## D2.2 - Process Industry Domain Analysis and Use Cases

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Executive Summary

The purpose of this deliverable is to document and describe the aluminium and plastic domain-specific and cross-sectorial use cases, defining how the MONSOON platform will be used for predictive optimization and scheduling tasks in production plants and sites.

The second chapter of the document is dedicated to the state of the art analysis for the aluminium and plastics domain on both the technological and business aspects.

The third chapter defines the detailed use cases and the initial requirements engineering. It presents an initial taxonomy for the involved technologies and processes that will be fed into the development of the cross-sectorial models and the platform development.

Next iterations of this document, will enrich the use cases descriptions and detail the cross-sectorial aspects, will also focus on process modelling and life-cycle aspects and with analysis on methodologies and key indicators to account for “circularity” aspects in the use cases definition.
1 Introduction

The purpose of this deliverable is to document and describe the state of the art analysis for the aluminium and plastics domain on both the technological and business aspects. It describes the aluminium and plastic domain-specific and cross-sectorial use cases, defining how the MONSOON platform will be used for predictive optimization and scheduling tasks in production plants and sites.

The deliverable documents the work undertaken in task T2.2 with the objective to define Initial (month 3) Process Industry Domain Analysis and Use Cases.

Two other iterations are scheduled month 15 as an update and month 24 for the final Process Industry Domain Analysis and Use Cases.

It the next iterations of the deliverable the detailed use cases will be developed on the technological aspects but also, based on the “MONSOON Platform Usage Scenarios” D2.1 deliverable, with the description for each the future use of the MONSOON platform as well as more detailed scenarios either common or specific to the Aluminium and Plastics domains.

The cross-sectorial aspects will be addressed giving details on the methodology to duplicate our use cases to similar ones in other industries.

Next iterations will also focus on process modelling and life-cycle aspects and with analysis on methodologies and key indicators to account for “circularity” aspects in the use cases definition.

1.1 Related documents

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Table 1 – Related documents
2 Domain State of the Art Analysis

2.1 Aluminium industry domain

2.1.1 Aluminium production

The production process goes through several main steps, two of which are in scope of this project – Carbon plant and Potline processes.

The heart of the plant (smelter) is constituted by the Potline. It is constituted by a set of several hundred pots where liquid aluminium is being produced from electrolyte based on utilization of electrochemical process (electrolysis). Each of these pots is in a different production condition and with slightly different architecture. The main inputs to the process are electricity, Alumina (Al2O3), anodes and cryolite bath. As an output not only the aluminium but emissions is produced as well. The process is highly energy consuming – electrical energy from an external supplier is used.

In order to run the electrolysis, pots must be equipped with anodes and cathodes. Anodes are consumed during the process within typically 28 days and therefore they have to be continually replaced. Anodes and their quality are the one of the most important inputs for the electrolysis pot which can be controlled. Each anode position in the pot has its own specific condition of operation (very strong magnetic field, current distribution and thermal conditions in pot).

After putting the anode into the pot, the alumina reduction process in the pot continuously consumes the anode and decreases the height thereof. Therefore each anode in a pot has different height. When the anode is consumed (the height reaches a critical level), the anode is replaced by a new one. After removing the spent anode (butt) from the pot, it is cleaned and electrolyte as well as anode butts are recycled.

New anodes are being prepared in-house within the Carbon plant. Anode blocks go through three successive stages:

- Green anodes (produced from calcined petroleum-coke, coal-tar pitch and recycled scraps and anode butts by mixing and subsequent forming and vibro-compaction in the paste plant),
- Baking anodes (produced from green anodes in chambers of Baking furnace),
- Rodded anodes (produced from baking anodes by splicing them together with stems – two anodic blocks on one stem).

Besides usable anode blocks, tar emission and anode scraps are co-produced. From energy point of view, the baking process is usually using natural gas. The rodded anodes represent the final product stage of the Carbon plant. They are subsequently distributed to electrolysis pots to replace consumed anodes.

The aim is to optimize anode production procedures, distribution of anodes to pots and selection of anodes for specific positions in pot as an anode replacement. In an ideal case, all produced rodded anodes would be with high quality only. In reality not all of the typically 200 anodes (400 blocks) produced per day are of the best quality – due to several challenges (e.g. quality distribution of raw materials, technical abnormalities in production process, normal distribution of the process) there is a chance to produce anodes not in the best quality which can cause problems in electrolysis pots.

Aluminium Pechiney has proposed its Dunkerque plant (in northern France) as an indicative use case as there is an intensive need for plant-wide monitoring within its aluminium production, electrolysis process and potline process. The Dunkerque plant is in fact the highest-producing primary aluminium plant in the EU-28 area. It is equipped with 264 electrolytic pots (potline) operating at 390 kA, yearly producing 280,000 tons of aluminium, and consumes 3.7 TWh of electricity, equivalent to a 1-million people city consumption. The Dunkerque plant is also the first aluminium factory in France with 65% of total national production and Europe’s largest sheet-aluminium producer as well as one of the most modern smelters.
2.1.1.1 A continuous process

The aluminium process consists in breaking by electrolysis the bonds through which the aluminium metal atom is tight to oxygen in alumina. This process can be simply described as follow:

- Metallurgical alumina (aluminium oxide – $\text{Al}_2\text{O}_3$), the main aluminium production input, is transported to the plants.
- Alumina, which has a high melting point, undergoes over an electrolytic reduction within the so-called electrolytic pots. In the electrolytic pots, high direct current passes through a negative carbon cathode and a positive carbon anode. The reaction with oxygen, present in the alumina, consumes the anode when generating $\text{CO}_2$ ($2\text{Al}_2\text{O}_3 + 3\text{C} + e^- \rightarrow 4\text{Al} + 3\text{CO}_2$ at 960°C)
- Liquid aluminium is periodically drawn from pots using specific vehicles and is casted into extrusion ingots, sheet ingots, billets, or different other products depending on how it will be further processed in transformation plants.

Figure 1 - A continuous process: 24 h / day, 365 days / year over the 30-50 years of plant operation.

Figure 2 - overview of the aluminium electrolysis process
The production process is happening at high temperature. Like in any electrochemical reactor, there are several equilibria that need to be monitored, managed and kept under control and in steady levels in real time:

- Thermal balance: adjustment of the Joule effect generated in the pot to balance the heat losses.
- Chemical balance: raw material feeding rates and bath chemical composition adjustments.
- Magneto-hydro-dynamic equilibrium: stable Laplace forces induced liquid bath and metal movements.
- The mass balance: produced metal tapping, and the liquid bath volume control.

### 2.1.1.2 A typical aluminium smelter

![A typical aluminium smelter](image)

**Figure 3 - a typical aluminium smelter**

### 2.1.1.3 Finished aluminium products at Casthouse

The objective of a casthouse is to manufacture a product with the shape, composition, properties and internal structure that correspond to the customers’ requirements with:

- safety, cost effectively and a way that does not harm the environment,
- the best value potline metal purity.

The main final customers are aluminium transformation businesses.

Main finished products:

![Main finished products](image)

**Figure 4 - main casthouse finished products**
2.1.1.4  A typical potline and pot

Managing a potline process of such size is similar to managing a population. The pots involved in aluminium production line are like individuals behaving according to common rules and trends and individual behaviours, which can drift with time and events, or as a reaction to potline process setting changes.

An optimum performance of the potline happens when the whole population is operating in average at an optimum target setting point, and expected behaviour, and when the standard deviation of the population is minimal (i.e. there is no problematic individual pots).

![Figure 5 - a typical potline view](image)

Figure 5 - a typical potline view

![Figure 6 - Schematic cross-section of an AP pot](image)

Figure 6 - Schematic cross-section of an AP pot

2.1.2  The anode assembly

2.1.2.1  Description

An anode assembly (AA) comprises:

- an aluminium stem
- a cast or welded steel bracket, on which cylindrical pins are welded (this assembly is also called a hexapod when there are 6 pins)
- one or more amorphous carbon anodes rodded to the pins
The stem/bracket connection is formed by an aluminium/steel composite part or clad, welded on its aluminium side to the AA stem and on its steel side to the AA bracket. The bracket/anode connection is formed by the pins rodded into the anodes using cast iron. Anode assembly design and anode geometry are closely linked to the design of the electrolytic pot itself. The table below gives the main characteristics of anodes and anode assemblies used in pots currently in operation.

Anode Assemblies characteristics for AP-30 technology:
- Length: 1500 mm, Width 650 mm, Height 600 mm, Mass 930 kg
- 2 anodes blocks per anode assembly (total mass of anode assembly: 2700 kg)
- 20 anode assemblies per pot, 6 pins per anode assembly (pin diameter: 170 mm)

2.1.2.2 Anode composition

An anode is a parallelepiped-shaped block of amorphous carbon. Its top surface features grooved cylindrical holes, in which the cast iron-rodded pins are located. On a macroscopic scale, the anode structure is composed of carbon grains smaller than 15 mm, bonded with carbon cement. Two-thirds of these grains come from petroleum coke and one-third from pieces of anode recycled after use. The bonding cement is a blend of fine particles of similar origin and a carbon binder called pitch, reduced to an amorphous carbon state after baking at 1,100 °C.
An anode is therefore formed of two intimately mixed types of carbon. This important notion conditions many of its properties. One third of the volume of this structure is composed of microscopic pores intercommunicating to a greater or lesser degree, which makes the anode permeable to gases. It contains small quantities of metallic impurities, which can have serious consequences in the event of deviation.

An anode is an electrical conductor. Its geometric density (ratio of its mass to its external volume) varies between 1.52 and 1.62 according to its quality. A good quality anode is exempt of internal defects such as areas of constituent segregation or cracks, or else it contains only limited, controlled proportions thereof.

### 2.1.2.3 Anode Assembly usage

The following picture shows a new AA being placed in a pot using a pot tending assembly (PTA).

![Figure 9 - Placement of a new AA (AP30 technology)](image)

The AA is held approximately 5 cm above the pot liquid metal pad by means of a tube that clamps the stem to the pot anode beam, which also distributes current to all the AAs.

In the case of an AP-30 pot, the average current circulating in an AA from the beam to the pot is 15,000 A. As soon as anodes are placed in the pot, they are covered with crushed bath to protect them from oxidation. 27 to 30 days later, two-thirds of the anode height has been consumed and the AA has to be replaced by a new AA. AA usage time in the pots – typically 28 days - is called the “anode cycle”.

![Figure 10 - Spent anode removal at end of cycle](image)

During their cycle, anodes must fulfill a number of conditions to ensure optimum operation of the electrolytic process.
### 2.1.3 Anode Quality criteria

#### 2.1.3.1 Low carbon consumption

Two factors contribute to carbon consumption, the first corresponds to an electrochemical reaction and second to purely chemical reactions.

**Electrochemical consumption**

The anode/bath interface is the center of the following basic reaction:

\[
\text{Al}_2\text{O}_3 + \frac{3}{2} \text{C} \rightarrow 2 \text{Al} + \frac{3}{2} \text{CO}_2
\]

According to this reaction, the theoretical carbon consumption is 333 kg/t of aluminium produced. Parasitic reactions result in re-oxidation of part of the metal with the produced \(\text{CO}_2\) (back reaction), so the aluminium quantity actually produced is slightly less than the theoretical quantity. The ratio between actual and theoretical production is called the current efficiency, which may vary between 92 and 97%, depending on pot performance.

Effective carbon consumption per tonne of aluminium produced is therefore slightly higher than 333 kg/t and, if the current efficiency is 95%, it is, for example: \(333 \times 100 / 95 = 351\) kg/t

**Chemical consumption**

Part of the \(\text{CO}_2\) produced when reducing alumina disperses by circulating within the porosity of the anode which is at very high temperature when in contact with the electrolytic bath, which causes further oxidation of the carbon by carbon dioxide reactivity based on the following reaction:

\[
\text{CO}_2 + \text{C} \rightarrow 2 \text{CO}
\]

This so-called Boudouard reaction is a chemical reaction that is accompanied by excess carbon consumption of approximately 40 kg/t of aluminium produced. Its value depends on the reaction intensity, which itself depends on pot temperature, anode permeability to pot gases and various catalyzers present in the anode in the form of impurities (especially sodium, vanadium, nickel...). Another cause of chemical consumption is due to oxygen in the air, which manages to come into contact with the top of the anode, despite the layer of bath protecting it:

\[
\text{O}_2 + \text{C} \rightarrow \text{CO}_2
\]

\(\text{CO}_2\) produced by this reaction is discharged along with the other pot gases.

This new excess consumption due to anode oxygen reactivity varies between 10 and 30 kg/t of aluminium produced, depending on the airtightness of the bath cover, the anode permeability and and the above mentioned metallic impurities.

![Figure 11 - Reaction causing carbon consumption](image)

**Net consumption and net carbon**

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This is the total carbon consumption per ton of aluminium actually produced. Its breakdown is as follows:

- electrochemical consumption (at 95% current efficiency) 350 kg/t,
- consumption due to carbon dioxide reactivity 45 kg/t,
- consumption due to oxygen reactivity 15 kg/t,
  Total net carbon 410 kg/t.

In practice and depending on anode properties and pot operation, net carbon varies between 395 and 450 kg/t or even more.

The example below illustrates the case of a downgraded situation:

- electrochemical consumption (at 91% current efficiency) 365 kg/t,
- consumption due to carbon dioxide reactivity 60 kg/t,
- consumption due to oxygen reactivity 20 kg/t,
  Total net carbon 445 kg/t.

This case corresponds to downgraded pot operation with a current efficiency of 91% instead of 95%, as well as increased consumptions due to oxygen and carbon dioxide reactivity resulting from both the operating conditions at this pot and insufficient anode quality.

**Gross consumption or gross carbon**

Unlike net carbon, gross carbon takes into account the anode quantity remaining at the end of the cycle because it is defined as the anode quantity supplied (or lost) to the pot, reduced to each tonne of aluminium produced.

In general, gross consumption varies between 550 and 580 kg/t, depending on the net carbon and the anode quantity remaining at the end of the cycle.
2.1.3.2 Long anode cycle

In the case of the pots referred to above, the end-of-cycle anode height must not be less than about 200 mm to ensure that the pins do not come into contact with the liquid bath, if the anode is submerged during operations to suppress pot polarization. Steel dissolves quickly in the bath and this effectively leads to rapid pin wear and unwanted aluminium contamination by the iron dissolved in the bath. With 600 mm high anode, the wear is approximately 400 mm, i.e. for an 80-shift cycle, 5 mm per 8-hour shift. Other things being equal, the rate of anode wear and thus the cycle time effectively depend on:

- the net carbon,
- anode density or quantity of carbon per unit volume.

The rate of anode wear is all the lower when the net consumption is low and the anode density is high. Dense, lowly reactive anodes are therefore preferred, either to reduce anode changing frequency by prolonging the cycle time or, with the same cycle time, to have higher spent anodes to improve pin protection and reduce iron contamination of the metal.

2.1.3.3 Resistance to carbon dusting

We have seen that the CO₂ produced by reducing the alumina consumes the anode carbon due to carbon dioxide reactivity and that the anode carbon is made up of coke grains cemented by a carbon binder. If the CO₂ reactivity of the binder is higher than that of the coke grains, the binder is consumed quicker leading to dislodgement of the coke grains, which then fall into the pot before being consumed themselves.

![Figure 14 - matrix and binder cokes](image)

This reaction, known as carbon dusting, seriously destabilizes pot operation and must be avoided at all costs. Drawn by movement of the metal, the carbon grains concentrate effectively at different points of the bath/metal interface, where they form magmas called mushrooms that adhere to the anodes.

![Figure 15 - carbon dusting](image)

The resulting reduction in the anode/metal distance immediately above the mushrooms constitutes as many zones of preferential current passage, which destabilize pot operation by disrupting the uniformity of the current distribution at the anode assemblies.

One of the principal effects of this disturbance is an increase in temperature of the pot, whose performance deteriorates. Moreover, because temperature accelerates the CO₂ oxidation rate, the phenomenon spreads to other anodes, which would not have produced carbon dust at a lower temperature. The phenomenon therefore propagates throughout the pot.
The treatment applied to the pots involves extracting the carbon dust concentrated at the tapping hole and finding, then breaking, mushrooms after removing the anode assemblies concerned. These additional tasks can make potroom results worse because they significantly increase the potline operation workload and process disturbance.

It is therefore essential that anodes resist dusting, which means that the binder and matrix cokes must have comparable $\text{CO}_2$ reactivities, so that the anode/bath interface is uniformly consumed.

### 2.1.3.4 Thermal shock resistance

When the anodes are being installed, they are at ambient temperature and are immersed in 20 cm of bath at 960 °C. At this moment, they are subjected to a thermal shock, which may result in one of the following consequences.
After a longer period (one or two hours), cracking across a vertical plane mid-way between pins, both anode sections being held by roddings.

After an even longer time, cracking across a horizontal plane possibly causing separation of the bottom section, which then falls into the pot.

The first case is the most characteristic of thermal shock and results in a rise in pot temperature, which must be avoided to prevent destabilization of the pot. As soon as a crack appears, the anode must be removed and the corner broken off, if it is still attached. If the broken corner is small, the anode can be placed again in the pot; if not, a new anode is required.

The second case has less impact on pot operation and current passage because the two pieces of anode remain part of the anode assembly.

The last case is usually linked to an anode structural defect created at mixing/forming stage, aggravated by the thermal shock to the extent of causing anode separation. The detached section must of course be removed from the pot as soon as possible, a major task involving pieces weighing several hundreds of kilograms.

We see that the additional remedial work required, when such incidents occur, can itself also severely disrupt potline operations and, in turn, pot performance.

It is therefore essential to ensure that anodes have high thermal shock resistance.

