# COGNITWIN

## Cognitive plants through proactive self-learning hybrid digital twins

DT-SPIRE-06-2019 (870130)

# Deliverable Report

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# Executive Summary

This document is a deliverable "D1.1: A report on existing level of digitalization and describing challenges for Nonferrous pilots, incl. identification of novel sensors" of the project COGNITWIN. This report describes the work carried out for the following two pilots:

- Hydro Pilot
- Elkem Pilot

In Hydro pilot, the main aim is to spread out adsorbed HF in the fed primary alumina evenly. This because the variation of fluoride in alumina fed to electrolysis cells influences the heat balance of the electrolysis cell. This is sought to be achieved through logging the HF to be adsorbed, and feed alumina so that the weight fraction of F becomes as even as possible. Several concerns will have to be appreciated, such as alumina quality, humidity and temperature. The temperature can be adjusted in the pilot and sought to be held as constant as possible (~90°C± 5°C), to ensure even conditions for adsorption. Also, in the pilot, active regulation of the three main fans, which in total of the three fans on can consume up to 3,6 MW when on max load. By regulating these fans based on the actual need and seek an even mass flow of off gas from electrolysis, one can save some energy, here stipulated to 5% reduction compared with today.

In Elkem pilot, the main goal is to develop an online model for refining of ferrosilicon alloys combining state-of-the-art sensors and a dynamic model for mass balance and heat transfer. By adjusting to real-time measurements, the refining and alloying of liquid ferrosilicon will be more precise, and this will eventually lead to higher yield, improved accuracy and lower specific energy consumption. The development and implementation of a cognitive twin will help to reduce the process variations caused by human interpretation as well as well as enhancing the decision support for the operators.

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# Acronyms

| | |
|---|---|
| GTC | Gas Treatment Centre |
| HF | Hydrogen Fluoride |
| MW | Megawatt |
| $Nm^3$ | Normal cubic meter, at 1013 mbar and 273,15°K (DIN 1343) |
| GE | General Electric |
| IHEX | Internal Heat Exchanger |
| SGA | Smelter-Grade Alumina |
| IoT | Internet of Things |
| KPI | Key Performance Indicator |
| PTH | Post-Taphole |

# 1 Introduction

This report summarizes the work performed during the time period M1-M7 related to Task 1.1 (Co-innovative preparations). The objective has been to define the existing level of digitalisation of the two pilot plants that are part of WP1 (Non-ferrous). Project feasibilities, limitations and opportunities has been analysed and a set of key process indicators (KPI) has been identified and will be used to monitor the success rate of the project. The report is divided into two main parts, one for each pilot.

# 2 Hydro Pilot

## 2.1 Introduction to Hydro & Process description

The raw materials for electrolysis of aluminium are, aluminium oxide ($Al_2O_3$), anode carbon (C), aluminium fluoride ($AlF_3$) and electrical current. The electrolysis process with its Gas Treatment Centre (GTC) consists of two major material flows, a gaseous flow from the cell, and a bulk solids flow to the cell. In Figure 1 a sketch of the process flows is given. The alumina is discharged from a buffer or main storage (A) and fed to the dry scrubber reactor in the GTC (B). Here it adsorbs the HF and some $SO_2$ and the alumina is separated from the gas in a filter and collected in the filter house hopper (C). From this hopper the reacted alumina (secondary alumina) is sent to the electrolysis cell (D), either directly or via buffer storages before and after alumina distribution to individual electrolysis cells. The gas is collected from the electrolysis cell by means of suction (1), then drawn through the reactor (2) where it is mainly stripped for the HF gas (~95%) and moved further to the filter bag house where the filter cake adsorbs the rest of the HF gas. In total the efficiency of HF removal by the dry stage is 99.9%. After the dry stage the gas is pulled further by fans placed after the dry scrubber (3). The gas is after the fans pushed either directly to a stack (4), or into a wet scrubber stage for removal of $SO_2$ and rest HF. The wet scrubber stage uses either sea water or $NaOH+H_2O$ solution. The liquid absorbing the $SO_2$ and rest HF is returned to sea (5), often via make-up and conditioning and settling basins.

