate the heat and mass balance for all operational conditions, both for an entire plant as well as for single equipment units. It can compare ‘reality’, as measured in the DCS, with the ‘theory’ and thus advise changes for optimizing plant operation. The set-up is shown in Figure 5.

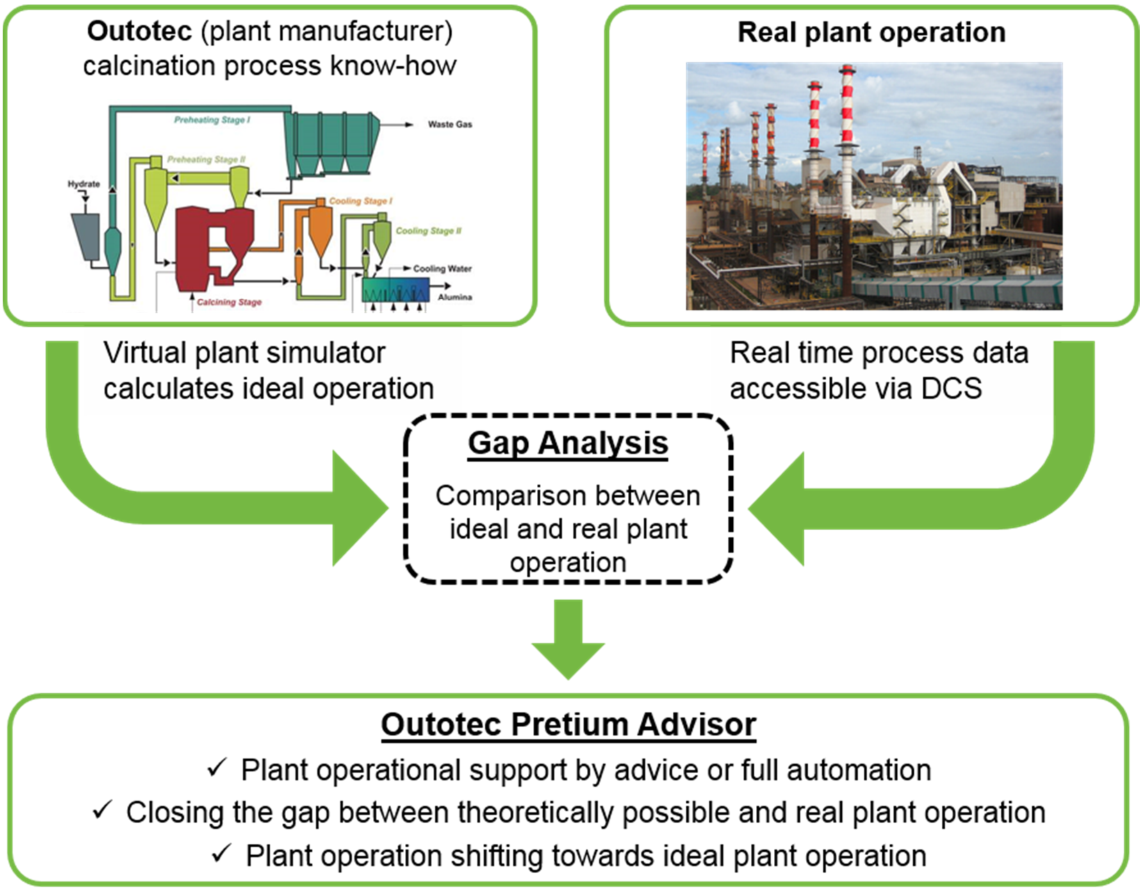


**Figure 5: Set-up of Outotec Pretium Advisor - including Outotec alumina calcination process know-how in plant operation.**

Outotec's digital tool can predict plant operation using a virtual process simulation model. The know-how includes:

- Overall process design and operation;
- Equipment performance;
- Impact of equipment and operation on product quality and recovery rates;
- Impact of feed composition and properties on process performance;
- Energy efficiency of process equipment;
- Parameters influencing a plant's environmental footprint.