**Figure 20 - Relative weight of parameters versus thermal shock resistance**
2.1.3.5 **Low anode voltage drop**

The following diagram represents a typical breakdown of voltage drop along an anode assembly. It should be noted that the rodding itself (pin > cast iron > carbon contact) represents 50\% of the anode voltage drop because of the relatively poor conductivity of the cast iron, as well as the pin/cast iron and cast iron/carbon contacts. Rodding cast iron must therefore meet strict specifications to obtain the required quality and limit the anode voltage drop at this location.

![Diagram showing voltage breakdown](image)

**Figure 21 - Breakdown of AA anode voltage drop at mid-life**

2.1.3.6 **Anode uniformity**

The structure of a given anode must be totally identical throughout, to ensure a uniform wear front throughout the usage cycle. Internal non-uniformities can effectively cause deformations of this surface and these disrupt pot operation.

Wear regularity concerns the whole anode bottom level, implying also that all anodes forming this bottom level must be mutually identical to ensure regular pot operation.

The carbon dust propagation mechanism illustrates this necessity because a small number of defective anodes is enough to extend the phenomenon to other healthy anodes by a simple rise in temperature. Similarly, pot destabilization due to thermal shock-induced breakage of a few anodes causes breakage of other anodes that would have remained intact under normal conditions.

2.1.3.7 **Low impurity contents**

The following table shows the main impurities contained in anodes, along with their usual concentrations and consequences on all processes.
Most of these impurities originate from raw materials, which must therefore be selected accordingly.

Those whose concentrations are increased by the anode preparation process must be subjected to particularly careful control:

- iron results from mill wear and recycling of spent anodes from which iron particles have been incompletely excluded (splatterings of rodding cast iron, shot used for cleaning),
- sodium, calcium and fluorine are introduced by recycled anodes from which pot bath has been incompletely excluded.

Consequences of these impurities are of three types:

- **Quality of metal produced:**
  Iron, silicon and vanadium must not exceed specific levels for certain applications. In the casthouse, there are processes for eliminating part of the vanadium but their efficiency is limited, imposing raw material selection. In the case of iron and silicon, care must be taken to ensure recycled anode cleanliness.

- **Potroom and anode preparation processes:**
  Vanadium, nickel and sodium are catalysts of carbon oxidation, the two first by air, the third by CO₂ (this second reaction is itself inhibited by sulfur). They play a dominant role in carbon consumption mechanisms.
  Sodium coexists with fluorine introduced by the bath in a 1.7 to 1.8 mass ratio.
  Both have a highly corrosive action on the alumino-silicate refractory materials used in the anode preparation process (baking and induction furnaces). This is the main reason why they must be eliminated in the most efficient way.

- **Environment:**
  Sulfur is released during anode combustion and cannot be stopped by potroom gas treatment installations.
  Limiting of emissions therefore depends on the choice the coke, which is the main source of sulfur.

### Review of required characteristics

Anode characteristics are not independent and, depending on their nature, there are more or less marked correlations between them. Thus, resistivity varies in the same direction as density and certain metal impurity contents influence reactivity.

<table>
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<th>Element</th>
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<th>Si</th>
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</tbody>
</table>

Table 2 - Main chemical impurities present in anodes

**2.1.3.8 Review of required characteristics**

Deliverable nr. | D0.0  
Deliverable Title | Process Industry Domain Analysis and Use Cases
Version | 0.03 - 13/01/2016
Reactivity appears an essential anode characteristic because it conditions three of its usage values:
- carbon consumption
- anode cycle time
- resistance to carbon dusting (more in the form of differential reactivity than overall reactivity).

The term "optimization of mechanical properties" means ensuring that a few composite indicators are kept within determined value ranges, resulting in anodes that are resistant to thermal shock.

2.1.4 Anode manufacturing overview

2.1.4.1 Process overview

Anode and anode assembly production comprises carbon raw material selection, green anode preparation, anode baking and anode rodding with hexapods.

![Figure 22 – “cold” part of the anode manufacturing process](image)

**Coke and pitch handling and storage shop:**
- Receive and store the pitch
- Receive coke arriving from the main on-site stock
- Prepare the mixture of the coke qualities if necessary: the coke “blend”.

**Paste plant:**
The function of this shop is to produce paste by mixing coke, recycled anode products, recycled dedusting products and pitch. The stages of the process are as follows:
- Crushing and sorting the dry products (coke, recycled green and baked products, dedusting fines)
- Preheating and mixing the raw material products with pitch
- Heating and distributing the heat transfer medium for the dry product preheating.

Once the paste is produced, a forming step occurs in the paste plant.
- Forming the green anodes by vibrocompaction of the paste in a mould
- Cooling the green anodes.
- Green and baked anode handling and storage shop
The shop manages the following stocks:

- Green anodes arriving from the paste plant and going to the baking furnace
- Baked anodes arriving from the baking furnace and going to the rodding shop.

A sufficient stock of green anodes is built up to supply the baking shop when no anodes, or not enough anodes, are produced by the paste plant (in particular when the paste plant is stopped for maintenance). The baked anode stock comprises baked anodes produced by the baking furnace, but not required for consumption by the rodding shop. This stock must be sufficient to supply the rodding shop regularly with baked anodes independently of the baking furnace production rate.

Anode baking shop:
The function of the shop is to produce baked anodes from green anodes. The baking furnace comprises sections. Each section consists of pits. In each pit the anodes are arranged in rows and layers. The baking furnace uses packing coke to cover the loaded green anodes. The baking furnace is in continuous operation.

Anode assembly rodding shop:
The function of this shop is to:

- Produce new anode assemblies for the potroom from baked anodes, recycled stems and cast iron
- Recycle spent anodes returned from the potline
- Recycle rodding cast iron.

The stages of the process covered by the rodding shop are as follows:

- Storing anode assemblies
- Preparing stem-bracket assemblies
- Rodding anode assemblies
- Repairing stem-bracket assemblies
- Recycling cast iron.

Carbon recycling shop:
The function of this shop is to crush green and baked recycled products:

- Rejected green anodes
- Rejected paste
- Rejected baked anodes
- Spent anode carbon.

Anode baking furnace fumes treatment:
Combustion fumes produced by anode baking are treated in the Fume Treatment Center. Fresh alumina is used to fix the particles and pollutants carried in the fumes. The charged alumina is collected through filters and subsequently mixed with the fluorinated alumina in the potline silos.

Each stage has a specific impact on obtaining final product characteristics.

2.1.4.2 Properties the anode needs to meet the Electrolysis requirements

Table 3 reviews schematically the characteristics that anodes must have in order to meet quality criteria specified by the potroom.
Table 3 - Schematic review of anode characteristics meeting user quality specifications

2.1.4.3 Raw materials

Levels of reactivity, geometric density, resistivity and chemical purity of anodes and their thermal shock resistance properties depend, to a large extent, on characteristics of the petroleum coke from which they are derived. For financial and availability reasons, the choice of coke entails a compromise resulting in cokes from different sources being mixed and process parameters being adapted accordingly.

Through its wettability, pitch plays a no less determining part in establishing the parameters referred to above, except for chemical purity, which is most often unaffected by pitch origin.

Anode uniformity depends primarily on the raw material consistency, which requires rigorous monitoring of acceptance operations and establishment of long-term relations with suppliers to ensure stable supplies in compliance with issued specifications.

2.1.4.4 Green anode manufacturing

High anode geometric density, low resistivity, homogeneity and no cracking depend on the green process capacity for delivering high mixing powers and times, as well as temperatures suited to each green anode preparation stage.

Soundness characterizes the process capacity for ensuring that these characteristics remain constant; it must be high to ensure production uniformity.

When coke characteristics do not permit sufficient thermal shock resistance to be reached, adopting a suitable dry products grain size distribution is usually enough to achieve the target objective.
2.1.4.5 Anode baking

The majority of anode characteristics are acquired at the green stage and reach their final values at baking with coking of the binder, followed by baking to 1,100 C.

End-of-baking temperature, in particular, results in reducing reactivity to an acceptable level with respect to pot usage conditions. It is especially important that the baking level is uniformly distributed in the chambers/pits to ensure baked anode homogeneity.

The volatile matter emission stage may be the cause of anode cracking and it must be negotiated at a sufficiently slow heating rate in the corresponding temperature range to prevent any deformation of this type.

2.1.4.6 Anode Assembly rodding

Low anode voltage drop is obtained by rigorous control of rodding cast iron quality.

At the rodding stage, there is a major risk of anodes being contaminated by spent anode bath, which results in increased anode reactivity and accelerated ageing of baking furnace refractory materials. Spent anodes must be cleaned with the utmost care, in particular to prolong the service life of baking furnace flue walls.

2.1.5 Green anode manufacturing stages

2.1.5.1 General

The following figure recalls typical green anode composition with 85% Dry Products (DPs) and 15% pitch.

![Figure 23 - Typical green anode composition](image)

DPs themselves comprise 2/3 petroleum coke and 1/3 anodes recycled after previous usage (baked recycled products).

Schematically, pitch comprises 2/3 fixed carbon and 1/3 volatile matter. It forms the binder that cements the coarsest DP grains, when blended with the finest DPs.

Green anode preparation, which takes place in the Paste Plant (PP), includes the following stages:

- crushing and sizing of coke and recycled carbon products to obtain DPs of constant, determined grain size,
- mixing of DPs and pitch to obtain a uniform paste,
- forming of paste in a vibrating machine.
Green anodes are characterized by their geometric and dry densities. Derived from geometric density by excluding the pitch from the green anode, dry density measures the compactness achieved by the DP stacking.

Usual green anode geometric densities are between 1.65 and 1.60, corresponding to a dry density range of 1.42 – 1.38 with 14% pitch (i.e. 86% DPs).

Densities obtained result from optimizing many factors involving the raw materials and preparation process:
- coke density,
- baked recycled product content,
- DP grain size distribution,
- pitch softening point and wettability characteristics,
- pitch content,
- mixing and vibrocompacting intensity.

By "mixing and vibrocompacting intensity" we mean the capacity of these two essential process stages to produce, as fully as possible, the following state of the green anode forming material:
- DP grains coated with binder,
- DP grain porosity filled with binder,
- intergranular space minimized and filled with binder.

In this respect, dry density is a favored indicator measuring the efficiency of the green anode manufacturing process.

### 2.1.5.2 Milling, screening, classification

Coke and baked recycled products are continuously mixed at constant ratio calculated to ensure recycling of all spent anodes produced by the potroom. In general, this ratio is 2/3 coke and 1/3 baked recycled products.

Coke is itself a mixture of 2 different quality cokes proportioned in relation to the anode characteristics sought.

Conveyed to the highest point of the PP by a bucket elevator, this mixture is separated into three grain size-based fractions by a screen:
- oversize: > 15 mm,
- coarse: 3/15 mm,
- medium: < 3 mm.
The last two fractions are stored in holding silos. Their ratio is adjusted according to needs, by:
- milling oversize (over-coarse) grains to be used as such using roll mills,
- milling part of the “Coarse” fraction using a hammer mill.

Part of the “Medium” fraction is directed to the main feed silo for a ball mill producing the last “Fines” fraction. This mill is also fed with all dust fines collected by different anode shop filters (crushing of baked recycled products, dedusting of anode baking furnace overhead traveling cranes, general PP dedusting).

A pneumatic conveyance system directs the dust fines produced by the ball mill to a classifier, which returns oversize particles to the mill inlet for additional milling. Other dust fines are collected by a filter and stored in a silo awaiting usage. These dust fines, smaller than 0.2 mm, contain 70 – 80% of fines smaller than 74 microns. Part of these fines passes through the mixing fume treatment center, where they are fixed by mixing vapor adsorption in a Venturi-type reactor.
2.1.5.3 Proportioning and mixing

Dry products (DPs) are obtained by mixing the three extracted fractions supplied at a constant rate by continuous proportioning units. The target DP grain size distribution is obtained by adjusting the grain size distribution and extraction rate of each fraction. The following diagram shows an example of a frequently used DP grain size distribution. There are others, depending on the anode characteristics sought.
A bucket elevator conveys the DPs to the highest point of the mixing line, which includes the following forming stages:

- preheating of DPs to 200 °C in an exchanger containing heat transfer fluid,
- feeding of liquid pitch at 160 °C,
- mixing of pitch and DPs at 180 °C,
- mixing and cooling of paste produced at 150/160 °C,
- green anode forming by compacting paste into molds,
- cooling of green anodes.

The exchanger incorporates a trough containing the DPs and Archimedean screws ensuring their conveyance. Preheating is performed by heat transfer fluid circulating inside the trough and screws, supplied at 280 °C by an electrical boiler.

Paste temperature in the mixer is fixed to optimize the DP mix and blending of the pitch with the DPs. Mixing intensity increases with:

- temperature,
- developed energy,
- paste holding time.

We recall that the purpose of mixing is to produce a uniform paste, in which the binder coats the DP grains and fills their porosity and intergranular space as much as possible.

---

**Figure 28 - Proportioning/mixing block diagram**
2.1.5.4 Vibrocompacting

A weighing hopper alternately delivers doses of paste to two molds. Once filled, these molds are transferred and locked to a vibrating table, then closed by a cover equipped with a pressing mass that rests on top of the paste:

Vibrating tables are equipped with a pneumatic suspension and a system of eccentric masses that induces vertical vibration at a frequency close to 25 Hz. Table vibration is transmitted to the paste by the cover, the vertical oscillations of which cause the paste to compact within the mold by a succession of shocks.
Vibrocompacting intensity results from optimizing forming parameters:

- vibration cycle time (50 - 60 seconds),
- cover pressure on paste (0.5 kg/cm²),
- vibrating table excitation frequency (25 Hz),
- suspension stiffness,
- paste temperature.

Depending on the paste composition, some of these parameters may be adjusted (especially the temperature, limited by the appearance of cracks).

We recall that the objective of anode forming is to minimize intergranular space, monitored by measuring the dry density of each anode after the mold has been stripped.

After unmolding, anodes are at 140/150 °C and can easily deform. They are transferred to a cradle conveyor, which transports them through a cooling tunnel, where they are sprayed with water for approximately one hour. On leaving the tunnel, anode cores are still at their tunnel entry temperature, but their exterior has been cooled to about 60 °C. This permits application of the different mechanical stresses during handling operations, without risk of deformation. The cooling water is recycled.

### 2.1.5.5 Key parameters of the Paste plant

<table>
<thead>
<tr>
<th>Parameters/Stages</th>
<th>Influenced characteristics</th>
</tr>
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<tbody>
<tr>
<td>Aggregate size, coke type</td>
<td>Anode density, resistance to thermal shock, resistivity, air permeability, resistance to compression</td>
</tr>
<tr>
<td>Binder (pitch) type and rate</td>
<td>Anode density, resistance, air permeability, resistance to compression</td>
</tr>
<tr>
<td>Mixing</td>
<td>Paste homogeneity, anode density</td>
</tr>
<tr>
<td>Forming</td>
<td>Anode density, resistance, air permeability, resistance to compression, anode cracking</td>
</tr>
<tr>
<td>Impurities: V, Ni, Na, Ca</td>
<td>Anode consumption, air oxidation, Anode consumption, reactivity to CO₂</td>
</tr>
</tbody>
</table>
2.1.6 Baking anodes

2.1.6.1 Why are anodes baked?

The main goal is to bake the anode at requisite temperature to optimize anode properties and performance in electrolytic pots (at optimized baking costs).

The anode has acquired many of its properties at the green stage. However, it does not conduct electricity because of the nature of pitch and it could not sustain the temperatures and mechanical stresses encountered in the electrolytic pots.

Anodes must be baked to reduce the pitch to an amorphous carbon state by coking and make them usable.

Baking takes place in an open-type, moving fire furnace or in a ring furnace.

Coking occurs between 350 and 500°C and is accompanied by emission of pitch volatile matter (figure 33).

The pitch residue remaining within the anode is called “semi-coke”. Its structure is far too different from that of the matrix coke for the anode to be used in this condition.

The semi-coke structure is changed by continuing baking above 500 °C until it resembles that of the matrix coke, which results in a lowly reactive anode that is relatively insensitive to carbon dusting (figure 34).
From ambient to coking temperature, the pitch passes successively from a solid state through pasty and liquid states to an ultimate gaseous state. This change of state makes the anode fragile during this baking stage and cracks can result. This stage must therefore be performed at a rate of temperature rise not exceeding 15 °C per hour. Total baking time is between 150 and 170 hours and an equivalent time, at least, is required for the baked anodes to be cooled to ambient temperature prior to usage, resulting in a total cycle of about 13-15 days.

2.1.6.2 Anode Baking Furnace description

Anodes are placed in pits separated by hollow flue walls, through which hot gases flow during the baking phase and air flows during the cooling phase. The flue wall structure is internally reinforced by baffles and tie bricks arranged to create uniformity not only of gas circulation, but also of thermal exchanges.

In the pits, anodes are completely covered with packing coke ensuring the following functions:
- anode support during baking,
- protection against oxidation by air,
- transfer of exchanged energy between anodes and gases circulating inside flue walls,
- insulation of pit tops to reduce thermal losses,
- insulation of furnace against unwanted air infiltrations.
A set of 8 parallel pits and 9 flue walls forms a furnace section. Sections are separated by headwalls through which flue walls in the same row communicate from one section to the next, thereby forming individual flue wall lines extending along the entire furnace.

The 34 sections of a furnace are arranged in two parallel 17-section bays, between which flue wall line communication is ensured at the ends by crossover flues.

Each bay is contained within a U-shaped concrete casing, whose external walls are cooled by natural air circulation; the casing interior is thermally protected by several thicknesses of insulating brickwork. Flue walls and headwalls are built from alumino-silicate refractory bricks containing 45 – 55% alumina. Their maximum service temperature is approximately 1,450 °C.

![Figure 36 - View of anode baking furnace section](image)

### 2.1.6.3 Description of a fire

A fire comprises:
- 6 sections in baking,
- 7 sections in cooling,
- sections in handling and maintenance.