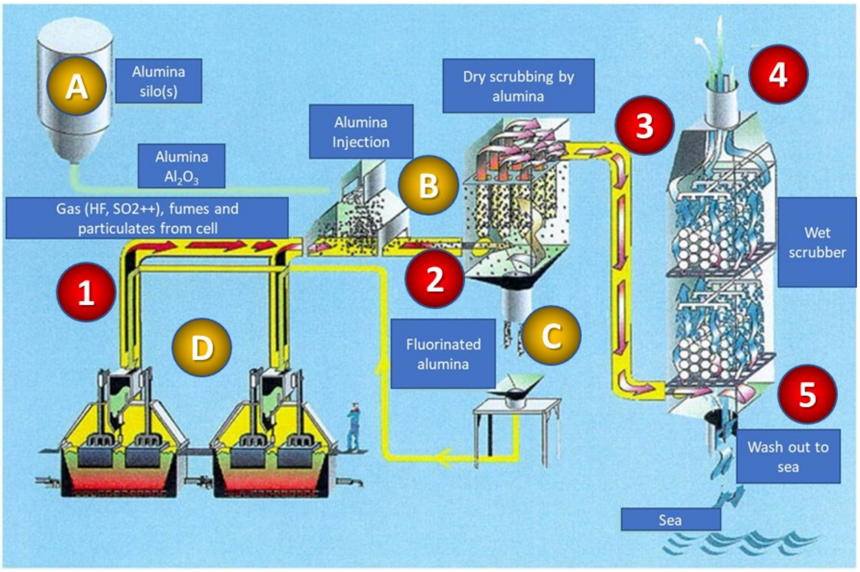


*Figure 1. Flow Sketch of aluminium electrolysis process, with Gas Treatment Centre (GTC).*

GTCs will vary in size, hence the capacity depends on the number of electrolysis cell it is set to serve. This can vary from a few cells (6-20), and all the way up to several hundreds, meaning that the capacity might go from gas capacities of ~200 000 $Nm^3/h$ to ~2 000 000 $Nm^3/h$ at 80 °C.

The GTC facilitating the Hydro pilot for the COGNITWIN project consists of 9 chambers of GE type ABART 600 with IHEX (internal heat exchanger). This gives a capacity of approximately 710 000 $Nm^3/h$ at 90 °C, and an alumina feed capacity above 20 t/h.

## 2.2 Current challenges

Different alumina and ambient conditions influence the evolvement of HF from formation in the electrolysis cells until recovered from the off gas in the GTC. Furthermore, ambient conditions and temperature also beside the electrolysis operation influence the conditions for the recovery of HF from the raw gas by dry scrubbing using Smelter Grade Alumina (SGA). If the SGA is fed flat based on alumina consumption in the electrolysis, the variation in HF adsorbed to fresh primary alumina will have the same variation since the primary alumina feed is constant. This will accordingly influence the cell operation. In Figure 2 we see an example of this HF evolvement and how the concentration in the raw gas changes through time and alumina type used.


*Figure 2. Raw gas HF concentration from a production site (not pilot case)*

Moreover, the conditions in which the adsorption shall take place are influenced by humidity and temperature, hence the grade of achieved adsorption depends much on the raw gas temperature and humidity, se Figure 3. Accordingly, we will seek to keep the temperature condition as constant as possible.