As a next step, actual measured plant data is compared to the ideal plant data provided by the simulation. This gap analysis can be performed with the Outotec Pretium Advisor and reveals the potential for improved operational performance. Additionally, equipment is constantly monitored to verify that the operation is within design limits, preventing increased maintenance costs and negative effects on process operation.

In addition to using Outotec Pretium Advisor to support the operational performance of the alumina calcination plant, the simulation models can be utilized to identify unused performance potential by upgrading process equipment. The *Perficiency* factor can help reveal the potential of modernization measures, and allows customers to precisely prioritize decisions based on individual needs. Combining operational support with process upgrades aims to bring a process plant to the current level of technology and operation. An increase in *Perficiency* will reflect the modernization process.

## 5. Targets and Results in Alumina Calcination Technology

The Outotec Pretium Advisor is essentially a learning journey and takes its user from a starting point, or baseline, to an optimum performance using a learning curve.

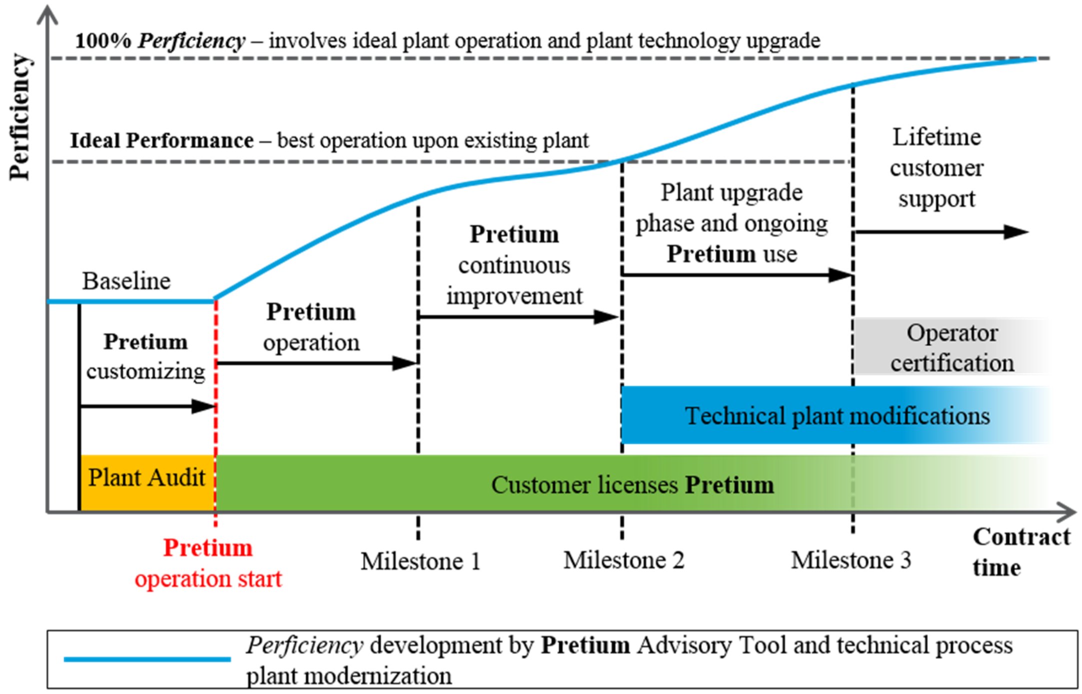


**Figure 6. *Perficiency* development with the Outotec Pretium Advisor support and technical plant upgrades.**

A typical optimization process is depicted in Figure 6. Prior to the commissioning of the Outotec Pretium Advisor, a plant audit must be performed. The plant baseline performance (key performance indicators or KPI's) is recorded, based on extensive data analysis. During such an audit, not only the absolute KPI values, but also the distribution can be captured. Additionally, plant *Perficiency* is also measured. Based on the plant's *Perficiency* and known operational and theoretical *Perficiency* values, potential improvements can be assessed. The audit phase can be summarized in three steps:

1. Detailed analysis of the plant operation and *Perficiency* rating;
2. Comparison with reference *Perficiency*;
3. Outotec Pretium Advisor customization and identification of debottlenecking measures.