Gas circulation throughout the flue wall lines of a fire is established using a fume exhaust ramp installed at one end of the fire and an air blowing ramp located 10 sections downstream. The exhaust ramp is connected to a fume collection duct, linked to the fume treatment center (FTC), in which negative pressure is maintained by the FTC exhaust fans. At the other end, cooling air is injected into the flue wall lines by individual fans mounted on the blowing ramp.

The pressure difference in a flue wall line varies continuously between -100/-200 Pa at section 1 and +100/+200 Pa at section 10. It is around 0 at section 7.
Three zones can be distinguished:

**Preheating zone**

In sections 1, 2 and 3, the fume temperature increasing from 300 to 900 °C raises the anode temperature from ambient to 550/600 °C. Emitted between 300 and 500 °C, pitch volatile matter is sucked into the flue walls through interstices between bricks, called degassing joints. The temperature within the flue walls at this time is sufficiently high to cause combustion of the volatile matter. The energy produced, complemented by the latent heat provided by fumes arriving from the heating zone, ensures the total energy requirements of the preheating function. Throughout preheating, anodes are in a plastic state exposing them to risks of deformation and cracking, which are prevented by imposing a baking rate of less than 15 °C/h and anodes well supported by the packing coke.

At 500 °C, pitch is converted into semi-coke, but baking continues right up to 1,100 °C to reduce the structural difference between binder and matrix cokes to a minimum.

**Heating zone**

Fume temperature at sections 4, 5 and 6 is raised from 900 to 1,150/1,200 °C, then maintained at this level by burner ramps that inject gas or fuel-oil into the flue walls. Simultaneously, the anode temperature rises from 550/600 to 1,100 °C, the temperature at which the binder coke acquires a structure similar to that of the matrix coke.

The final anode baking temperature is adjusted to the nearest 20°C, according to the type of packing coke.

**Blowing zone**

At sections 7 to 10, anodes are subjected to an initial cooling action from air supplied by the blowing ramp. This air is then directed to the heating zone, where it ensures oxygen requirements for combustion of the gas or fuel-oil injected by the burner ramps. Energy accumulated by exchange with anodes being cooled represents the third energy input for anode baking, after combustion of gas or fuel-oil and volatile matter respectively.
Forced cooling zone
Beyond section 10, anodes are subjected to a second cooling action by air blown from a second ramp of fans, but energy recovery does not take place at this stage. The following diagram shows typical temperature profiles in pits and flue walls throughout the 10 sections located between the exhaust and blowing ramps.

Figure 38 - Gas and anode temperature profiles

2.1.6.4 Fire moving period

After each period of 24 to 32 hours, both the exhaust ramp and the blowing and cooling ramps are moved forward by one section, the last burner ramp being transferred upstream of the heating zone.

This operation causes the fire to enter a new section of green anodes and, at the other end of the furnace, releases a section of baked anodes, which goes into cooling. Further downstream again, a cooled section is released and becomes available for coke and baked anode unloading.

The following diagram represents the different baking stages to which a given section is subjected. It can be seen that 6 periods are required to bake a section and 7 periods to cool it completely (4 blowing and 3 forced cooling periods).

For a 28-hour fire moving period, baking and cooling times are therefore as follows:

- baking: \( 6 \times 28 = 168 \) hours,
- cooling: \( 7 \times 28 = 196 \) hours,
- total time: \( 13 \times 28 = 346 \) hours.

Fire production varies inversely with the fire moving period. At 24 hours, it is one section per day, i.e. 140 anode tonnes; at 28 hours, it is reduced by \( 24/28 \), i.e. to 120 anode tonnes per day, etc.
2.1.6.5 Heating equipment

Heating equipment includes:
- 1 exhaust ramp,
- burner ramps,
- 1 blowing ramp,
- 1 cooling ramp.

The exhaust ramp features fume flow control dampers and a device for measuring fume flows and temperatures in each flue wall line.

Each heating ramp is fitted with a pair of burners and one control thermocouple per flue wall. Burners are arranged either with the flow for gas or against the flow for fuel-oil, to improve fuel combustion.

![Successive baking phases for a furnace section](image)

**Figure 39 - Successive baking phases for a furnace section**

![Heating equipment](image)

**Figure 40 - Heating with flow (gas) and against the flow (fuel-oil)**
Blowing and cooling ramps have one fan per flue wall. Blowing ramp fans are driven by variable speed motors to control blowing air flow.

Each ramp has its own PLC that controls locally the measuring, alarm and actuator control functions. PLCs are network-linked to a central baking process control and supervision system.

**Figure 41 - Fire structure and heating equipment**

### 2.1.6.6 Handling operation

The anode baking furnace is tended by one or more multi-purpose overhead traveling cranes or furnace tending assemblies (FTAs), fitted with a telescopic grab for gripping and picking up sets of anodes, and an 80 t/h capacity packing coke suction and restitution device.

**Figure 42 - FTA anode grab**
This device comprises a hopper connected to telescopic suction and restitution pipes. When unloading pits, the suction pipe extracts coke by creating negative pressure in the hopper using a vacuum system comprising a vacuum pump and a dedusting filter. When loading pits, coke is placed in the pits using the restitution pipe fed from the bottom of the hopper.

Coke dust fines collected by the filter are transferred on the ground to a storage hopper, from where they are conveyed to the Paste Plant for recycling with the DP fines fraction. After cleaning, the baked anodes are stored or directed to the rodding area.

Generally, the time required to load and unload a complete section is equivalent to one 8-hour shift. One FTA is therefore enough to tend two fires. In practice, the small capacity of the FTA hopper compared with the volume of coke transferred means that loading and unloading sequences must be alternated between different sections.

2.1.6.7 Brickwork maintenance

The term brickwork designates all furnace refractory material construction, essentially the flue walls and headwalls. Several factors are responsible for brickwork deformation with time:

- falsification (alteration) of alumino-silicate refractory material caused by sodium and fluorine in anodes,
- expansion and contraction stresses due to thermal cycles,
- stresses applied by anodes and packing coke to flue walls during handling operations and baking/cooling cycles.

Flue walls are affected by deformation and cracking, to the point where proper process performance is seriously compromised. Their service life can be prolonged by implementing the following actions:

- aim for an anode sodium content that is as low as possible (~150/200 ppm),
- control the process according to stringent procedures, especially furnace loading and unloading operations,
- maintain brickwork at each fire moving, especially the expansion joints at junctions between flue walls and headwalls, so that flue walls can move freely.

Implementation of these actions largely conditions flue wall service life, which usually varies between 80 and 160 fire rotations, i.e. 4 to 8 years.

Old flue walls are demolished and removed from the furnace using a grab. They are replaced by new flue walls prefabricated outside the furnace. One 8-hour shift is required to replace an internal flue wall and two shifts for an external flue wall. Lifting operations are ensured by the multi-purpose overhead traveling crane fitted with a 25 tons hoist.
2.1.6.8  Fumes treatment

Fumes extracted from the furnace contain various impurities, in particular:
• tars (unburnt volatile matter and fuel - gas or fuel-oil),
• carbon dust fines (unburnt and packing coke),
• fluorine emitted by the bath traces coming from recycled fraction contained in anodes,
• sulfur dioxide produced especially by combustion of gas or fuel-oil.

Owing to their impurity concentrations (100 - 200 mg/Nm$^3$ for each of the first three and 500 mg/Nm$^3$ for the fourth), these fumes cannot be discharged as such and must be subjected to treatment to reduce their impurity contents to acceptable levels.

A fume treatment process, based on the reactive alumina property of fixing tars and fluorine by adsorption, is employed to achieve acceptable impurity levels. Charged alumina is collected by filtration, along with the carbon dust fines, then recycled via the electrolytic pots. This process has no effect on the sulfur dioxide and low sulfur content fuels must be used to limit SO$_2$ emissions.

The ABF fume treatment center (FTC) includes:
• a cooling tower, where the temperature of fumes leaving the furnace (200/150 °C) is stabilized at 100 °C by controlled water spray,
• several alumina-fed reactors,
• an equivalent number of filters,
• exhaust fans,
• a system of valves directing fumes to an emergency stack in the vent of FTC malfunction,
• an alumina handling and flow control system,
• storage silos for fresh alumina feeding the reactors and charged alumina collected by the filters.

A baking furnace FTC producing 250 kt/y has a capacity of approximately 150,000 Nm$^3$/h and consumes around 40 tonnes of fresh alumina per day, resulting in production of a large quantity of charged alumina.

With trapping efficiencies of over 95%, concentrations of gaseous effluents emitted with treated fumes are reduced to several factors of 10 lower than those at the FTC intake.
2.1.6.9 Transformation of the anode during baking

<table>
<thead>
<tr>
<th>TRANSFORMATIONS</th>
<th>CELSIUS DEGREES (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; Softening of the pitch.</td>
<td>Up to 250°C</td>
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<tr>
<td>&gt; Limited release of volatile materials from the pitch.</td>
<td></td>
</tr>
<tr>
<td>&gt; Important release of volatile materials.</td>
<td></td>
</tr>
<tr>
<td>- Pitch (200°C and 400°C).</td>
<td>250°C to 450°C</td>
</tr>
<tr>
<td>&gt; Anode in plastic phase.</td>
<td></td>
</tr>
<tr>
<td>&gt; Limited release of volatile materials.</td>
<td>450°C to 550°C</td>
</tr>
<tr>
<td>- Hydrogen and methane (400°C and 1000°C).</td>
<td></td>
</tr>
<tr>
<td>&gt; Transformation of the pitch into coke-pitch.</td>
<td></td>
</tr>
<tr>
<td>&gt; Completion of the transformation.</td>
<td>550°C to 900°C</td>
</tr>
<tr>
<td>&gt; Target physical properties obtained at 1100 – 1150°C.</td>
<td>900°C to 1200°C</td>
</tr>
</tbody>
</table>

Table 5 – transformation of the anode during baking

2.1.6.10 Key parameters of the baking furnace

Level of baking:
- If level too low, then:
  - anode resistivity too high => increased energy consumption;
  - increased anode consumption;
  - increased anode reactivity and dusting in the pots reducing cell current efficiency.
- If level too high, then higher operating cost.

Flue wall service life:
- Average service life: 50–170 fire cycles (open furnace).
- Average: about 20 fire cycles per year.
- Factors influencing service life:
  - design of furnace and flue walls;
  - refractory lining quality;
  - sodium content in anode;
  - heating equipment performance characteristics;
  - quality of baking process operations;
  - quality of handling operations;
  - quality of flue wall routine maintenance operations.

2.1.7 Anode Assemblies Rodding anodes

2.1.7.1 General

In the anode rodding shop, anode assemblies returning from the potroom are cleaned and stripped of bath, spent anodes and cast iron, which are processed for re-use. Stems and hexapods are then inspected and repaired if necessary, before new anodes are rodded with them using molten cast iron.
In the rodding shop, cooled anode assemblies are suspended from an overhead conveyor, which moves them to the different processing stations installed at ground level. Conveyor lengths between stations are designed to allow storage in accordance with actual production and OEE of each of them.
2.1.7.2 Cooling

Before entering the rodding shop, AAs must be cooled to a temperature below 100 °C, compatible with allowable temperatures for the machines equipping the different processing stations. Spent AAs are therefore immobilized on transport pallets stored in a building. Cooling is by natural ventilation and, on average, requires a holding time of five 8-hour shifts to ensure a temperature drop from 800/900 °C to 80 °C.

![Figure 48 - Cooling the spent anodes](image)

2.1.7.3 Hooking / Unhooking

The following functions are performed at this station:
- introduction and setting down of a pallet of 3 cooled AAs, transported from stock by special vehicle, onto a transfer gantry,
- hooking of AAs onto overhead conveyor trolleys and departure to next processing station,
- tilting of unloaded pallet above a bath pit to evacuate remaining bath crusts,
- setting down of new AAs onto clean pallet,
- picking up of pallet by the special vehicle for storage, awaiting usage by potroom.

2.1.7.4 Bath removal

This station features a first so-called breaking machine, whose purpose is to break up covering bath crust by means of punches thrusting horizontally between the pins.

The next finishing stage features two machines working in parallel, in which pieces of bath still cemented around the pins, in cavities or between anodes, are removed using hydraulic breakers. For greater efficiency, AAs are unhooked and tilted horizontally, then replaced in their initial position on completion of finishing.

The functions of this station are automatic, except for the finishing breakers, which are controlled by operators.

2.1.7.5 Shotblasting

Bath films remaining at various places, especially beneath the anodes, are removed at this station by shotblasting performed by a turbine unit. The shot is recycled after separation of carbon dust fines and bath.
2.1.7.6 Anode breakage

After shotblasting, the AAs are introduced into an automatic press that breaks up the spent anodes. Pieces of anode are evacuated by a conveyor supplying the recycled carbon product crushing shop.

2.1.7.7 Thimble stripping

This station features automatic presses that pull off the cast iron thimbles still encasing the pins after anode breakage. Pieces of cast iron recovered are cleaned of residual bath and carbon scale by shotblasting, then stored in a hopper awaiting recycling for new roddings.

2.1.7.8 Inspection

Prior to re-use, anode stems are subjected to inspection involving:

- stem and hexapod geometry (stem straightness and pin center-to-center distance),
- condition of stem surface in contact with pot beams,
- condition of clads,
- state of wear of pins and hexapods.

Non-conforming stems are unhooked and dispatched for repair in a smelter shop or at a subcontractor.
2.1.7.9 Graphite coating

To facilitate subsequent thimble stripping, pins are dipped in a liquid containing graphite powder in suspension, then dried by crossing gas burner ramps.

2.1.7.10 Rodding

New AA fabrication at the rodding bench comprises the following operations:

- unhooking of a stem and assembly with new anodes,
- pouring of liquid cast iron into first row of anode holes,
- rotation of AA through 180°,
- casting into second row of anode holes,
- hooking of AA onto conveyor.

Liquid cast iron is obtained by melting of recycled and cleaned cast iron charges in crucible induction furnaces heated to 1,450/1,500 °C. Cast iron is transferred from induction furnaces to the rodding bench by a trolley carrying a casting ladle.

Good rodding resistance requires the cast iron to have the following properties:

- low shrinkage to reduce anode voltage drop and ensure a strong mechanical connection through good cast iron contact with the pins and anode carbon,
- low resistivity to reduce anode voltage drop,
- mechanical strength suited to thimble stripping.

These properties are obtained with gray cast iron containing very tight composition specification. This composition tends to deviate with successive recycling and is kept constant by adding alloying elements during charge melting.
2.1.7.11 Inspection of new AAs

Before being directed to the unhooking station, new AA roddings are inspected and the top of the anodes is cleared of possible cast iron spillages, which worsen the iron content of the metal produced.

2.1.7.12 Bath treatment

Bath recovered at the cleaning and hooking/unhooking stations is directed to a crushing and classification shop by a conveyor system. This shop also handles bath crusts arriving directly from the potroom, produced when placing anodes. Pots also produce liquid bath in excess, which is recovered by tapping the pots.
### 2.1.7.13 Treatment of recycled carbon products

Baked recycled carbon products are made of spent anodes recovered at the rodding shop breaking station and a very much smaller proportion of whole anodes rejected at baking. Green recycled products come from the paste and green anodes rejected at the paste plant.

To be suitable for re-use in the paste plant, recycled carbon products must be milled to a 0/30 mm grain size distribution, which requires three reduction stages owing to their original dimensions.

The three crushers are interlinked by belt conveyors carrying the recycled carbon products. Magnetic separators protect them from metallic parts, that could damage them (pins and cast iron shells).

Green recycled products are separately processed in campaigns undertaken during rodding area stoppages. Shop dedusting fines are stored and dispatched to the PP for re-use.

![Figure 54 – treatment of recycled carbon products](image)

#### 2.1.7.14 Key parameters of the rodding shop

- Excellent conductivity of stems and pins: Cleanliness and purity of the cast iron
- Excellent cleaning of the butts: Minimum amount of sodium (Na) in the baked anodes
- Absence of deformation in the anode assemblies (vertical straightness)
- Minimum treatment cost
2.1.8 Introduction to the electrolysis process

The reduction of alumina into primary aluminium is a continuous electrochemical process at high temperature, happening in so called electrolytic pots.

2.1.8.1 The main steps of electrolysis

During the electrolysis process, anodes are continuously consumed in the pot (1 anode = 28 days). Cathodes are not (although 5-6 years practical life).

![Figure 55 - The main steps of electrolysis](image)

2.1.8.2 Bath, Alumina, Anode and Electrical Energy

**Electrolytic bath:**
The reduction process is taking place in a very thin bath layer inserted between the anodes and the metal layer above the cathode. The bath is characterized by its chemical composition and its operating temperature.

![Figure 56 – electrolytic bath](image)

The main role of the electrolytic bath is to dissolve alumina while conveying the current through the pot.

**Composition:**
- Cryolite (Na$_3$AlF$_6$) 79 - 80 %
- Alumina (Al$_2$O$_3$) 2,5 %
- Aluminium fluoride (AlF$_3$) 11.5 - 12%
- Calcium fluoride (CaF$_2$) 5 - 6.5%
- Others 1%

Factors to be considered when selecting bath chemistry
- Current efficiency.
- Fluoride emissions.
- Pot operation.
- Crust hardness.
- Alumina dissolution.
- Electrical conductivity.
- Technology/monitoring system.

**Alumina (Al$_2$O$_3$):**

**Role:**
- Raw material to produce aluminium.
- Adsorb fluoride emissions.
- Cover anodes and reduce their oxidation.
- Thermal insulation (crust).

**Physico-chemical characteristics:**
- purity (Fe, Si, Zn, Na$_2$O, CaO, P$_2$O$_5$),
- grain size distribution (particularly the fine part),
- specific surface (SSA),
- density,
- attrition.