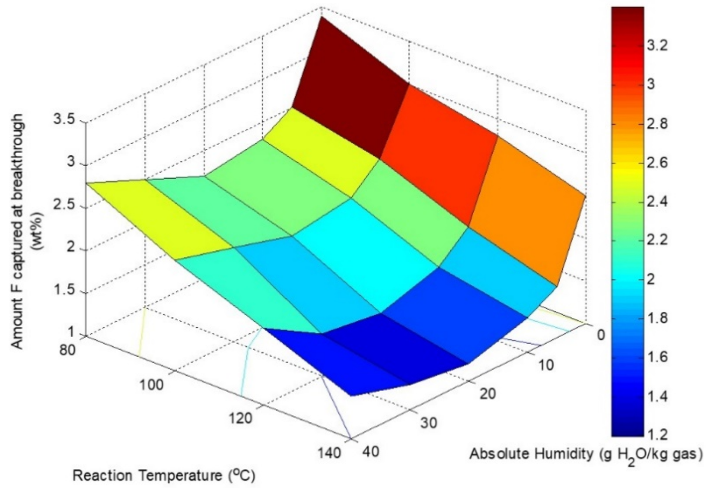


*Figure 3. Adsorption capacity for SGA as function of humidity and temperature (ref. Gordon Elinam Kofi Agbenyegah;"* ***Mechanism and Kinetics of Hydrogen Fluoride Capture with Smelter Grade Alumina",*** *PhD Thesis, University of Auckland, June 2019)*

When exhausting the electrolysis cells, a constant extraction of air mass flow is desired, since it is the air mass flow that convey energy. Since fans operate with actual volume flow and not normalised cubic volume flow rates, a fixed load on the fan will give variation in normalised cubic metre due to temperature. In this, there is fan energy to be saved if one could follow suit with the temperature, se area below blue line Figure 4.

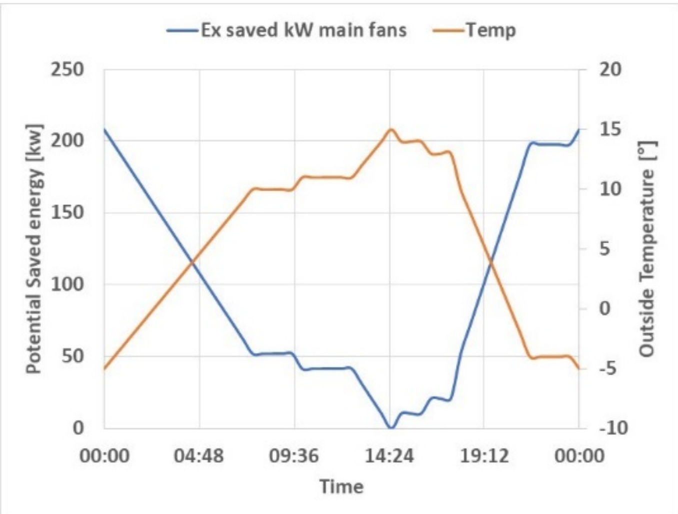


*Figure 4. Generated example of surplus energy usage of constant mass flow ($Nm^3/h$) with set point at 15 °C.*

## 2.3 Pilot specific aim

The specific aim for the cases in the pilot WP 1.1, is to flatten out the amount of adsorbed HF on the alumina fed to the electrolysis cells. Furthermore, reduce any unnecessary use of fan energy by regulate the fans based on needs from electrolysis operations.

## 2.4 Innovation

The innovation of this pilot case, taking a macroscopic view, is to make the GTC as an interactive operating extension of the electrolysis process. In detailed view, the GTC will seek to return the removed HF to the electrolysis with the concentration of adsorbed HF in the alumina as even as possible, and at the same time save energy by providing off gas suction on demand.