The plant audit phase results in a customized Pretium Tool for the specific customer's plant. During the usage phase, the tool is continuously being improved, increasing *Perficiency* for process plant operation (blue curve). A hypothetical evaluation (using artificial data) for the evaluation of one indicator of the *Perficiency* rating of an alumina calcination plant is shown in Figure 7, where the specific energy consumption is indicated. Using the same hypothetical figures as in the previously discussed example, the technological optimum (ideal operation) for this hypothetical plant is an energy efficiency of 85% (see Figure 3).

The achieved mean energy efficiency is 77%, revealing a lost potential of 8% in the energy efficiency indicator. Apart from depicting the potential improvement in this indicator, the graph also reveals the distribution. It shows that the plant is able to run close to its optimum at 85%. In this instance, it can be assumed that a more stable operation using the Outotec Pretium Advisor will not only increase the energy efficiency rating, but it will also lower the standard deviation in the indicator. This can also have a positive effect on the equipment's life-time by reducing fluctuations in plant operation.

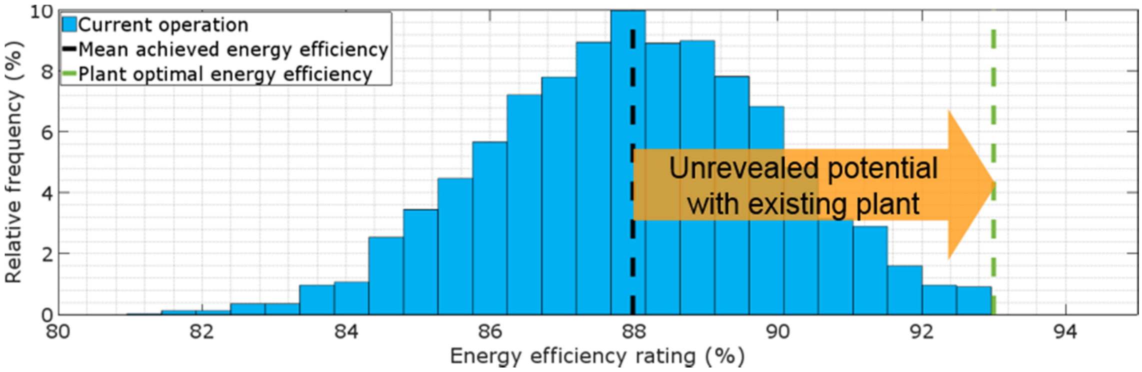


**Figure 7. Energy efficiency evaluation for a hypothetical alumina calcination plant.**

The Outotec Pretium Advisor will reach an initial milestone after a certain time in operation. When a flattening learning curve in *Perficiency* has been reached, the next set of measures in terms of advanced functions will be used. These features are based on customer feedback and also on opportunities recognized during the Pretium operating time.

Reaching Milestone 2, Figure 6: The Outotec Pretium tool has been fully utilized and the ideal performance of the existing plant equipment reached. At this point, further optimization involves process and equipment debottlenecking. Naturally, reaching a level of up to 100% in *Perficiency* would involve running all the time at full capacity, with no waste and at the highest level of efficiency. To ensure the process plant continues at a high level of operation in terms of the *Perficiency* rating, Outotec support shifts from debottlenecking to ongoing operational and maintenance support. Apart from the Outotec Pretium Advisor helping to consolidate at such a high level of operation, the importance of continuous operator training, education and certification has been highlighted to further ensure a top-of-the-range production process.

Table 1 outlines 14 major losses in *Perficiency*, which are partially responsible for the losses affecting OEE [9]. Insufficient process operation as a factor for performance loss can also include bad performance during the plant start-up phase. Therefore, performance loss includes all times that the plant is in operation, while availability loss includes plant stoppages caused by an equipment outage or errors in operation. The main driver for performance loss is normally equipment malfunction, limiting the plant's ability to reach its full capacity. In terms of process efficiency losses, it becomes clear that there are primarily two factors which reduce the *Perficiency*:

1. Outdated process technology;
2. Insufficient process operation.

While outdated technology hinders the plant from reaching the technologically achievable level, the plant can still be operated at the *Perficiency* target, set according to the technology used in the specific plant. Insufficient process operation is usually caused by fluctuations and plant shut stoppages. This issue is addressed by the Outotec Pretium Advisor and minimizes the negative impact on *Perficiency*. Environmental losses are mainly caused by operating the plant above the design range or by defective equipment. The latter can lead to an increase in dust emissions.