**Anode:**
Refer to previous chapters.

**Electrical energy:**

**Role**
- allow the electrolytic reaction,
- provide heat through Joule effect to compensate the heat losses and to keep the bath liquid.

**Characteristics:**
- direct current,
- stable amperage.

\[
\text{Power} = U \times I = R \times I^2
\]

Electrical energy consumption is measured in kWh \((V \times kA \times h)\)

**2.1.8.3 Current Efficiency and potline production**

Three electrons are required to produce one aluminium atom, i.e.: 96 485 A for 1 s $\rightarrow$ 8.993 g Al

Consequence (Faraday’s law): Relationship between theoretical daily production \(P\) (kg of Al) and pot amperage (in kA): \(P\ (\text{kg / day}) = 8.053 \times I\ (\text{kA})\)

Ex: if pot amperage \(I = 380\ \text{kA}\ (380 000\ \text{A})\) then \(P_{\text{theoretical}} = 3060\ \text{kg Al per day}\)
Current (Faraday) efficiency:
- Amount of metal actually PRODUCED / Actual amount POSSIBLE
- If current efficiency = 100% then: Actual production = Theoretical production

Current Efficiency is not at 100% because:
- The aluminium produced redissolves into the bath and reoxidizes with CO₂;
- Other metals (undesirable) are electrolyzed at the same time than aluminium.

In industrial reality, current efficiency is nowadays between 92 and 96 %.

The annual aluminium production of a plant with the following characteristics:
- 400 pots
- 94% current efficiency (typical value)
- 300 000 amperes
- Daily production = 8.053 x CE (%) x Current (kA) x nb pots
  is 331 558 tons.

2.1.8.4 Thermal Balance

The overall thermal balance of a pot has to be maintained in almost real time, taking into account inputs, losses and used energy.

Power input (RxI²) is the setting variable of the thermal balance:
- Global potline cooling/heating trend will trigger a reaction on the common parameter, ie. I
- Individual pot imbalance will trigger a reaction on the specific pot parameter, ie its individual resistance

Therefore, managing a pot/potline is largely managing a heat and power balance where 50% of the input is useful production related energy to heat, dissolve the raw materials and electrolyse them, and 50% is dedicated to heat losses management.

![Figure 57 - Thermal balance (AP 35 technology)](image-url)
Thermal balance and Voltage drop:

![Diagram of anode frame of pot](image)

**Figure 58 - Voltage drop (AP 35 technology)**

The biggest lever to set the power input is the variable resistance within the 3 cm bath layer. This bath resistance can be calculated in the following formula:

\[
\text{Bath resistance} = \text{resistivity} \times \frac{\text{anode to metal distance}}{\text{pot surface}}
\]

The pot surface being a structural given based on the technology, and the resistivity being related to the bath composition which is kept more or less stable and constant, the adjustment variable is indeed the anode to metal (or interpolar) distance. This variable is adjusted by raising or lowering the anodic beam to which all the anodes assemblies are connected.

### 2.1.8.1 Anode effects

When accidently reaching a low level of alumina concentration in the bath or a too high anodic current in one specific anode, the electrolysis reaction does change. Instead, $\text{AlF}_3$ – a bath component - is electrolyzed, according to the following reaction:

\[
\frac{y}{3} \text{AlF}_3 + x \text{C} \rightarrow \text{C}_x\text{F}_y + \frac{y}{3} \text{Al}
\]

This parasitic reaction is in fact generating Per-Fluoro-Carbon (PFC’s) which have a strong green house effect. The main are $\text{CF}_4$ and $\text{C}_2\text{F}_6$, with respectively a greenhouse effet of 6900 and 12500 times $\text{CO}_2$. Besides the detrimental effet in terms of global warming, these anodic gases have a very strong superficial tension and tend to block the anodic surface by a non conductive bubble. This electrical insulation generate a strong increase in heat generation through Joule effet in the bath, with possible catastrophic consequences if not treated timeously.

The process control system is able to prevent this incident to happen most of the time. In average, one particular pot will have an anode effet every 4 to 5 days, and this will be automatically treated by the process control system within seconds. But in some cases, this event cannot be treated automatically (5% of the cases) and need a manual intervention.

Anode effect rate and duration are the two parameters quantifying the level of disturbance to the process associated to this event.
2.1.8.2 Magneto-Hydra-Dynamic (MHD) balance

The second main equilibrium to be maintained in a pot is the MHD balance.

Any conductor crossed by a direct current generates a magnetic field $B$.

$$B = k \times \frac{I}{d}$$

Conductors crossed by a current $I$ in a magnetic field $B$, are submitted to a Laplace Force

$$F = k_2 \times i \times B$$

Liquid bath and metal are indeed conductors at 960° seeing a current and are at the same time immersed in a magnetic field generated by all the conductors surrounding the pots and conveying the current from one to the other. In application of the physics principle expressed here above, both bath and metal will be submitted to the Laplace forces that will make them move in the pot trough. They move permanently at a variable speed depending on the busbar design and pot operation and state.

MHD behavior modeling of a given technology is key for the design as it warranties that these movements are minimum and predictable. It cannot be avoided to have a metal / bath pad deformation due to Laplace forces, but the design has to provide a naturally stable deformation to keep anode to metal distance under control:

- This is defined by position and current distribution in the pot-to-pot busbar
- Besides basic design, process adjustments or out of standard pot operation may have a catastrophic effect on MHD stability
- MHD instability can be detected on real-time pot resistance

![Figure 59 - Metal pad speed and Metal pad deformation](image)

2.1.8.3 The main operations

The main operations are typically based on a 32 hours (or 4-8h shifts) cycle:

- Anode change – happens every 32 h on a given pot. An anode last 28 days.
- Anode covering – idem, synchronised with anode change. This operation consists in protecting the new anode by a cover made of a mow of crushed solid bath and alumina, and aims at protecting the anode against air-burn. Another benefit is to keep the heat inside the pot and therefore save some energy consumption.
- Metal tapping: the metal production of the 32 hours is retrieved from the pot in one batch, using a tapping ladle.
- Anode beam raising - every 14 days or so.
Operations do impact the process and its KPI's. Each of these operations are characterised by typical KPIs allowing quality assessment.

2.1.8.4 **Highlight on Anode Changing operation**

An anode cycle is the service life of an anode assembly. It is expressed in number of shifts or hours.

In practice, an anode assembly is changed every 80 8-hour shift, i.e. 42 cm (80 x 0.526 = 42 cm) of wear and a 6 cm margin (in reality less, as wear occurs from the top).

At end of life, 4 to 5 cm of carbon safety margin is maintained for:

- Faster wear rate of anode blocks, depends on anode current density, density, overconsumption factor (mainly corrosion in air);
- high bath height;
- operating delays;
- an anode effect: on anode squelching → anode bottom level drops by 1 cm = bath rises by 5 to 6 cm (PISTON effect).

![Figure 60 - Maximum usable height](image)

![Figure 61 - Safety margin](image)

**Anode change order rules:**

- Anode assembly # 1 is on the upstream fume aisle end.
- first anode assembly 1 is changed, then anode assembly 15 and lastly anode assembly 18.
- Change assemblies in different quarters of the pot in turn.
- Never change adjacent anode assemblies consecutively.
- Space out corner anode assemblies as well as possible.
- Simplify setting under the positive risers (dimensions to be respected).
- Ensure a number of shifts close to half the cycle between changed anode assemblies that are adjacent to or facing each other.
- One anode assembly every 32 hours.
Anode change order in one particular pot is given in the specifications. Once the potline is in operation, it is very hard and even pointless to modify this order. Should anode problems occur with several anode assemblies used, it is recommended to try to retrieve hot anode assemblies to avoid having several cold anode assemblies in the pot at the same time.

Anode assembly gauging:

- Gauging is important to insure the proper setting of the new anode, with its bottom interface at the same height above the metal pad than the spent anode that has been retrieved. This insures the proper MHD stability after anode change and a good current distribution in all the anodes after the operation.

Gauging quality depends on:
- the gauge condition,
- the position of the anode assemblies on the gauge base,
- the condition of the underside of the spent anode assembly,
- the importance of gauge condition and cleanliness,
Gauging quality is characterised by the anodic current distribution measured after the operation.

**Crustbreaking:**
- limit stresses on the clad, when removing spent anode,
- clear the location for the future anode assembly,
- avoid picking up very large pieces with the crust shovel,
- avoid uncovering adjacent anode assemblies,
- avoid sending for cleaning anode assemblies with cover product wings.

Moreover, incorrect crustbreaking results in:
- introduction of alumina, disrupting alumina feed control,
- solid bath deposits on the cathode, resulting in insulation and instability.
- To avoid insulating the cathode, a mechanised shovel is used to remove the crusts and passed as many times as necessary to clean the anode cavity before setting the new one.

![Figure 64 - Main anode changing steps: crust breaking, extraction, crust removal, anode gauging, insertion and covering](image)

**Anode covering:** Covering the new anode assembly with covering product mix (bath + alumina) allows pot’s thermal insulation and limit oxidation.

The anode covering is done several hours after anode change to limit pot contamination with the crushed bath. Delay between anode change and covering is a quality indicator, as well as the volume of cover material being poured on the new anode and visual quality control of the cover integrity.

**Measurement of anode current distribution:**
The purpose of this operation is to monitor current flowing through the anode assembly (relationship of proportionality between voltage and current).

The measurement is taken 16 hours later anode changing.
Normal value: 1.4 to 1.9 mV on AP-30. If the value is higher than 1.9 mV, the anode assembly will be raised.

Many factors cause the value read to vary:
- anode problem,
- polarized anode assembly,
- anode assembly age,
- partially insulated cathode,
- very low or very high bath height,
- anode stem/beam connection quality.
There is a general trend to move towards continuous anodic distribution measurement instead of punctual ones. Continuous measurement is seen as a prerequisite for a performing anticipative process control.

2.1.8.5  **Key levers of the electrolysis area**

Main technical indicators driving value creation:

- Amperage: average value flowing through the electrolytic pots to produce metal (kA).
- Current efficiency: ratio of the metal tonnage really produced over the theoretical tonnage expected as per the amperage used (%).
- Energy consumption: average DC energy consumed to produce metal (MWh/t Al).
- Pots in operation: average of pots in operation in the aluminium smelter (pots).
- Net carbon consumption: carbon mass consumed to produce metal (kg C/t Al).

Main KPIs related to HSE and right to operate:

- Anode effects (CO2 equivalent emission):
  - Anode Effect Frequency (AEF): average number of anode effects per pot and per day.
  - Polarization duration: average time during which voltage is higher than ~ 8 V.
  - Anode effect overvoltage.
- Fluorinated emissions:
  - Mass of fluorine discharged into the atmosphere per tonne of Al: at the potline roof and at the scrubber stack.
- All injuries frequency rate
- Professional illnesses rate

2.1.9  **Main KPIs to drive production**

2.1.9.1  **Key Performances Indicators of the carbon area**

- Baked anode density per anode
- Resistivity (MIREA measure)
- Net carbon consumption (butt weight)
- Sodium content in butts and anodes
- Binder (pitch) content in anode
- Furnace fluewall life duration
- Furnace energy consumption
- Number of anode produced / number of incidents in potline
- Pins / Clads replacement rates
- Sulfur emissions...

2.1.9.2 Key Parameters Indicators of the electrolysis area

In real time > shift level: measured / calculated by the pot-microcomputer
- Pot Instability, number of instable pots
- Average pot resistance → energy consumption
- Anode effect rate – pots with anode effects
- Anodic incidents (spikes, broken anodes, etc)
- Potline normal/scheduled events: operations, delays, measurements, etc
- Potline abnormal events: power outages, pot stoppages...

At day/32h timescale > week/month: given by potline system
- Metal quality and quantity produced,
- Alumina and anode quality
- Manual measurements (bath T and comp., cathodic/anodic voltage drops, anodic current distribution...)
- Current efficiency
- Potline energy consumption
- Trends,
- Potline standard deviations – individual outlier pots

Long term
- General potline trends, global adjustments, production strategies

2.1.9.3 The challenge of electrolysis

The usual electrolysis industrial challenge is to increase production as much as possible while keeping the costs as low as possible. Most of the Key Performance Indicators quantifying these are in fact process related:
- Increase production by increasing:
  - amperage; → process related
  - the number of pots in operation;
  - current efficiency. → process related
- Reduce costs by:
  - reducing energy consumption; → process related
  - increasing current efficiency; → process related
- reducing energy costs;
  - reducing raw material consumption & costs. → process related

Reduce emissions (GHG and fluorinated emissions) → process related
- Meet customer requirements (metal purity) → process related
- Zero injuries → partially process related

Therefore, process control is a critical aspect of the aluminium industry profitability and sustainability.

2.1.10 Gas treatment and environment

The process is emitting a number of different types of pollutants in the two main processes described above. The most important are the fluorides, gaseous or within the particulates released.
Emissions at the pot = what is generated by the pot or by the process. 
Atmospheric release = what goes into the atmosphere, with or without treatment.

Modern potlines, with typical bath composition do emit around 35 kg of total fluorides per ton of aluminium. Most of these fluorides are collected in the pots or in the anode bake furnace and stopped/treated in the gas treatment centers or fume treatment center. The same goes for the tars and PAHs which are generated in the carbon plant at anode production stage. In addition, all the dust collected in the processes are as well treated.

The following collection methods are employed:
- Gaseous fluorides and light tars $\rightarrow$ adsorption + filtration
- Heavy tars $\rightarrow$ condensation + filtration
- Dust and fluoride particles $\rightarrow$ filtration

$SO_2$: partially caught by the alumina then re-issued.

Nevertheless, the following 3 main pollutants are released in small fractions in the air:
- Fluorides: 0.4 kg/t Al (99% collection/treatment efficiency)
- SO2: 15 to 25 kg/t Al (totally re-issued – no constraints on SO2 emission)
- Greenhouse gasses: 1.5 to 5.4 t CO2e/t Al (the most modern plants are in any case below 2 t CO2e/t Al)

Other pollutants: dust, tar

The 3 main pollution source locations to treat: Electrolysis, anode baking furnace and paste plant.
2.2 Plastics industry domain

In plastic domain we are considering injection molding process industries to implement the concept of MONSOON. The injection molding production technology has emerged as the main vehicle to produce highly complex, precise, value-added commercial parts with tight tolerance and surface finish. Because of this success, there is a sustained pressure for increased standards of part quality while requiring reduced product development time and work-cell costs. Additionally, within the last 10 years the constant demand of diversity and customization in the sector of plastics industry has led to more and more molds with smaller and smaller batch production making the tuning of production cells extremely challenging because of the product time-to-market decrease. This is not to mention the globalization factor leading to more frequently process lines transfers from one production plant to another during a product life. These process lines still have to produce good parts within minimum time of process validation and setup assessments. Due to these new manufacturing constraints, it can be argued that the requirements and standards directed to the injection molding industry often exceed their capabilities. For service-oriented industry this leads towards long development cycles, increased tooling costs, low process yield and inferior product quality. The MONSOON concept will address these issues to improve the overall production process through integrating data oriented process control and monitoring systems.

2.2.1 Injection molding process in general

Under the MONSOON - Plastic Domain use cases are concentrating towards the injection molding industry. Injection molding production process represents 2/3 of the overall number of plastic parts manufactured. Almost 90% of the total high-tech polymer materials production is processed by injection molding, from which 8.5% polymers are used for the production of communication or electronic products, 8% for automotive products, 3% for medical equipment, 33% for small house appliances and 42% for sport, toys and packaging and other high quality products. The actual market is very demanding and, and the production of plastic pieces is changing from a low quality mass production to high quality injection processes, where the pieces obtained must comply with rigorous quality tests. The characteristics of a certain piece do not depend only on the raw material, but also on the process of transformation used in its fabrication. Because of this, it is convenient to carry out an exhaustive control of the injection process, controlling all the parameters present in this process. The process of plastic injection is based on melting a plastic material and make it flow inside a mold, where a cavity is filled up, obtaining various forms that allow obtaining a wide variety of products. In the following figure, there is a schema of an injection machine, where the three main parts of these machines are specified.

![Figure 67 - Schematic of an injection molding production cell and related equipment layout](image)
2.2.2 Process phases

The injection process is a sequential process called injection cycle. This process can be divided into five phases:

1. Plasticization phase.
2. Injection phase
3. Compaction phase
4. Cooling phase
5. Ejection phase

In the following sections the different phases will be explained more in depth.

2.2.2.1 Plasticization phase

In this phase, the screw, by means of a rotated movement, moves the solidified plastic through injector barrel. In this process the plastic is heated up by resistors surrounding the barrel.

![Image](image_url)

**Figure 68 - Melting and transportation of the plastic**

In the following figure it can be seen where the principal parameters of this phase are controlled:

![Image](image_url)

**Figure 69 - Elements taking part in the melting process**

Among the different parameters being monitored, the temperature of the melted plastic is fundamental. Depending of this temperature, the characteristics of the injected pieces can vary ostensibly. The temperature has great influence in the viscosity of the material and this, in the injection process. This temperature is proportional to the temperature of the resistors and the heat generated by the friction between the solid plastic and the screw.
2.2.2.2 Injection phase

In this phase, the empty mold is closed, while the melted material is prepared to be injected. The screw injects the material, acting as a piston, without spinning, forcing the material to go into the cavities of the mold with a determined injection pressure. This process can be seen in the next schematic figure:

![Schematic figure of injection phase](image)

Figure 70 - Closing of the mold and filling of the cavity

In this phase there are several parameters that must be controlled for the correct fabrication of the piece, such as:

- Maximum injection pressure: This is a limitation of the machine as a security condition.
- Injection speed: This is an important parameter to have a constant speed of the material inside the mold.
- Mold temperature: The mold is heated up with the objective of getting a uniform temperature in the cavity surface.
- Temperature of the injected material: It is the temperature distribution of the material along the mold cavity.
- Pressure of the injected material: Depending on the walls and cannels of the mold more or less pressure will be required.
- Volume of the injected material: This volume must be less than the volume of the plastified material.
- Viscosity of the injected material: It is the resistance of fluid material to flow inside the mold.
- Time of injection: It is the time taken by the whole injection phase.