## 2.5 IoT platform and architecture in use

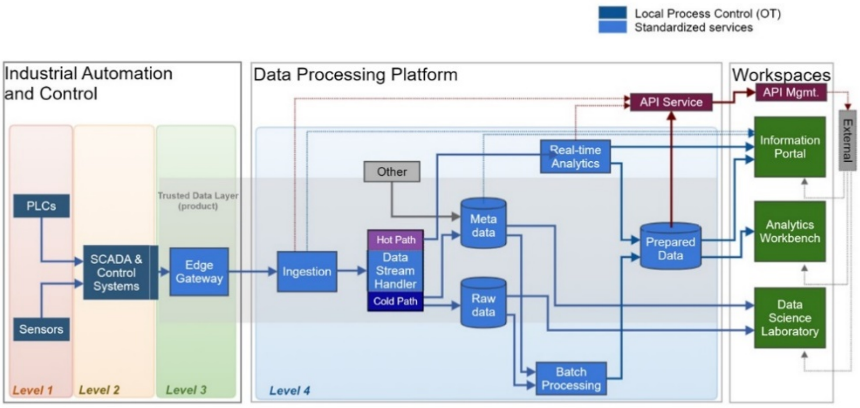


*Figure 5. Conceptual IoT architecture in use at pilot site.*

## 2.6 Current data analytical models in use

As of today, there are no more advanced models in use than simply complying to the alumina consumed. The alumina is fed based on the overall average consumption by production, i.e. approximately 2 times the metal production rate in t Al/h (Case 1). Concerning the temperature in the GTC reactor inlet, the set points are set manually based on experience (Case 2). The regulation of the fans, are as of today put on flat operation, meaning that the fans are in fixed load mode (Case 3).

## 2.7 Description of Data available

Today all vital data is logged once every minute and where the logged values are time averages. Time averaged data is built from instruments measuring "continuously", such as temperature T100, pressure transducers and HF sensor with sampling rate down to 4 Hz. Additional lab data, either on shift basis (1/8h) or day basis (1/24h) is available. It is the initial idea to group the data by 5 min intervals, if not shorter, to reduce the data load. So far there is identified 30-40 variables that will be the preliminary source of information. In Figure 6 the physical origin of some of the variables are indicated.

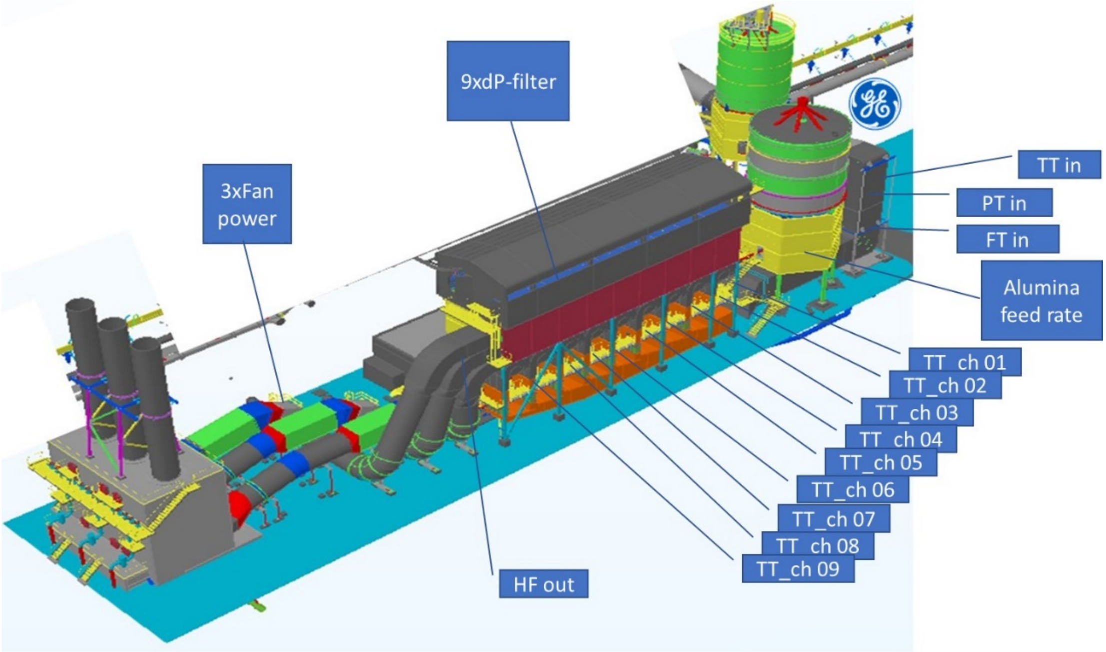


*Figure 6. Rough sketch of where the temperature, pressure, power and temperatures are measured in the GE supplied GTC (Gas Treatment Centre).*

## 2.8 Measurable KPIs and Final impact

Since the pilot is divided into several cases, in which all aim to increase the raw material stability to the electrolysis and reduce the energy consumption of the GTC. Each of the cases are set up with a tangible KPI. These KPIs will play into the overall KPIs in the application.