**Table 1. Reasons for major losses in the *Perficiency* rating, distinguished by indicators effecting OEE and process efficiency.**

| | Indicator | Reason for loss |
|---|---|---|
| Overall Equipment Effectiveness (OEE) | Availability loss | Equipment prone to failure |
| | | Plant stops caused by operator mistakes |
| | Performance loss | Equipment throughput limitation |
| | | Insufficient process operation |
| | Quality loss | Production rejects |
| | | Startup rejects |
| Process Efficiency | Energy loss | Process technology outdated |
| | | Process operation not in optimum |
| | Raw material loss | Process technology outdated |
| | | Process fluctuations, operating errors |
| | Utility loss | Process technology outdated |
| | | Process fluctuations, operating errors |
| | Environmental loss | Operation above nominal capacity |
| | | Equipment malfunctions |

All indicators above can affect the *Perficiency* rating. The six losses affecting OEE are based on [9], but modified to match the requirements of the process industry.

Continuous technological improvements might open new opportunities for the customer to enhance performance to keep up with technological benchmarks. Using the *Perficiency* measurement, an assessment of a plant's rating compared to technological evolution can be easily done.

## 5. Applying the Outotec Pretium Advisor

### 5.1. Operating Modes

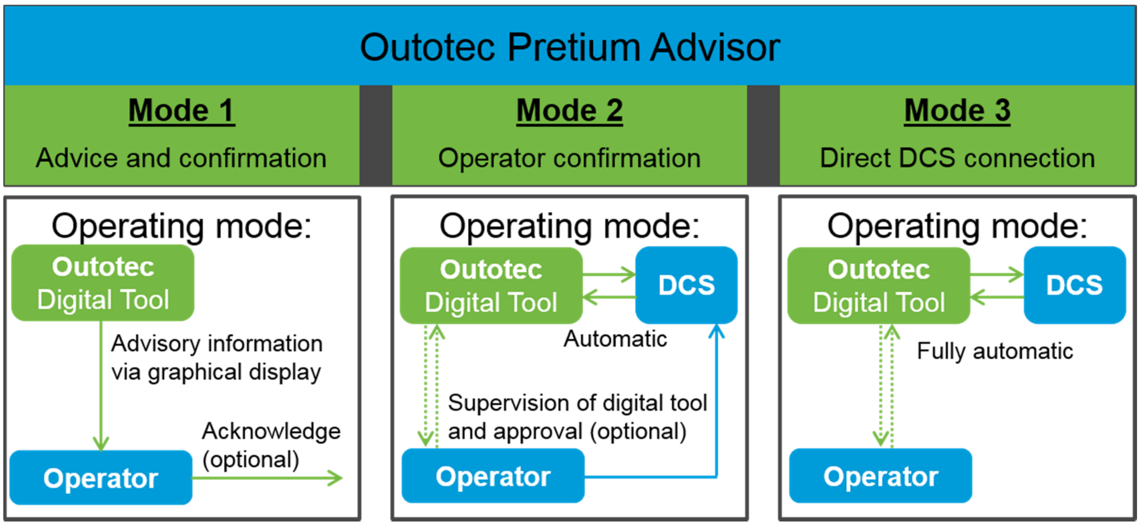


**Figure 8. Three modes for the implementation of the Outotec Pretium Advisor.**

For the implementation of the Outotec Pretium Advisor, three modes which support plant operation have been selected and are depicted in Figure 8. The first mode has purely advisory functionality with the tool suggesting an improved way of operating the plant. This can be a message advising an operator to adjust a certain controller set point. The operator has to acknowledge that the message has been read. The second mode requests a confirmation from the operator that the Pretium tool has permission to apply changes to the DCS automatically. The third mode enables the tool to apply operational changes fully automatically while the operator monitors the operation. The three modes can be customized for each plant with respect to its operating philosophy and requirements.