2.2.2.3 Compaction Phase

In this phase, the screw is maintained forward, compacting, applying constant pressure before the solidification of the material, with the aim of avoiding the contraction of the piece while cooling. This pressure is usually less than the injection pressure and it is maintained until this pressure loses efficiency. The main parameters to control in this phase are:

- Theoretical compaction time: The time established in the machine to apply pressure
- Theoretical compaction pressure: The pressure established in the machine to apply pressure.
- Real compacting pressure: It is the evolution of the pressure in each point of the piece while compaction phase.
• Real compacting time: It is the time while pressure in the cavity exists.
• Compacted material temperature: It indicates the temperature evolution in different points of the piece while compacting.
• Material density: Its evolution depends on the compaction temperature and compaction pressure.
• Solidified quantity of the material: It is important to control the solidification of the material in each phase.

2.2.2.4 Cooling Phase

In this phase the material continues losing temperature inside the mold, where the heat is dissipated by refrigerating liquid. While on this phase, the screw already has the material for next injection process.

The parameters in this phase are:
• Mold Temperature: The mold must have a system or refrigeration system to be able to refrigerate all the heat.
• Cooling time: The time passed from the end of the compacting phase until the piece is rigid enough to be extracted.
• Ejecting piece temperature: Temperature at which the piece can be ejected without being damaged.
• Cycle time with closed mold: The time the mold is closed, counting the phases of loading the material, compacting and cooling.
• Piece stresses: superficial and internal stresses in the piece if the cooling is very fast.
• Quantity of solidified material: This parameter controls the quantity of material solidified in the cooling phase.

![Figure 71 - Quantity of solidified material in the cooling phase.](image)

2.2.2.5 Ejection phase

In this phase, the mobile part of the mold is opened and the piece is extracted. The ideal situation would be that the piece would fall by gravity, but the piece remains adhered to the mold because of adherence forces or internal tensions. Because of these problems, the ejectors take the piece out from the mold.

The parameters necessary to be controlled in this phase are:
• Expulsion force: It is a very important factor when selecting the size and quantity of ejectors.
• Ejectors movement: It is the distance that the ejectors must move to extract the piece from the mold cavity.
• Expulsion speed: It is the speed the ejectors must have.
• Cycle time: It is the sum of melting, injection, compaction, cooling and ejection times.
2.2.3 Process signals injection machine

During the injection molding process many technical variables have to be measured in order to describe the process and to prevent damages from the injection molding machine. These technical variables can be divided into electrical signals to define the stage of the process and continuous signals (pressures, temperatures, positions etc.).

2.2.3.1 Technical drawing

![Injection molding machine signals diagram]

Figure 72 - Injection molding machine signals.

2.2.3.2 Main Control/Command Signals

- MCP Mold Closing/Clamping Phase
- INJ Injection phase
- DYN Dynamical phase
- PCK Packing Phase
- HOL Holding phase
- COO Cooling phase
- DBD Decompression Before Dosing
- DOS Dosing phase
- DAD Decompression After Dosing
- MOP Mold Unclamping/Opening Phase
- PEJ Product Ejection Phase

2.2.3.3 Main Physical Measures

- MIP Machine Injection Pressure
- SPO Screw Position
- SRO Screw Rotation
- STO Screw Torque
- NIP Nozzle Injection Pressure
- NIT Nozzle Injection Temperature
2.2.4 Process signals injection mold

2.2.4.1 Technical drawing

![Figure 73 - Injection mold signals.]

2.2.4.2 Main Control/Command Signals

- MBC  Mold Block Command (hydraulic/Pneumatic)

2.2.4.3 Main Physical Measures

- MMP  Material Molding Pressure
- MMT  Material Molding Temperature
- CMT  Cavity Molding Temperature
- MCT  Mold Component Temperature
- CHF  Cavity Heat Flow

2.2.5 Process signals interpretation of physical measures

All figures shown below show various variables which can be measured during the injection molding process. These variables can be compared to reference values measured during a reference cycle. Due to this, errors in the injection molding process can be detected and the fault parts can be rejected. Therefore important points of the curves (i.e. maximums, mean values, integrals) and tolerances can be defined. It is then also possible to detect variables coming close to the end of a tolerance and to give a signal to the machine worker that he stabilizes the process manually. The figures give some example of the principle behaviour of different variables.
### Physical measures

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>ERrefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPO</td>
<td>Injection Screw Position</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>SRO</td>
<td>Screw Rotation</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>STO</td>
<td>Screw Torque</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>MIP</td>
<td>Machine Injection Pressure</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>NIP</td>
<td>Nozzle Injection Pressure</td>
<td>Injection Molding Machine Nozzle</td>
</tr>
<tr>
<td>NIT</td>
<td>Nozzle Injection Temperature</td>
<td>Injection Molding Machine Nozzle</td>
</tr>
<tr>
<td>MMP</td>
<td>Material Molding Pressure</td>
<td>Injection Mold</td>
</tr>
<tr>
<td>MMT</td>
<td>Material Molding Temperature</td>
<td>Injection Mold</td>
</tr>
<tr>
<td>CMT</td>
<td>Cavity Molding Temperature</td>
<td>Injection Mold</td>
</tr>
<tr>
<td>MCT</td>
<td>Mold Component Temperature</td>
<td>Injection Mold</td>
</tr>
<tr>
<td>CHF</td>
<td>Cavity Heat Flux</td>
<td>Injection Mold</td>
</tr>
<tr>
<td>CIT</td>
<td>Channel Input Temperature controller</td>
<td>Mold Temperature Controller</td>
</tr>
<tr>
<td>COT</td>
<td>Channel Output Temperature controller</td>
<td>Mold Temperature Controller</td>
</tr>
<tr>
<td>CFR</td>
<td>Channel Flow Rate</td>
<td>Mold Temperature Controller</td>
</tr>
<tr>
<td>HRT</td>
<td>Hot-Runner Nozzle Temperature</td>
<td>Hot-runner Nozzle</td>
</tr>
<tr>
<td>VGL</td>
<td>Valve Gate Latency</td>
<td>Sequential Injection Molding Controller</td>
</tr>
</tbody>
</table>

Table 6 - Injection process physical measures.

### Control/Commands

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>ERrefs</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCP</td>
<td>Mold Closed Phase</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>INJ</td>
<td>Injection phase</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>DYN</td>
<td>Dynamical phase</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>PCK</td>
<td>PaCKing phase</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>HOL</td>
<td>HOLding phase</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>COO</td>
<td>COOling phase</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>DBD</td>
<td>Decompression Before Dosing phase</td>
<td>Injection Molding Machine</td>
</tr>
<tr>
<td>DOS</td>
<td>DOsing Phase</td>
<td>Injection Molding Machine</td>
</tr>
</tbody>
</table>
Table 7 - Injection process control and commands.

Illustration of Injection Molding process Control/Command Signals:

Figure 74 - Typical illustration of injection process control and commands.

Graphical representation process features illustrated in the next section.
2.2.5.3 Screw Position

![Screw Position Graph](image)

Figure 75 – Screw position

This figure shows the position of the screw during the injection molding cycle. Between INJ.STA and HOL.STA the plastic melt is injected into the cavity. Afterwards there is a holding phase to equalize the shrinkage and warpage. At the point HOL.END the gate is frozen, so that there is no holding pressure still necessary. The dosing phase follows.

2.2.5.4 Screw Rotation

![Screw Rotation Graph](image)

Figure 76 – Screw rotation

During the dosing phase the screw rotates in order to haul the melt. Therefore the screwrotation is defined (SRO.MEA). Due to tolerances and the process there is small belt in which the screw rotation swings.
2.2.5.5 **Screw Torque**

![Screw Torque Diagram]

Figure 77 – Screw torque

2.2.5.6 **Machine Injection Pressure**

![Machine Injection Pressure Diagram]

Figure 78 – Machine injection pressure
2.2.5.7 Nozzle Injection Pressure

![Nozzle Injection Pressure Diagram](image)

Figure 79 – Nozzle injection pressure

2.2.5.8 Nozzle Injection Temperature

![Nozzle Injection Temperature Diagram](image)

Figure 80 – Nozzle injection temperature
### 2.2.5.9 Material Molding Pressure

![Material molding pressure diagram](image1)

**Figure 81 – Material molding pressure**

### 2.2.5.10 Material Molding Temperature

![Material molding temperature diagram](image2)

**Figure 82 – Material molding temperature**
2.2.5.11 Cavity Molding Temperature

![Cavity Molding Temperature Graph](image)

Figure 83 – Cavity molding temperature

2.2.5.12 Cavity Heat Flow

![Cavity Heat Flow Graph](image)

Figure 84 – Cavity heat flow
2.2.5.13 **Channel Input Temperature controller**

![Figure 85 - Channel input temperature controller](#)

2.2.5.14 **Channel Output Temperature Controller**

![Figure 86 - Channel output temperature controller](#)
2.2.6 General Scheme of a DACS for Plastic Domain

The purpose of any data acquisition system is to gather useful measurement data for characterization, monitoring, or control.

Data acquisition is the process of measuring electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound in concordance with real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisitions typically convert analog waveforms into digital values for processing.

The components of data acquisition systems include:

- Sensors: There is a great variety of sensors measuring many process parameters present in industrial systems, using many physical principles for transduction. These give an electrical response, current or voltage, which can afterwards be transformed for process identification and control.
- Signal conditioning systems: Signal conditioning is used to amplify, attenuate, shape, or isolate signals from transducers before they are sent to the measurement hardware. Many of the outputs provided by the sensors are not treatable directly by the digital systems used for process control, so there is a need of a signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values.
- Analog to digital converters: Convert the conditioned sensor signals to digital values

Data acquisition starts at the transduction done to a physical phenomenon or physical property of the process to be monitored. Examples of this include temperature, pressure, light intensity, gas pressure, fluid flow, and force. Regardless of the type of physical property to be measured, the physical state that is to be measured must first be transformed into a unified form that can be sampled by a data acquisition system. The task of performing such transformations falls on devices called sensors.

![Figure 87 - Basic schema of a DACS system](image-url)
A sensor, which is a type of transducer, is a device that converts a physical property into a corresponding electrical signal (e.g., a voltage or current) or, in many cases, into a corresponding electrical characteristic (e.g., resistance or capacitance) that can easily be converted to electrical signal. Many times, the electrical signal generated by the sensors is not directly usable by the processing unit, so almost always signal conditioning systems appear as the next natural step after the sensors to adequate the signal acquired to a readable and useful format. Once the signal has been conditioned it can digitized using an Analog to digital converter (ADC).

The ability of a data acquisition system to measure differing properties depends on having sensors that are suited to detect the various properties to be measured. There are specific sensors for many different applications. DACS systems also employ various signal conditioning techniques to adequately modify various different electrical signals into voltage that can then be digitized using an Analog-to-digital converter (ADC). In the same way, when the system controlling a process sends a control digital signal, this signal follows the inverse process, and it is converted to an analog value by a Digital-to-analog converter (DAC).

![Diagram of a complex distributed DACS system in Plastic Domain](image)

*Figure 88 - Example of complex distributed DACS system in Plastic Domain*
In DACS systems the processing of the signals acquired is generally done by a computer, mainly PCs or less commonly by embedded systems designed for specific applications. Attending to the most common systems, the PC based systems, the signals, after being acquired in the PC, are visualized, analyzed and recorded in the computer. All these operations can be developed using general purpose programming languages, such as C#, C, C++, Visual Basic .NET, or other more specific languages specially designed for this work, such as LabView from National Instruments or Matlab from Mathworks.

2.2.7 Configuration of data collection system for plastic domain

Figure 89 shows the complete configuration of injection molding unit to collect data to implement MONSOON concept and to build predictive model to analyze online variation of process variables and the effect on part quality. The part quality assessment will be assessed on bases of imbedded in-mold pressure and temperature sensors and by implementing an in-line opto-electric sensors and camera-scanning system selected on bases of use cases. The figure below shows the MONSOON system elements in general for plastic domain.

![Figure 89 - Configuration of injection molding unit for data collection at field level](image_url)
3 Domain Use Cases

3.1 Aluminium industry domain

3.1.1 General objective

AP needs and interests in MONSOON project is at carbon production area and at potline (or shared multiple potlines) supervision level. The vision is to allow on the long term shared “Process Excellence Centers” to be able to assist operations of several potlines, such as analysing this volume of available data to be able to detect and manage the outlier pots, providing early warnings or even predictive signals on global or individual anomalies more efficiently than what is achieved currently, giving to the process people a better analysis of the root cause of the abnormal behaviour, going towards predictive metal quality or maintenance, detecting common trends between potlines, that could be related to – for example – common raw materials supply, etc.

There are several issues in aluminium production process that can be improved by proposed methodologies of the project such as pots process anomalies prevention, predictive detection of anode spikes and environmental air emission avoidance. For pots process anomalies prevention MONSOON project will apply trend analysis techniques, in order to identify and detect structural changes and anomalies during pot process. For predictive detection of anode spikes MONSOON project will apply data analysis techniques and multi-scale modelling based on trend analysis and inductive learning techniques (machine and deep learning techniques), so as to build predictive models for spike detection and monitoring. For environmental air emission reduction MONSOON project, again will apply multi-scale modelling so as to build predictive models that could simulate several scenarios for air emissions with main objective to maintain the environmental footprint of the plant low.

While early proof-of-concepts will be implemented in small scale “test” environments (3 pots) available in AP plants, it is important to observe that the high amount of data required to apply the MONSOON methodology will only be made available thanks to significant investments made privately by AP to prepare the infrastructure of the Dunkerque plant for such an ambitious project. The ambitious deployment and innovative methodology foreseen by MONSOON would in fact not provide enough historical data to run complete analysis and thus would not result in significant outcomes, if only applied to small scale test-site environment only.

3.1.2 Expected impacts

3.1.2.1 Impact on productivity and production efficiency

It is to be noted that the current primary aluminium production process is a fairly mature one, result of more than 130 years of optimization. The value drivers of the industry are as represented in the following figure.

**Figure 90 - Costs breakdown for the aluminium production**
Based on this breakdown, on the top of the process briefly described before, it is possible to anticipate some MONSOON concrete impacts on raw material consumption, in relation with the aluminium production:

**Alumina** – The aluminium production process is currently typically operating at 103% of the minimum stoichiometric consumption. There is therefore very few opportunities and impact expected on this aspect.

**Anodes** – the process is operating at 121% of the minimum stoichiometric carbon consumption. There are more opportunities in this area, related to anodic incidents minimization through a better process anticipation and management. The anticipated impact is a 2 to 5% improvement, i.e. 10 to 25% of the gap with theoretical minimum. The same improvement is expected on the corresponding handling volume.

**Energy (electrical power)** - Even if EU companies are quite efficient as regards costs for alumina per-tons of final product, expenses by EU smelters for electricity are still the major source of competitive disadvantage. Primary aluminium production is an electro-intensive process, requiring 13300 kWh in average to produce 1 ton of product. The current consumption for the best operating plants / processes is about 190% of the theoretical minimum. Most of this difference is related to process design and inherent to the fact that the process is operating at high temperature. By allowing a better and more proactive control of the process, the project should enable major energy consumption gains either directly through better control of existing processes (max 1-3%, ie 150 - 450 kWh/t) or indirectly by unlocking design improvements potential (5 to 10%, ie -1000 kWh/t).

This is representing a bigger step than what the global aluminium industry has achieved over the past 25 years. It is equivalent on the long term, if applied to the whole primary aluminium industry in the EC (2,0 Mt/year) to an yearly energy consumption of 3,8 TWh (or more or less a 1 million people city).

Furthermore, when considering the costs of converting alumina into aluminium, thus including not only power cost, but also carbon cost, labour cost, fuel cost, bath material cost, other consumable costs as well as maintenance and sustaining capital expenses, producers in the EU face a competitive disadvantage vis-à-vis all international competitors. It is also possible to foresee also some wider spectrum advantages:

**Other costs and manpower**: This aspect is highly related to the process productivity in tons/hour or tons/employee. The biggest driver is the potline amperage (defining the process productivity) and the level of automation and control (defining the complement of operators and staff required to operate and maintain the process and the related equipment).

**Amperage and process productivity**: the amperage able to go into the process is given by the design of the electrolytic pot. For a given pot technology, due to the specifics of the electrochemical nature of the process, the rule of the game has always been to keep the amperage as constant as possible, not to disturb the process. However, a much better and predictive process control will allow more flexibility resulting in 1) Amperage / production creeping potential on a given pot technology, 2) Ability to fluctuate pot amperage in a wider window with the energy availability and market, with a resulting decrease in average kWh cost, 3) Minimization of the cost related to inefficiencies. Allowing a 10-15% flexibility in the process amperage due to this better control would allow a global win-win scenario with energy producers in a context of higher proportion of renewable energy in the mix.

**Plant staffing and maintenance costs**: productivity and costs gains can be achieved through less incidents treatment related manpower requirements (see business case section).

**Revenues and products quality**: Product quality improvement and access to new markets: the quality of the metal produced is linked to raw materials purity and to the level of process disturbances generating in-process metal pollution. Less disturbance will allow a higher metal purity. Typically a plant producing metal with an average Fe pollution of 1000 ppm could achieve more sustainably a 900 or 850 ppm average pollution and access other metal markets as a consequence.
3.1.2.2 Impact on environmental efficiency

The process of aluminium production generates direct CO$_{2eq}$ emission and indirect ones related to the energy mix of the electrical power production. Typically, one ton of aluminium is generating 2 tons of CO$_{2eq}$ directly (anode consumption and incidental Per-Fluoro-Carbon (PFC) emission during process excursions), and 0 to 15 tons of indirect CO$_{2eq}$ emission per ton of aluminium through the energy mix contribution (purely hydro to 100% coal based).