Case 1. Matched and even distribution of HF to primary alumina feed, by demonstrating primary feed matching HF mass flow (calculated from logged operational data).

Case 2. Keep constant temperature for best possible adsorption, i.e. 90°C ±5°C (from logged data)

Case 3. Reduce the power consumption on the 3x 1 200 kW fans by 5%, measured by logged energy consumption from fans before and after activation of Case 3.

# 3 Elkem Pilot

## 3.1 Introduction to Elkem & Process description

The goal for this project is to develop a dynamic, on-line model for a complete mass/energy balance for the post tap hole processing of liquid ferrosilicon, utilizing measured process data in real-time and continuously updating the optimal process route. The model should consider cost of raw materials, product pricing as well as energy cost and optimize with respect to maximizing the profit.

### 3.1.1 Production of Ferrosilicon

The production of ferrosilicon (FeSi) requires multiple process steps that will be described briefly in the following. A schematic of the production route is given in Figure 7.

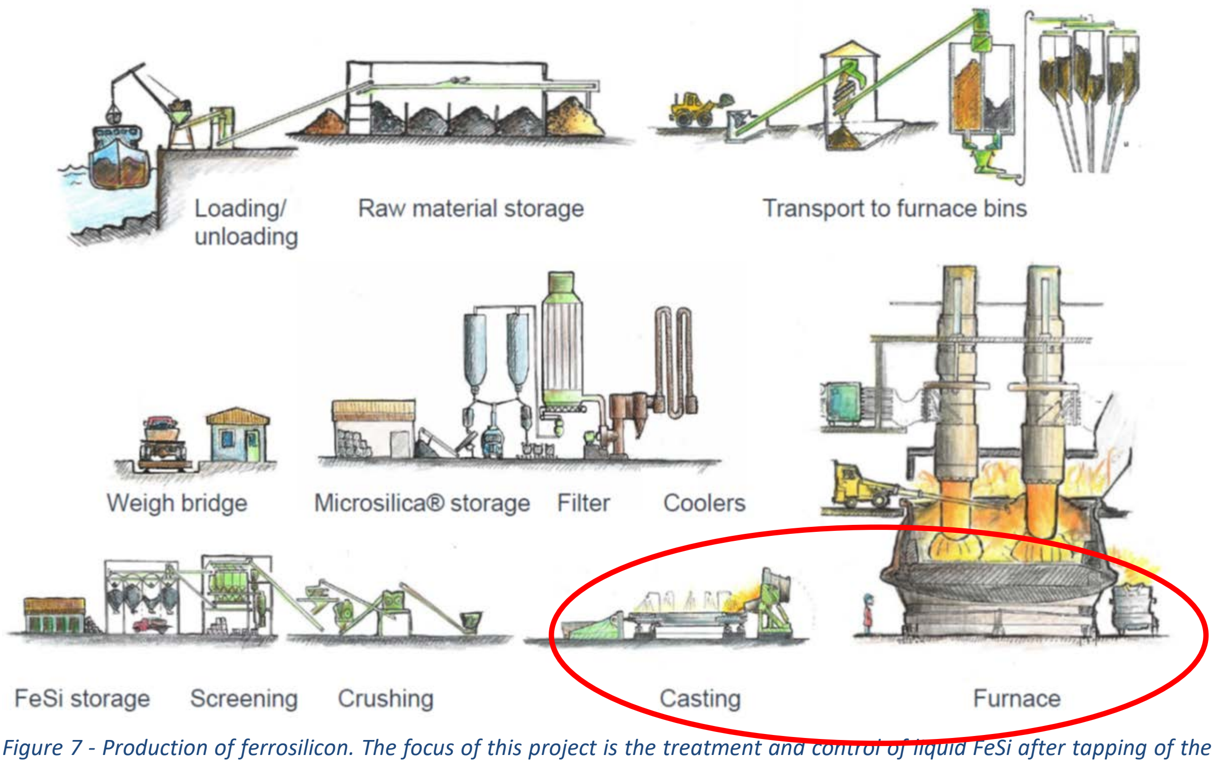


*Figure 7 - Production of ferrosilicon. The focus of this project is the treatment and control of liquid FeSi after tapping of the submerged arc furnace.*

The scope of the COGNITWIN project is to develop a digital twin with cognitive elements for the post taphole process (tapping-refining-alloying-casting), see Figure 2.

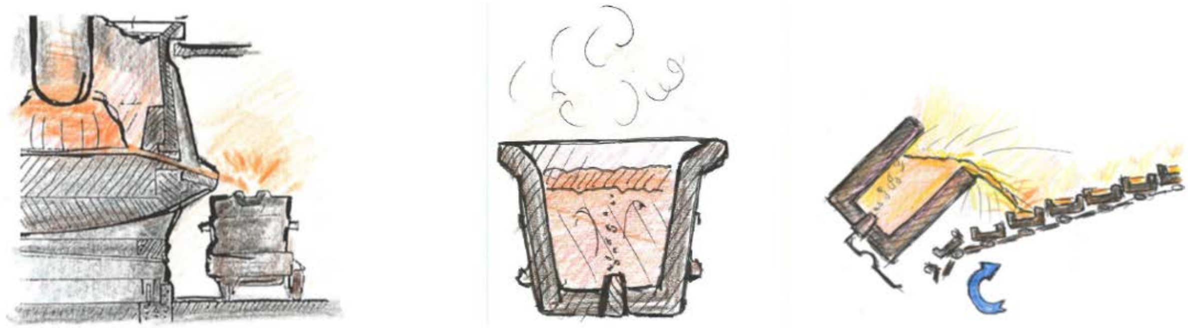

*Figure 8 - Tapping, refining/alloying and casting of ferrosilicon. The ladle may (as here) or may not be equipped with a bottom plug for addition of oxygen/air.*