In addition to the advisory or automation functionality, the tool allows monitoring of the plant unit performance down to plant equipment. In case of mismatches between expected and measured behavior, algorithms search for the root causes and provide warnings. These warnings or error indications go far beyond normal process surveillance by the DCS (distributed control system). In the DCS, typically only individual values are monitored and warnings are generated in case of exceeding low or high limits. The monitoring capabilities inside the Outotec Pretium Advisor combine many process variables to find malfunctions which otherwise would remain undetected. More details about the Outotec Pretium Advisor features are described in [10] and [11].

### 5.2. Beyond Calcination in the Bayer Process

Alumina calcination is only one part of an overall alumina refinery. It is well understood that factors outside calcination, such as hydrate moisture, can have an impact on specific energy consumption, or the calcination off gas temperature. Normally, alumina refineries take hydrate samples to verify the hydrate moisture entering the alumina calciner with the disadvantage that operators need to wait for the results from the laboratory before being able to interpret the process changes or take any actions. Thus, operational problems which can occasionally occur in a hydrate filter may be taken into account too late in the overall process flow of the alumina calcination plant. This can lead to operational difficulties in the alumina calciner. Hydrate moisture typically varies between 4 and 10%, depending on filter performance and operational activities, such as washing and cloth changes.

To address this challenge, the Outotec Pretium Advisor can create links between facilities at a production site. An increase or drop in filter moisture can be detected by comparing certain values of theoretical and measured process variables. The estimated moisture value can then be taken into account to reduce the impact of fluctuations in upstream process steps. By doing so, the tool generates an operational link between the various plants at a production site and targets a site-covering optimization.

## 6. Conclusion

As process technology and equipment know-how are constantly undergoing improvement measures in alumina calcination process technology, modern plant operation has become increasingly reliable and efficient. Operating companies seek better metrics to evaluate their plant's operation and equipment utilization. Overall equipment effectiveness (OEE) and total effective equipment performance (TEEP) are well established metrics, which consider production time and equipment effectiveness in their evaluation.

As a new metric, *Perficiency* has been introduced as a combination of TEEP and process efficiency, covering a combined assessment of performance indicators such as *total energy consumption*, *raw material utilization*, *utility utilization* and *environmental footprint*. The *Perficiency* rating has been evaluated for a hypothetical alumina calcination process plant. It has been introduced to have a metric covering not only production time and effectiveness, but also technological excellence in terms of the responsible and sustainable handling of natural resources. Furthermore, these resources are increasingly cost drivers in the production process and can be fully captured using the *Perficiency* rating.

The utilization of the *Perficiency* rating allows bottlenecks in process plants to be identified by comparing single plants or plant units to individual target values and to technological reference values, representing the best achievable *Perficiency* rating for the respective technology. Revealing indicators with shortfalls against reference values, measures can be taken to bring the process plant to the highest operational and technological levels.

To bring the plant to operational excellence, Outotec has developed the Pretium Advisor, a digital solution incorporating the plant manufacturer's theoretical process know-how and operational experience. The tool provides advice and assumes responsibility for certain high-level operational tasks as well as monitoring and fault detection, which have proven too demanding for human operators. Thus, the production process can be streamlined, resulting in improved energy efficiency, with stable and increased production rates. The outcomes resulting from the improved *Perficiency* rating by operational support can be observed. Based on solid theoretical background, the Outotec Pretium Advisor can be extended to upstream and downstream plant units, such as hydrate filtration and precipitation as seen in the example of alumina production. Utilizing an ever-increasing set of digital tools such as the Outotec Pretium Advisor will change the way a plant operates in the future in terms of automation. Based on the features described and the impact of the Outotec Pretium solution, the first steps towards 'autopilot' operation have been made.

As a second measure to improve the *Perficiency* rating, process technology and equipment have been improved to close the gap between technologically possible and measured plant performance. The combination of the digital tool supporting the operation and the mechanical process upgrades allows operating companies to fully utilize the production facilities and to operate process plants at the highest level.

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