Direct emissions: emissions represent another key relevant impact factor on the MONSOON project. Indeed, the CO2 generated by the anodes is representing 1.5 t CO$_2$ / t Al. As for the carbon consumption mentioned above, the improvement associated to a better process control and anodic consumption should be around 2 to 5%. With respect to PFC’s (CF$_4$, C$_2$F$_6$ with a GWP respectively of 7390 and 12200), the potential is much bigger because these emission are process control and incident related. The current world average for the industry is 0.60 t CO$_{2eq}$ / t Al and the European average is more around 0.20 t CO$_{2eq}$ / t Al, with best in class operating at 0.03 t CO$_{2eq}$ / t Al. The potential gain order of magnitude for a typical plant should therefore be around 0.1 t CO$_{2eq}$/t Al, i.e. 250,000 t CO$_{2eq}$/y in the EC, or the equivalent emission of 100,000 cars.

Indirect GHG reduction: the enabling of a potential gain of 5 to 10% mentioned above on power consumption applies also to indirect GHG emissions, associated to energy consumption. All the impacts related to Energy and GHG have been listed and evaluated. The report anticipates an overall improvement potential of 21% on energy consumption and 66% in GHG emission before 2050, and although not all of these gains may come from process control improvements, they will definitely contribute or enable a significant part thereof.

3.1.2.3 Additional impacts related with the aluminium production (HSE)

It has been anticipated that a better process control, with much less excursions and incidents, will result in a general HSE improvement in the smelters, specifically regarding:

Health: During incidents treatment, the pots are opened and expose the workers to very high heat (the electrolytic bath is at 960°C) and fumes that contain amounts of HF, CO, CF$_4$, C$_2$F$_6$, SO$_2$. Less incidents in an optimized process, necessitating less manual intervention by operators in degraded conditions, will decrease overall exposure to these stressors. This is expected to improve industrial hygiene profile of the industry.

Safety: A significant part of the All Injuries Frequency Rate (AIFR) is finding its cause in abnormal situations management. A minimized number of abnormal situations to manage and less exposure to deteriorated conditions will result in less incidents and accidents. The AIFR of the plants beneficiating of the results of the project should improve (-10 to -20%) consequently.

Environment: The process environmental impact is largely minimized by a proper reduction pot design and operation. Fluoride emissions are in average below 0.5 kg F/t Al in the most recent plants, with benchmark values around 0.2. A large part of residual emission and difference between benchmark and average is related to the fugitive and incidental emission during process drift and incidents. A reduction of these occurrences will therefore contribute to improve smelters performance. With respect for solid waste, the biggest stream is indeed valorised as alternative raw material in third parties industries. This waste stream is constituted by the dismantled cathodes at their end of life (i.e.: after more or less 6 years). Other wastes are almost fully recycled in the process. The value at stake in waste recycling associated to a better process control is essentially related to a longer cathode life that would be allowed by a smoother operation. This said, cathode life duration is much more a matter of pot design than operation. It is possible to expect a 5 % life increase (and therefore a 5% less waste to valorise) with process excursion avoidance.
Society: thanks to the increase of the competitiveness of European aluminium industries, it is expected to keep employment in Europe and avoid redundancy plans. Aluminium industry represent today 90,000 employees in 2010. Between 2008 and 2009, a 7.5% reduction of the workforce could be observed and is directly linked to the reduction of the primary aluminium production.

3.1.3 Use cases selection

We have first reviewed all the potential use cases among the three main families of industrial Big Data.

![Figure 91 - Initial selected use cases areas](image)

We have chosen to work on the whole anode value chain (anode life cycle), from raw materials, anode manufacturing and finally anode behaviour on electrolysis pots.

The three selected use cases:

- Predictive Anode Quality
- Carbon process optimization: Paste Plant, Baking Furnaces, Rodding
- Predictive Maintenance (e.g. main motor of the Paste Plant)
- Electrolysis process optimization: anode behavior on pot
- Electrolysis process optimization: other

The predictive maintenance use case was selected as the first one for the ramp-up phase and is supposed to be an “easy one” because the scope is clear and limited and the predictive maintenance is one of the most popular and known domain in Big Data Analytics. Moreover the mixer is one of the key equipment of the Paste Plant which is critical for good quality paste production, this first use case could be seen as a zoom on the work on the global anode quality prediction.

3.1.4 Overview of the infrastructure already on the field

From a typical potline it is possible to extract information such as, pots instantaneous resistance, the line amperage, status indicators, bath temperature or chemical analysis, voltage drop manual measurements, anodic or cathodic current distribution, raw material quality analysis, metal quality analysis at a tapping cycle based schedule, equipment condition monitoring, operating equipment status, etc.

This information is collected at pot process control computer level, and through information transfer from other sections of the plant (e.g., bath or metal quality comes from the analytical lab MES). All this information is computed and presented to process control people at potline control room level. In terms of architecture,
Model based control framework for Site-wide Optimization of data-intensive processes

each pot is fitted with its own process controller. Each controller sends aggregated and partially processed data to the central potline supervision computer, which role is to package this information and historize. The process control (PLC or DCS) and supervision (SCADA) of others workshops in the plant (carbon area, casthouse, utilities, substation, cranes and load transportation) are interconnected and integrated to an Historian layer to retrieve all elementary data. The MES measures, visualizes, analyses and manages production operations, planning, quality, inventories, etc. and finally production performance. The MES is unifying automation & supervision levels with business management level by supplying critical data to the ERP. The ERP is standardized across AP/Rio Tinto and is SAP based.

The functions that will be useful for our use cases:

- Most of the existing MESAL™ functions implemented in the carbon area of the aluminium smelter.
- Historization of process data (covered by the OSIsoft PI Historian)
- Reduction production management (covered by the ALPSYS Pot Process Control System)
- Management of analyses (execution of analyses), managed by the LIMS

Data types:

- Master Data for each function
- Data associated with each business and common functions (equipment, materials and products, recipes and quality data)
- Operation of installations and shops: indicators, performance, work orders, etc.
- Etc.

Infrastructure already on the field:

![Figure 92 - Functional automation and IT architecture in Aluminium Dunkerque](image)

Note: to date the Carbon sector has an old fashioned IT layer that we plan to replace in parallel to the MONSOON project by our Rio Tinto (AP) standard MESAL™ solution.
Data volume:

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anodes Annual production</td>
<td>~ 140,000 baked anodes per year</td>
</tr>
<tr>
<td>Electrolysis area: Number of pots</td>
<td>1 potline of 264 pots</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of shift indicators</td>
<td></td>
</tr>
<tr>
<td>Carbon (MESAL)</td>
<td>500 including 250 for materials (not all are useful)</td>
</tr>
<tr>
<td>Reduction (ALPSYS)</td>
<td>1000 (not all are useful)</td>
</tr>
<tr>
<td>total</td>
<td>~ 1500 indicators</td>
</tr>
<tr>
<td>Number of Carbon historian tags (PI)</td>
<td>~ 5000 tags</td>
</tr>
<tr>
<td>Number of analysis (laboratory)</td>
<td></td>
</tr>
<tr>
<td>LIMS (avg. 10000 requests)</td>
<td>~ 100,000 samples (each has roughly 30 characteristics)</td>
</tr>
</tbody>
</table>

Table 8 – Aluminium domain use cases data volume

3.1.5 Functions capturing data

Existing Process Control and MES functions capturing data on the anode life cycle:

![Diagram of anode life cycle](image)

3.1.6 Carbon area Historian, MCS and MES

3.1.6.1 MCS and Historian

The automation (MCS and historian) layer in AD carbon sector (plant/company standards):

- PLC: S7 Siemens
- RTS: Citect Schneider Electric
- Historian: PI OSIsoft
3.1.6.2 **MES**

The MES provides production monitoring and management. It provides tools for monitoring the production procedure, the behavior of installations and the quality of manufactured products.

The main MES functions are:

- To provide long-term data storage acquired by the MCS, from the ERP or entered and/or calculated at MES.
- To present the collected data
- To provide the necessary analysis tools
- To print reports
- To provide ERP with management data
- To make calculations on the received data.

To date the Carbon sector has an old fashioned IT layer that we plan to replace in parallel to the MONSOON project by our standard MESAL™ framework.

The MES layer in Aluminium Dunkerque (AD) carbon area (plant/company standards) will be:

- MESAL, homemade MES solution developed using Microsoft tools: .NET, SQL Server
- Reports are done using Microsoft Reporting Services.
- Dashboards and Data Analysis are done using one of the top Business Intelligence tool of the market: Qlikview from Qlik.

3.1.6.3 **Main MES functions useful for the use cases**

**MATM - Material Flow Management:**

This module provides functions for:

- Stock management (stock level calculation and adjustments)
- Traceability of all material and product movements
- Validation of material and product movements using check data

Examples of materials followed-up for the Carbon Paste Plant:

- Raw materials: coke, pitch
- Intermediate materials: recycled baked products, recycled green products, dedusting fines, classified products (coarse, etc.), dry matter, rejected paste, good paste, rejected green anodes
- Materials produced: green anodes, rejected anodes, rejected paste, packing coke.

**EQPF - Equipment Performance:**

This module manages, for each equipment to be monitored by the MES:

- Equipment configuration
- Management of scheduled downtime planning
- Equipment operation monitoring (traceability of breakdowns with reason)
- Equipment performance monitoring (performance indicator calculation, e.g. Overall Equipment Effectiveness, operating rate, etc.)
- This module needs the MCS to supply the running bit for the equipment to be monitored as well as maybe a tag containing the downtime cause when a stoppage occurs.

**ANAM - Analysis Management:**

The objective is to have in each sector a unique interface to the LIMS. It provides the following functions:

- Reception of analysis result
- Storage and processing of analysis results.
SLOG - Shift Log:
The module provides the following information to the shift supervisors:
- Shift-to-shift information
- Limited life instructions as well as management instructions
- Operator assignments to workstations
- Operation Work orders to be done this shift
- Summary and indicators of previous shift
- Production targets and current status
- Indicators follow up during the shift
- Access to all previous shift logs.

It also accesses some functions covered by other functional modules, such as:
- Validation of material and product movements (raw material consumption and finished products produced)
- Possibility of keying in equipment breakdown causes and validation of performance indicators.

KPIM - KPI Management:
This module manages the reception and storage of all data received from the MCS or calculated by the MES. It identifies the indicators elected as KPIs. It includes KPI report.

TRAC - Traceability:
This module manages tracking function and is designed to carry out tracking both at “equipment” and at “material” level through manually entered events, uploaded from the MCS or a specific function call. This function allows:
- Configuration of equipment on which tracking is required
- Configuration of material classes on which tracking is required
- Configuration of associated events (production steps or process event)
- Configuration of utilization periods (tracking indicators).

For each event, the configuration of the HMI used to collect the associated data. From an operational viewpoint (in manual or automatic):
- Creation of an event for a given material class or item of equipment, and input of the data associated with this event.
- Modification of a previously entered event.
- Post viewing of a list of events as per criteria to be defined.
- Post viewing of an event.

PERM - Product and Equipment Recipe Management:
This module manages all parameters (recipe) used by an equipment to execute a production operation. Parameters are always linked to equipment; some parameters are also linked to the manufactured product. The module manages two types of recipe:
- Equipment recipe: parameters corresponding to equipment configuration independently to the manufactured product.
- Product recipe: parameters for product manufacturing.

This module is following a 3 steps process:
- Configuration of parameters and configuration of operator screens for data entries
- Management of equipment and product recipes
- Parameters sending to MCS
AQUA - Anode Quality: The Anode ID Card

The MESAL AQUA module centralizes all the information regarding the monitoring of anode life from manufacturing quality in Paste plant, Baking, Rodding shops through to their behavior on pots.

This function is enabling:

- Automatic gathering of green production parameters from RTS systems
- Manual input of baking furnace unload parameters
- Manual input of rejected anodes in Baking furnace and Rodding shops
- Automatic gathering of analysis results from the LIMS for Coke, Pitch, Baked Recycled and Anode Core Samples
- Automatic gathering of anode events from ALPSYS
- Multi-criteria reports production about:
  - Single anode sheet
  - Anodes batch sheet
  - Green and baked rejected anodes
  - Quality of baked anodes
  - Anode problems on pots
  - Anode behavior on pots

All data are captured for an individual anode (per carbon block). These data are then to be linked with the anode assembly (2 carbon blocks) to allow monitoring anode behavior on pots.

![Figure 94 - MESAL Anode ID Card (AQUA, Anode Sheet report)](image)

AGGD - Dry product grain size distribution:
This module manages the grain size distribution of the dry product used in anode production.

ABFO – Anode Baking Furnace Operation management:
This module manages:

- Loading/unloading operations at the baking furnaces (detailed material flow management)
- Follow-up of baking shop flue walls life (construction, deterioration/reparation)
- Follow-up of FTA operation quality
3.1.7 Electrolysis Pots Process Control and Supervision (ALPSYS)

3.1.7.1 Pot Process Control system overview

Pot Process Control system main roles:

- Adjusting alumina/fluoride feeding strategy
- Moving anodic beam up and down to set pot « R »
- Dealing with operations and anomalies and alarms
- Transferring information and getting settings to/from supervision level

Each pot is equipped with:

- A motorized system that vertically moves a beam that supports the anodes
- 8 solenoid valves controlling 4 alumina feeders and 4 crustbreakers for the feed of alumina (CAFД)
- 1 solenoid valve that operates the AlF₃ feeder (ATFD)
- 1 solenoid valve that operates the oversuction valve.

A two-level automation system is used for pot monitoring and control and potline monitoring:

- Level 1: each group of two pots is controlled-monitored by a dual potmicro connected to the dual pot control cabinet.
- Level 2: a central computer system with peripheral equipment is used for the supervision of the pots and reduction shop management (the system is designed to support two potlines).
- The Level 2 architecture is a 3-tier Web-based architecture with the following 3 levels:
  - A set of redundant computers for data acquisition and storage
  - A set of redundant Web applications for the Man-Machine Interface
  - Operator workstations connected to the Web servers to provide the Man-Machine Interface.
3.1.7.2 The Level 1 potmicro

The pot control cabinet includes the potmicro which is mounted on the front door of the cabinet. This cabinet ensures the following functions:

- Production of the various power supply and monitoring voltages
- Electrical protection
- Reception of control signals from the dual potmicro via the ASi network
- Transmission of instructions to the anode beam and solenoid valves
- Transmission of the dual potmicro of the pot input status via the ASi network
- Enabling the operator to maneuver the anode beam, in manual mode, using the selector and pushbuttons mounted on the front panel
- Enabling the operator to switch ON/OFF the circuit breaker control of the beam motor of each pot
- Control and monitoring of the pot with the potmicro

The pot monitoring and control program makes it possible to:

- Set the operating modes
- Acquire analog and binary signals
- Maintain the pot resistance around a setpoint value and control the orders sent to the anode beam
- Ensure bath alumina regulation and control the CAFD
- Detect and treat anomalies and events that occur on the pot
- Detect Forced Convection Network status and transmit it to L2
- Adapt the operation of the pot to the various actions that concern it
- Manage AlF₃ corrections and control the ATFD
- Manage Crustbreaker Chisel-bath contact
- Calculate the specific operation values of the pot and establish reports
- Dialogue with L2 (reception of parameters and transmission of monitoring data)
- Managing operator dialogue (keyboard, display, single line, and LED).

3.1.7.3 Main Level 2 Supervision functions

The Level 2 server performs the supervision functions:

- Dialogue with:
  - The potmicros
  - The operator via operator workstations linked to the Web server
  - The substation to transmit the potline setpoint current
- Calculate the potline setpoint current
- Perform thermal regulation
- Modify the dual potmicro parameters
- Supervise and monitor, in real time, the pots and the potline by means of alarms, instant values, 1-minute values, 5-minute values, pot servicing operations and sorting operations
- Control the horns in the potrooms
- Print out reports and balance sheets at shift or day intervals for technical monitoring and control.

The Level 2 server performs also some management functions:

- Configure the whole application (groups of pots, schedule creation, parameter definition)
- Perform work management and monitor jobs in the potline
- Produce periodic activity reports such as weekly and monthly reports
- Exchange information with the other sectors by means of the plant local network
- Manage lining-related data
- Manage a database and make it available in order for operators to perform potline operation analysis using standard tools.
3.1.8 Use case: predictive anode quality

3.1.8.1 Impacts of bad anode quality

Quality Management is a critical process at each step of anode manufacturing. The cost of scrapped anodes that don’t meet electrolysis’ quality standards can be quite significant. Scrap may be reintegrated to the production process at a certain cost (best case scenario), but sometimes, especially when non-conforming anodes are detected at the end of the production cycle, when the stem is rodded on the anode blocks, electrolysis is forced to use them or the anode assemblies are scrapped with high reprocessing costs.

Worse case scenario, if the quality issue isn’t caught in time and non-conforming anodes are sent to the potline, it could lead to dramatic operation disturbance at the potline level.

3.1.8.2 Anode predictive quality principle

Predictive Quality Management:

The goal of predictive quality management (QM) is to detect quality defects in products before they are mass-produced. Predictive quality management means looking at historical data of a product and then developing a predictive model based on the data.

It’s a fact that almost 80% of all quality issues are repeat issues. The carbon plant lacks the ability to capture, continuously improve, and leverage performance knowledge from lessons learned so that preventive action can be taken.

This problem comes first to the challenge of integrating, tracking, sharing and analyzing quality data that comes from many sources and processes within the carbon plant.