The output of the digital twin is a dynamic description of the status of the batch process. The minimum requirement is a continuous evaluation of chemistry and temperature. Based on this evaluation, the model should suggest future actions by the operator. The goal is to maximize the post tap hole yield (tonnage cast/tonnage tapped) and meet chemical specifications for every batch. In addition, slag that follows the metal during casting should be automatically detected so that the batch can be downgraded if necessary and not shipped to customer if the slag content is too high. Most customers have an upper tolerance for slag contamination of the product. Preferably we should be able to stop the casting process if slag is detected and make necessary adjustments, for example by checking and modifying the temperature. High temperature during casting will result in a less viscous slag that will have a higher tendency to follow the metal.

### 3.1.2. Tapping

Liquid ferrosilicon is tapped from the submerged arc furnace at fixed intervals depending on the production rate. The temperature of the metal is 1800-2000 °C when it leaves the furnace, accompanied with significant amounts of hot gases and smoke. These conditions are quite extreme and severely limits opportunities to measure key process parameters such as temperature. After leaving the runner the metal falls into a ladle that can hold up to 5000 kg (density of FeSi75 is around 3.1 ton/$m^3$). The tapping time is of the order 15 minutes, after which the taphole is plugged with a semi-automatic plugging machine. In addition to liquid FeSi, there may be some partially reduced raw materials tapped as well in the form of a liquid slag, consisting of $SiO_2$, CaO and $Al_2O_3$, as well as silicon carbide particles.

Key process variables for this part of the process are the chemistry of the liquid ferrosilicon (Fe, Si, Al, Ca), temperature of the metal, mass and chemistry of the tapped metal and slag. At the present, the weight of the ladle is measured during tapping which allows for both the tapping rate as well as the final mass. However, no on-line information regarding slag or temperature is available today.