Monitoring the quality of anode production is a difficult challenge, especially when it will have to be implemented in real time on the production lines. This is firstly because anodes are made in batches which go through a sequence of operations, each taking place in strictly separate areas of the carbon plant, and secondly because each operation involves a high degree of specialist expertise.

The solution will be developed in order to improve quality management in the triple context of batch processing, monitoring by a large number of parameters and assessment by several different experts.

The solution will consist in collecting data on the different equipment while they are working, in order to fire an early warning on any detected quality drift and display to the operators what remedial action they should take. To achieve this early detection, the solution will have to integrate some of statistical tools, some simulation models of the reactions involved along the production line and a rule-based expert system encapsulating the multi-faceted knowledge of the operation and process experts.

Taking the above points into consideration, the MONSOON anode predictive quality solution will be implemented based on the following evaluation criteria:

- Predictive Quality Management: It should provide all necessary quality information and alerting in real-time, to address quality issues before they occur.

- Global and Integrated Solution: It must be able to consolidate quality data from disparate sources, standardize it, analyze it and display it through interactive role-based dashboards for different staff categories involved in the quality management process. Also share this information globally to learn “best practices” site to site.

- Quality Continuous Improvement: Find a solution that enhances quality planning through improved visibility of previous and existing quality issues, permitting the “never ending” cycle of quality improvement and permitting to allocate resources where changes are most needed.
• Compliance of Batch Manufacturing Quality “current Good Manufacturing Practice”: Batch consistency, validation, documentation and traceability will allow demonstrating that all the steps required by the defined procedures and instructions were in fact taken, and that the quality of the anode was as expected.

**Figure 96 - Anode Predictive Quality principle**

**Product Predictive Quality technologies for this use case:**
A promising approach for this use case could be the use of Data-Driven Model Predictive Control (MPC) of anode production batch processes.
To address the problem of unavailability of online quality measurements, an inferential quality model, which relates the process conditions over the entire batch duration to the final quality, is required. The accuracy of this type of quality model, however, is sensitive to the prediction of the future batch behavior until batch termination.
The "missing data" problem could be handled by integrating a data-driven modeling methodology, which combines multiple local linear models with an appropriate weighting function to describe nonlinearities, with the inferential model in a MPC framework.
To be detailed in next document drafting iterations.

**3.1.8.3 Anode predictive quality alerts and objectives**
Anode predictive quality management first objective will be to identify bad anodes with a high level of confidence and scrap them to avoid send them to the electrolysis area.

The second objective will be enabling and optimizing the quality strategy deployment with real-time actionable intelligence to best predict non-conformance production before it happens and immediately invoke behavioral change to correct the problem.

Successful performing of these optimization tasks at the Carbon plant will have the following impacts:
• Increase quality of the final product – rodded anodes
• Decrease consumption of raw material
• Bring flexibility to adapt to an actual conditions on raw material market
3.1.8.4 **New sensor: MIREA**

MIREA is a device which measures online anode structural homogeneity through voltage drop cartography and data analysis.

Data from MIREA could be a key enabler for anode predictive quality because MIREA enables 100% online backed anode characterization instead of 2 to 5 ppm samples with results most often delayed by few weeks.

![Figure 97 - MIREA device](image_url)

3.1.8.5 **Strategy: integrate the whole production chain data**

To be detailed in next document drafting iteration.
3.1.9 Use case: predictive maintenance on the paste mixer (ramp-up phase)

3.1.9.1 BUSS mixer at the Aluminium Dunkerque Paste Plant

Continuous mixing process:

![Continuous mixing process diagram](image)

**Figure 98 - Paste Plant continuous mixing process**

Buss AG (from Switzerland) introduced its first BUSS Kneader mixer for the continuous production of anode pastes in 1951. Since then, more than 250 BUSS mixers have been installed in aluminium plants worldwide (and more than 2500 in other industries). One BUSS mixer was installed part and parcel of the Paste Plant in Aluminium Dunkerque during plant erection in 1993.

![BUSS Kneader views](image)

**Figure 99 – BUSS Kneader views**
**BUSS Kneader operating principle:**

The characteristic kneading flights of the reciprocating mixing and kneading screw interact with each of the stationary kneading teeth in the barrel. The simultaneously oscillating screw shaft ensures intensive material exchange in the axial direction by multiple splitting, folding and reorientation of the product. This result is in a distributive mixing effect, ensuring optimal distribution of the solid raw materials and micro-dispersion of the pitch. This dispersive step-by-step mixing effect avoids product damage due to stress peaks and high radial pressures. Stress in the matrix is relieved after each shear cycle by distribution to neighbouring channels before renewed splitting, folding and reorientation during the next shear cycle.

Main process characteristics:
- Micro-dispersion for paste quality
- Uniform shearing effect reduces cracking of larger solid particles
- Adequate residence time for penetration of the pitch into the coke pores
- Narrow residence time distribution
- Optimized specific mixing energy
- Axial mixing

---

**Figure 100 - BUSS Kneader process section**

**Figure 101 - BUSS Kneader working principle**
Detailed process stages:

→ The coke fractions together with the butts are metered, conveyed and fed into the continuous preheater. Therein the solids are heated up to about 190°C.

→ The preheated solids are continuously fed by gravity into the BUSS mixer. Simultaneously the metered liquid pitch, at a temperature of about 210°C, is fed through one injection nozzle directly into the feed stock in the process chamber. The escaping air and fumes are led to a separate vent.

When the preheated liquid pitch is fed into the mixer via one or several injection nozzles integrated in the kneading teeth, small amounts of pitch are mixed thereby with small quantities of solids at a time. This ensures penetration and micro-dispersion of the pitch, and prevents the formation of undesirable pitch lumps. The kneading teeth are individually replaceable to allow the installation of pitch injection nozzles at any point along the process section of the mixer.

→ Micro-dispersion of the pitch in the process section of the mixer ensures thorough mixing for uniformly high-quality, high-density anode paste.

→ The anode paste emerging from the mixer, at a temperature of about 190°C, is fed by gravity via a closed system directly to a continuous paste cooler.

**BUSS mixer (K 500 CP) technical data:**

- Barrel diameter: 500 mm
- Process length: 9.5 L/D
- Speed max.: 75 rpm
- Drive power: 300 kW
- Output rates: 16-35 tons / hour
- Length: 14,500 mm – Width 2000 mm – Height 1900 mm

3.1.9.2 Impacts of breakdowns and malfunctioning

**Key equipment:**

The mixer is key equipment for the paste production at the paste plant which is stopped in case of breakdown. There is no redundancy on the mixer mainly because of the high initial CAPEX cost of such equipment.

**Malfunctioning:**

Deviation to the nominal running settings of the mixer has a major impact on anode quality in case of deviation. The “mixing intensity” is the capacity of the mixer to produce, as fully as possible, the following state of the green anode forming material:

- DP grains coated with binder,
- DP grain porosity filled with binder,
- intergranular space minimized and filled with binder.

In this respect, dry density is a favored indicator measuring the efficiency of the green anode manufacturing process.

**Actual maintenance actions:**

During the regular quarterly maintenance shutdowns of the anode production line, the process section of the BUSS mixer is checked and maintained as instructed by the provider (defective pieces replacement and preventive maintenance actions).
### 3.1.9.3 Predictive maintenance principle and technologies

**Predictive maintenance (PM):**

Predictive maintenance, also known as PM, techniques are designed to help determine the condition of in-service equipment in order to predict when maintenance should be performed. With the use of stochastic algorithms it is possible to calculate the probability of future events (malfunction, anomaly detection, machine downtimes etc.) at significant time before the event actually occurs. This approach promises significant cost saving over routine on planned and unplanned repairs.

PM evaluates the condition of equipment by performing periodic or continuous (online) equipment condition monitoring and/or time scheduled machine downtimes. The “predictive” component of predictive maintenance stems from the goal of predicting the future trend of the equipment's condition. This approach uses principles of statistical process control to determine at what point in the future maintenance activities will be appropriate. Most PM inspections are performed while equipment is in service, thereby minimizing disruption of normal system operations.

**PM technologies for the use case:**

To evaluate equipment condition, predictive maintenance utilizes nondestructive testing technologies such as infrared, acoustic (partial discharge and airborne ultrasonic), corona detection, vibration analysis, sound level measurements, oil analysis, and other specific online tests.

**Vibration analysis:**

Vibration analysis is most productive on high-speed rotating equipment and can be the most expensive component of a PM program to get up and running. Vibration analysis, when properly done, allows the user to evaluate the condition of equipment and avoid failures. The latest generation of vibration analyzers comprises more capabilities and automated functions than its predecessors. Many units display the full vibration spectrum of three axes simultaneously, providing a snapshot of what is going on with a particular machine.

**Model Based Condition Monitoring:**

This method involves spectral analysis on the motor's current and voltage signals and then compares the measured parameters to a known and learned model of the motor to diagnose various electrical and mechanical anomalies. This process of "Model Based Condition Monitoring" is used to monitor and detect developing faults in the equipment. It allows for the automation of data collection and analysis tasks, providing round the clock condition monitoring and warnings about faults as they develop.

**Other potential technologies:**

Acoustical analysis can be done on a sonic or ultrasonic level. New ultrasonic techniques for condition monitoring make it possible to “hear” friction and stress in rotating machinery, which can predict deterioration earlier than conventional techniques. Ultrasonic technology is sensitive to high-frequency sounds that are inaudible to the human ear and distinguishes them from lower-frequency sounds and mechanical vibration. Machine friction and stress waves produce distinctive sounds in the upper ultrasonic range. Changes in these friction and stress waves can suggest deteriorating conditions much earlier than technologies such as vibration or oil analysis. With proper ultrasonic measurement and analysis, it’s possible to differentiate normal wear from abnormal wear, physical damage, imbalance conditions, and lubrication problems based on a direct relationship between asset and operating conditions.

Sonic monitoring equipment is less expensive, but it also has fewer uses than ultrasonic technologies. Sonic technology is useful only on mechanical equipment, while ultrasonic equipment can detect electrical problems and is more flexible and reliable in detecting mechanical problems.

Infrared monitoring and analysis has the widest range of application (from high-to-low-speed equipment), and it can be effective for spotting both mechanical and electrical failures; some consider it to currently be the most cost-effective technology.
Oil analysis is a long-term program that, where relevant, can eventually be more predictive than any of the other technologies. It can take years for a plant's oil program to reach this level of sophistication and effectiveness. Analytical techniques performed on oil samples can be classified in two categories: used oil analysis and wear particle analysis. Used oil analysis determines the condition of the lubricant itself, determines the quality of the lubricant, and checks its suitability for continued use. Wear particle analysis determines the mechanical condition of machine components that are lubricated. Through wear particle analysis, one can identify the composition of the solid material present and evaluate particle type, size, concentration, distribution, and morphology.

### 3.1.9.4 Predictive maintenance alerts and objectives

The objective of PM is to allow convenient scheduling of corrective maintenance, and to prevent unexpected equipment failures and machine downtimes. By knowing which equipment or piece of equipment needs maintenance, maintenance work can be better planned (spare parts, people, etc.) and what would have been “unplanned stops” are transformed to shorter and fewer “planned stops”, thus increasing Paste Plant availability. Other potential advantages include increased equipment lifetime, increased Paste Plant safety, fewer accidents with negative impact on environment, and optimized spare parts handling.

The ultimate goal of PM is to perform maintenance at a scheduled point in time when the maintenance activity is most cost-effective and before the equipment loses performance within a threshold. This is in contrast to time and/or operation count-based maintenance, where a piece of equipment gets maintained whether it needs it or not. Time-based maintenance is labor-intensive, ineffective in identifying problems that develop between scheduled inspections, and is not cost-effective. Adoption of PM can result in substantial cost savings and higher system reliability.

Reliability-centered maintenance (RCM) emphasizes the use of PM techniques in addition to traditional preventive measures. When properly implemented, RCM provides companies with a tool for achieving lowest asset Net Present Costs (NPC) for a given level of performance and risk.

Diagnostic information is presented to the maintenance team – including the specific fault, the recommended action, and an estimate of time to failure. Electrical and mechanical problems are diagnosed, including common faults like insulation breakdown, damaged rotor bars, imbalance, and bearing defects.

### 3.1.9.5 Strategy: focus on real-time data and combine PM technologies

A potential promising approach for our use case is to combine several PM technologies:

- Vibration analysis
- Model Based Condition Monitoring
- Link with process performance data

Vibration analysis associated with Model Based Condition Monitoring and equipment wear units (cycle time) could be the key driver to identify correlation with some pieces of equipment potential default. Combining these measurements on the equipment with measurement of process performance could allow us to successfully predict developing problems.

Based on historical data, a series of data-driven methodologies and techniques (regression analysis, machine and deep learning techniques etc.) will be implemented so as to find a reference mathematical model, with significant classification performance, either on binary class or multi-class scenarios. This predictive model will include the most significant and the more useful information about all electrical and mechanical characteristics of the motor and its driven system. This learning process will include all operating states experienced during training, such as different speeds and loads. When the predictive model is decided, it will be deployed in real-time. Furthermore, the suggested predictive model will be re-trained and updated in regular bases.

The system will be then able to assess the severity of the problem and produce a series of indications to suggest what is wrong, what action should be taken and how soon it should be done.
### 3.1.9.6 Detected developing faults (TBC)

The following developing faults could be detected and diagnosed:

- Electrical supply,
- Internal electrical problems (like insulation breakdown),
- Mechanical faults (like foundation and coupling looseness, imbalance and misalignment, and bearing deterioration),
- Operational problems leading to changes in load or electrical characteristics.

### 3.1.9.7 Existing data (TBC)

Our initial objective is to use existing measurements only (voltage, current signals, etc.). Nevertheless some additional sensors could be introduced if they are promising to increase the robustness of our predictive function.

<table>
<thead>
<tr>
<th>ITEMS</th>
<th>NUMBER</th>
<th>DESIGNATION</th>
<th>UNIT POWER (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>362.J100</td>
<td>1</td>
<td>Bucket elevator</td>
<td>20</td>
</tr>
<tr>
<td>362.J110</td>
<td>1</td>
<td>Vibrating feeder</td>
<td>3</td>
</tr>
<tr>
<td>362.J120</td>
<td>1</td>
<td>Magnetic separator</td>
<td>1</td>
</tr>
<tr>
<td>362.J130</td>
<td>1</td>
<td>Preheating screw</td>
<td>37</td>
</tr>
<tr>
<td>362.J140</td>
<td>1</td>
<td>Plug screw</td>
<td>3</td>
</tr>
<tr>
<td>362.J150</td>
<td>1</td>
<td>Mixer</td>
<td>350</td>
</tr>
</tbody>
</table>

Table 9 – Aluminium use case #1 equipment

List of variable control equipment:
- J110 : flow rate
- J130 : rotation speed
- J150 : rotation speed
- J150 : rotation speed

List of equipment with measurements:
- J100 : elevator motor amperage
- J130 : screw speed
  - motor amperage
  - dry solid temperatures
- J150 : motor power
  - motor amperage
  - mixer speed
  - motor speed
  - paste temperature
  - pitch temperature at mixer inlet
  - flap position

Operator control on Preheating Screw J130:
- A local control box, with:
  - 1 "LOCAL - CENTRAL" selector
  - "PLUS" and "MINUS" pushbuttons for screw speed adjustment
  - 1 screw speed display
  - 1 dry solid temperature display
  - 1 screw inlet heat transfer fluid temperature display
Operator control on Mixer J150 (in proximity to the mixer valves, an operator terminal with):

- On the screen(s) (non-complete list):
  - Mimic screens displaying the mixer equipment, valves and auxiliaries and their statuses (positions, on, off, faults, measurements, setpoints, etc.)
  - A display screen of the operating modes, actual operations, selections, control statuses, etc.

- For the controls (by function keys or other controls):
  - Selection of "CENTRAL" or "LOCAL" mode (mixer, valves, etc.)
  - "FASTER" and "SLOWER" mixer speed controls
  - Mixer valve "OPEN" and "CLOSE" controls
  - "AUDIBLE ALARM OFF" control
  - "ACKNOWLEDGE" control

- 1 mixer “EMERGENCY STOP ” pushbutton

Remote measurements:

- Preheating screw J130
  - Screw speed
  - Motor amperage
  - Dry product temperature

- Mixer J150
  - Motor power
  - Motor amperage
  - Mixer screw speed
  - Motor speed
  - Temperatures of the paste in the mixer
  - Pitch temperature at mixer inlet
  - Flap position

Remote settings:

- Filling time of preheating screw J130 monitoring setpoint
  - Preheating screw J130 speed setpoint

- Mixer J150:
  - Power setpoint
  - Rotation speed setpoint
  - The various alarm and fault thresholds
  - Etc.

All start-up and stoppage sequences have to be taken into account.

Other electrical parameter measurements (like real and reactive power, total harmonic distortion, supply harmonic content, voltage imbalance, etc.) could also provide valuable analysis data.

3.1.9.8 Paste Plant Automation System Architecture – Section J – Mixer
Figure 102 - Paste Plant Automation System Architecture – Section J – Mixer
3.1.10 Use case: electrolysis process optimization, predictive detection of anodic incidents

3.1.10.1 Anode problems on pot and consequences

Problems that require replacement of the anode assembly:
- Anode block split, broken, unroded,
- Broken clad,
- Cut anode pin,
- Fallen anode block.

Problems that do not require anode assembly replacement every time:
- Mushroom (spikes),
- Flatness defect (deformation).

Depending on the type of problems, the following may arise: instability, burst anode block, fallen anode block, reduction of iron purity, temperature increase.

In all cases:
- Poor current distribution,
- Reduction in current efficiency.

![Figure 103 - Anode spike/mushroom and deformation](image)

3.1.10.2 Highlight on anode spikes / mushrooms

Periodic spikes crisis lead to production loss and carbon production overcost:

The specificity of spikes crisis is its “snowball effect”: as explained in the Anode Quality chapter, the root cause is due to bad anodes generating dust. Drawn by movement of the metal, the carbon grains concentrate effectively at different points of the bath/metal interface, where they form magmas called spikes or mushrooms that adhere to the anodes. The whole current distribution at the anode assemblies is destabilized in the pot and one of the principal effects of this disturbance is an increase in temperature of the pot, whose performance deteriorates. Moreover, because temperature accelerates the \( \text{CO}_2 \) oxidation rate, the phenomenon spreads to other anodes, which would not have produced carbon dust at a lower temperature. The phenomenon therefore propagates throughout the pot.

Because of the batch anode manufacturing process, several dozens of bad quality carbon blocks can create dust in other pots. This leads first to a work rate increase of anode changing operation to remove all the anode assemblies identified with spikes in addition to normal anode changing operations. A consequence of this increasing work rate is a decrease in anode changing operation quality with respect to operation best practices, especially regarding bath crusts removal from anode cavity when extracting the consumed anode. These crusts can adhere to the anodes, create new dust fixation points and finally create additional spikes.
This also leads to a work rate increase of anode production at the Carbon plant to replace all removed anodes. A consequence of increasing production beyond nominal rates is a decrease in anode production quality (for example, reducing anodes baking duration to speed up the production). These new anodes produced can also potentially generate dust when on pots and finally accelerate the “snowball effect”.

Figure 104 – anode spikes crisis "Snowball effect" principle

Figure 105 - Aluminium Dunkerque: Spikes/Mushrooms crisis over 2009-2014 period
(Average 3.1% with 8%+ during crisis)

3.1.10.3 Predictive detection of anode spikes principle

Generate a robust alert priori to traditional measurement (anode current distribution measurement).

To be detailed in next document drafting iterations.

3.1.10.4 Predictive detection alerts and objectives

Successful performing of these optimization tasks in the electrolysis potline will have the following impacts:

- Less anode effects implying less emissions
- Decrease cases with non-standard anode behavior implying higher energy efficiency
- Increased quality and quantity of aluminium produced
- Increase anode operating life in pot and reduction of manipulation implying safer working environment
3.1.10.5 Existing Data from ALPSYS

Monitoring variables:
The main monitoring variables are listed below:
- Voltage at pot terminals
- Current flowing through the pot
- Pot resistance calculated from the measurement of the voltage and current flowing through the pot
- All operator manual controls
- All pot status inputs.

Control variables:
- Anode-to-cathode (metal-to-anode) distance adjusted by vertical displacement of the anode beam
- Alumina feed intervals
- AlF$_3$ feed intervals

3.1.10.6 New sensor: anodic individual current measurement

New sensor: Anodic Current individual measurement.
We will equip ~30 pots in Aluminium Dunkerque plant with these sensors.

The information generated will be the main raw data for the predictive anodic incident detection on electrolysis pots.

3.1.10.7 Strategy: focus on real time data

To be detailed in next document drafting iterations.
3.2 Plastics industry domain

Under the concept of MONSOON project two use cases will be integrated at GLN production cell. A short description of each case study is presented in the next section.

3.2.1 General objective

The following figure shows the simplified cost breakdown for the plastic production in the 2015 (source: GLN). The impact of the raw materials costs is evident, hinting that waste reduction is a key aspect for optimizing this process.

![Costs breakdown for plastic production](image)

**Figure 108 - Costs breakdown for the plastic production**

3.2.2 Expected impacts

3.2.2.1 Impacts on productivity and production efficiency

Hereafter the main relevant topic to be addressed in order to reduce such value:

**Material handling reduction** - Addressing the decrease of resource consumption for companies in this market can be done by reducing the number of non-quality product and maximizing their recycling. This just will be possible if a product made of two materials can be recycled. Furthermore, the plastic production process depends on various aspects related to parameters setup and maintenance procedures, which if well calculated or designed, would increase the raw material savings.

**Revenues and products quality**: the quality of the plastic produced (and consequently the reduction of wasted products) is directly linked to raw materials moisture and parameters. To create the proper model to relate those information before the actual starting the injection process is necessary to drying the raw material. It is also important to consider in this model the geometry of materials, the lubrication required, the injection temperature, the mold temperature, the injection pressure, the number of injection cycles and the compulsory dimensional tolerances. The combination of these factors will affect the product quality. GLN has a KPI of 2% rejection rate for automotive, but observed rejection rates can reach 30% for complex products. The optimization foreseen by MONSOON in the definition and control of such models will sensibly reduce the losses, providing a tangible and replicable impact for this sector.

**Maintenance and molding parameters setup**: a machine operator changes usually a variety of parameters on the machines deputed to molding operations (mold temperature, injection speed, temperature, etc.). Today, the process is manually repeated until the machine starts to produce parts at desired quality level, producing an indefinite number of non-quality product or even waste. This process could be sensibly optimized, operating over different aspects, such as the temperature in different parts of the machine which knowledge helps to understand the changes in viscosity if parameters need to be changed. Parameters changes are today optimized by “trial and error” cycles (typically 5-6), producing scrap parts until the optimal level is reached. In the MONSOON an overall decrease of resource consumption by 10% will be pursued: this will be done by iterative interactions over the basic production flow in the plastic use-cases selected,
measuring production results and comparing them with settled parameters, so real-time tuning the molding process to drastically reduce the non-quality product creation. A predictive model will increase the production process, and consequently reduce the waste.

**Mold process problems:** if a non-quality product is spotted, the corresponding machine/mold has to be stopped until the problem is solved. The problem can be the consequence of a severe issue (e.g. mold damaged or broken), arriving at taking up to 3 weeks for the proper repair or substitution. The MONSOON approach is such that specific problem can be recognized by large scale data analysis over real time data acquisition and problem pattern recognition, reducing the number of wasted parts produced and immediately trigging the required repair operations.

### 3.2.2.2 Impacts on Environmental Efficiency

According to the British Plastic Federation “30% of the energy use is ‘discretionary’, this means that the cost is incurred because the site management has either decided to take no action or because it has not recognized the opportunities for such improvement. In most of the cases, energy use and costs can be reduced by over 30%”. Accordingly, the energy costs could be reduced by Management actions, Maintenance actions and Capital investment actions. For the next year GLN aims at reducing the total cost of energy (electricity) at about 8.23%. This strategy foresees the usage of sensors to be placed within injection machines, providing information about energy consumption spent by single machines. The MONSOON project will facilitate this transition process, also providing low level integration of physical sensor to real time collect data (exactly like electricity consumption), in order to address an analysis of energy lacks and performing a quickly energy consumption reduction process.

![Figure 109 - Energy savings strategy](image)

### 3.2.2.3 Additional impacts (HSE)

There are several key aspects that represent additional impacts of the MONSOON project:

**Manpower:** this aspect is highly related to the process productivity in pieces/hour or pieces/employee. Employees have to inspect the final product, after injection process (an operator inspects and checks (randomly) the product according to the product specifications) It is anticipated that a better process control, with much less excursions and incidents, will result in a general HSE improvement in the molding machines.

**Health and safety:** During incidents treatment, the molding machines are opened and expose the workers to very high heat (hot plastic). Fewer incidents in an optimized process, necessitating less manual intervention by operators in degraded conditions, will decrease overall exposure to these stressors. MONSOON will introduce a new approach that is expected to improve also industrial security and safety profile of the industry: less abnormal situations to manage and less exposure to deteriorated conditions will result in less incidents and accidents. Most work-related accidents occur during the maintenance process. Through the MONSOON project is expected to reduce 30% of work-related accident.

**Environment:** The environmental impact of plastic production process is largely minimized by a proper reduction pot design and operation. The reduction of non-quality products will therefore reduce the plastic waste (that cannot be recycled), thus contributing to improve environmental performances. In the GLN industry, the biggest waste stream is used as alternative raw material for other industries.
The other wastes are almost fully recycled in the process. The knowledge of waste material and the share of such information will be helpful for the entire ecosystem, also encompassing the primary circular economy objective of the SPIRE initiative.

### 3.2.2.4 Impacts on European Process Industry’s Innovativeness

The impacts for the European plastic industries exploiting the MONSOON innovation are potentially extremely relevant.

**Overall financial value at stake, and industry sustainability:** The European plastic industry is operating in a global market, and therefore competing with major production areas in emerging countries, where labour, raw materials and construction costs are much lower. In addition there are several global competitiveness challenges of the European plastics industry mostly resulting from aggressive competition by other countries such as Brazil (bio-plastics), Middle-east (advantages due to oil availability), India (growing internal market and low labour costs), China (market size and low structural costs).

It is clear that the maintenance of a significant EU capacity of primary plastic production will only be possible by focusing on high-quality products being produced by means of extremely optimized production processes. The process control has a direct influence on the final product and the economic aspects of the process. In this context, cost reduction and control is a major prerequisite for companies’ survival. Cost minimization of process disturbances and maintenance or even prediction of these inefficiencies is critical for industry cost competitiveness. The three main types of predictive functions are predictive maintenance (Asset Health Management), process optimization (on all injection processes: power, fusion, compression, injection), predictive quality (on the injection parameters definition: temperature, injection speed, and temperature). This functions will be the base analysis that the MONSOON project will implement through large scale data collecting and real-time analysis, implementing on top of such data the actual needed algorithms which will maximize the company value.

**Social Impacts:** accordingly to “Plastics – the Facts 2014/2015, an analysis of European plastics production, demand and waste data”, the growth of the plastics industry as affects in numerous sectors of the European economy. The plastics industry is a key to the innovation of many products and technologies in other sectors like: healthcare, energy generation, aerospace, automotive, maritime, construction, electronics, packaging or textile. On the other hand the Plastic Europe also defend that “the innovation and growth in Europe depend on manufacturing, in particular the plastics industry”. Finally, the unique characteristics of plastics allows to make a strong contribution to a more environmentally sustainable and resource efficient Europe.
3.2.3 Plastic Domain Use-Case-1

Use Case-1 (coffee capsules): This use case covers the commodity product area having large quantities with little variation and relative low quality specifications (currently running on 12 machines at the GLN production site). In Use Case-1 it is important to receive the correct diameter and height of the coffee capsules and to make sure that the holes at the bottom of the capsules are formed properly.

3.2.3.1 Use Case Delta-Line

Following picture shows the existing process line to be integrated in MONSOON project. Actually nothing can be measured and evaluated automatically. Due to this it is impossible to define the injection molding machine, the cavity or the injection molding cycle a part was made with. The MONSOON platform can provide the automatic evaluation of the produced capsules. With the help of this information it can be said if an error occurs randomly or if there is a systematic error, which would be the case if one specific cavity produces fault parts or if a complete cycle produces fault parts. In both cases further investigations can be undertaken in order to prevent the production of fault capsules. If there is a failure in a single cavity it can be seen if there is damage in the molding tool or in the injection molding process or even in the injection molding machine. If a whole injection cycle produced fault parts it is possible to identify the injection molding machine that produced these parts so that further investigations can be undertaken to find out why the fault parts were produced and how to stop it.

The inline quality control system is represented by the following picture and able to control 100% quality of the high volume production based on the visual system according to the defined specification.

Therefore a picture of each coffee-capsule is taken and compared with a reference. If a capsule doesn’t fit the requirements it is taken out. This step of the production process is very important to make sure that the capsules and the lids fit onto each other because both are welded after the coffee has been filled into the capsule. The measuring of the height is also important because it might happen, that the filled coffee capsule does not fit into the coffee machine.
3.2.4 Plastic Domain Use-Case-2

The case study SUBASSY expresses a more technical application regarding the injection processes. It is a part used in the automotive industry, where methods of over-molding metal inserts are applied - 6x M5 bolts, 6x M8 bolts and 2x M8 washers.

Because it is a complex part that also has an assembly process associated, an infrastructure was developed to allow the article to be automatically complete (plastic + metal inserts) at the end of each cycle. The production goes through 4 distinct phases, which are aided by robots, allowing it to reach the final product:

- Stage 1 - Selection (through a SCARA pick & place robot) of the different bolts and washers and positioning them in a pre-mold (templet);
- Phase 2 - Collection of the inserts through a robot (6-axis robot) and application in the mold;
- Phase 3 - Injection of the part and the over-molding of the inserts
- Phase 4 - Collection of the article (through a Cartesian coordinate robot), optical inspection, with due acceptance or rejection.

During the process it can happen that one of the metal inserts is missing. This part also has much higher quality requests than the coffee capsules and is not produced in such high amounts as the coffee capsules. During the manufacturing of SUBASSY it will also be possible to evaluate the variables of the injection molding process in order to detect failures of the process and the long-time-changing of process variables.
In both cases the machine worker can be informed by the system and change or stop the process in order to prevent the production of many fault parts.

3.2.4.1 The Mold

The mold consists of a two-cavity tool, from which two pieces are injected simultaneously per cycle. At the end of the injection two articles, with metal inserts and joined by a plastic Sprue, are extracted, with a weight around 1200 grams (450 grams / piece + 300 grams / sprue).

The mold has some limitations and aspects to improve, namely, the produced Sprue is very large and heavy, therefore its reduction will be addressed in the next modification of the mold - implementing this modification will slightly reduce the cycle time, consumption of raw material and will minimize the amount of burrs (by injection overpressure).

3.2.4.2 Metal Inserts

There is a sampling procedure to control the metal inserts, which are provided by an external supplier. However, the probability of having NOK elements entering the injection circuit is still around 20%. On the other hand, due to the wear of the gripers (robots accessories used to catch the components/parts), the probability of the occurrence of failures increases very significantly. If the robot in stage 1 does not put one or more inserts in the pre-mold, because there is no control mechanism present, the article at the end will be NOK - the cavity without the insert will be filled with plastic and in step 4 this error will not be detected. The same happens if the robot in phase 2 cannot catch or drop the insert. Still in phase 2, due to the wear of the grippers, there is a likelihood that the insert will be not correctly placed in the mold, resulting, at the end, in a part with displaced inserts and/or damaged stud bolts. Likewise, over time and the wear of the electromagnets, there is a reduction of the magnetic force, resulting in the falling of the inserts.
3.2.4.3 Optical Inspection

For this article, due to its complexity and need for constant control, an optical inspection system was fitted, allowing the maximization of production and allowing for more efficiency. However, the optical inspection system is not the most appropriate for this particular application: variations such as light, vibrations, air variations and noise contribute to incorrect inspection of the article when it is collected from the mold after the injection cycle. On the other hand, there is a fault in the separation of the OK and NOK parts: it will be necessary to create a physical barrier that guarantees the correct separation.

3.2.4.4 Additional data

- There is an average consumption of raw material (PA6 with fiber) around 240ton / year.
- An average of 500 000 articles/year is being produced.
- It is estimated an annual expenditure of 150K euros to be used between maintenance, NOK parts, production stoppages and production optimization.
- There is a time gap between the different robots, which if not respected, can make them collide with each other. This matter is normally related to human error.

3.2.4.5 Impacts

The MONSOON platform can provide better control of the injection process, translating a perfect harmony between the machine process and the robot activities. It can also predict possible errors, considering the time intervals of each robot cycle and also the absence of metallic inserts in the grippers. This will promote a reduction of NOK parts.

On the other hand, increasing the efficiency of the process, with the MONSOON platform, the economic issue will also be affected and it is expected to reduce the cost related to the maintenance process and the production stops.

4 Conclusions

This deliverable has documented the state of the art for the aluminium and plastics domain on both the technological and business aspects. It has described the aluminium and plastic domain-specific and cross-sectorial use cases, and particularly detailing the two first use cases that will be addressed by the MONSOON platform.
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>AA</td>
<td>Anode Assembly</td>
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<tr>
<td>ABF</td>
<td>Anode Baking Furnace</td>
</tr>
<tr>
<td>AD</td>
<td>Aluminium Dunkerque</td>
</tr>
<tr>
<td>ALPSYS®</td>
<td>Pots Process Control and Shop Management System</td>
</tr>
<tr>
<td>ATFD</td>
<td>Aluminium Trifluoride Feeding Device</td>
</tr>
<tr>
<td>CAFD</td>
<td>Crustbreaking and Alumina Feeding Device</td>
</tr>
<tr>
<td>DACS</td>
<td>Data ACquisition System</td>
</tr>
<tr>
<td>DP</td>
<td>Dry Products</td>
</tr>
<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
</tr>
<tr>
<td>FC</td>
<td>Fixed Carbon</td>
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<tr>
<td>FTA</td>
<td>Furnace Tending Assembly</td>
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<tr>
<td>FTC</td>
<td>Fume Treatment Center</td>
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<tr>
<td>KPI</td>
<td>Key Performance Indicators</td>
</tr>
<tr>
<td>LIMS</td>
<td>Laboratory Information Management System</td>
</tr>
<tr>
<td>LM</td>
<td>Left Mold</td>
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<tr>
<td>MCS</td>
<td>Manufacturing Control System</td>
</tr>
<tr>
<td>MES</td>
<td>Manufacturing Execution System</td>
</tr>
<tr>
<td>MESAL™</td>
<td>Rio Tinto MES ALuminium</td>
</tr>
<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>PQM</td>
<td>Predictive Quality Management</td>
</tr>
<tr>
<td>PM</td>
<td>Predictive Maintenance</td>
</tr>
<tr>
<td>PP</td>
<td>Paste Plant</td>
</tr>
<tr>
<td>PTA</td>
<td>Pot Tending Assembly (= electrolysis operation crane)</td>
</tr>
<tr>
<td>Right</td>
<td>Mold</td>
</tr>
<tr>
<td>RTBS</td>
<td>Rio Tinto Business Solution</td>
</tr>
<tr>
<td>RTS</td>
<td>Real Time Supervision</td>
</tr>
<tr>
<td>VM</td>
<td>Volatile Matter</td>
</tr>
<tr>
<td>WH</td>
<td>Weighing Hopper</td>
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