A sample is taken from the tapping stream with a frequency depending on what is currently being produced. For some qualities, the sampling is done every $4^{th}$ tapping and the result of the chemical analysis is used as initial melt composition for the current batch and the next three batches. Other qualities have a more frequent sampling rate, some every batch.

### 3.1.3 Refining and alloying

After completion of the tapping process, the ladle is transported with truck to the refining station. The temperature is measured, after which the alloying and refining elements are calculated from a pre-defined recipe based on the tap analysis as mentioned in the previous section and added to the ladle. Depending on the target specification, several elements can potentially be added to the ladle by an automatic silo-and weighing system. After mixing and stirring, a final temperature is taken and if necessary, cooling metal is added to adjust the temperature to the pre-defined casting temperature of about 1400 C. A dip sample for chemical analysis is also obtained at this point. This sample is used for reference and will not influence the overall treatment of the current batch.

### 3.1.4 Casting

The ladle is transported to a tilting chair which offers both manual and automatic control of the tilting speed. The ladle is slowly emptied into a runner which leads the liquid metal to the pig caster, which consists of multiple rectangular molds where the typical cast amount is 20 kg/mold. The molds are fixed to a moving belt. At the end of the belt, the molds are turned upside-down and the cast metal falls into a pre-crusher. This marks the end of the post-taphole process.

## 3.2 Current challenges

Durable and reliable sensors must be able to operate in a challenging environment:

- Smoke and dust
- High temperatures (Hot gases and liquid metal)
- Mobile vehicles
- Moving parts of other equipment

The second point on the list is a particular challenge, with the presence of dust and smoke also being very important. In our experience, there are relatively few off-the-shelf technologies than can be applied to the ferrosilicon production process. These can be grouped into contact and non-contact type of sensors.

Today, standard dip temperature measurements are taken for every batch using a lance that is lowered into the melt. This gives a fairly reliable temperature measurement. The temperature sensor can only be used once and must be manually replaced for every sample. A similar method is used to obtain a chemical sample. Temperature and sample by inserting a lance into the melt is a trivial and standard way of sampling for all metallurgical industry.

In some cases, a contact-free measurement can be easier to apply. Elkem has experience with different types of thermal cameras that can both establish a surface temperature as well as a slag/metal ratio based on the different emissivity of the two phases. These thermal cameras come in several variations, where the wavelength of the emitted radiation is particularly important and must be chosen to fit each application separately.

Elkem has also tested various radars with success. This offer a safe and reliable way of measuring the liquid level inside a ladle as opposed to a manual evaluation posing increased risk to the operator.

## 3.3 Pilot specific aim

In the COGNITWIN project we propose to use thermal cameras to obtain information regarding temperature and slag coverage. The information must then be logged and made available in real time for the digital twin. Typically, this requires some infrastructure modifications (cabling, electrical, air supply for cooling), coding and modification of existing computer systems. At the same time, the project is open for testing and evaluation of other potential sensors if they meet the requirements dictated by the industrial environment in which they must operate as well as having a reasonable cost for installation and use.

## 3.4 Innovation

The project will combine new information from thermo cameras and other potential new sensors, applied at the liquid silicon treatment processes, with existing first-principles models and develop on-line models for the tapping, refining and casting processes, as well as an on-line production flow model for this plant section.

By applying digital technologies to the post tap hole processes (tapping into the ladle, silicon casting into moulds), we will enable on-line estimates of the actual silicon flow and its temperatures. This will result in improved product quality and more profitable operation.

## 3.5 IoT platform and architecture in use

There is no IoT platform in use at this plant.

## 3.6 Current data analytical models in use

Elkem has developed a reasonably precise model for the mass/energy balance of the refining/alloying of liquid ferrosilicon. The model includes most of the thermal and thermodynamics that govern phase formation in the system (slag and liquid alloy), the respective amounts, temperature and composition. This model has been used successfully to predict the dynamic temperature and composition of the slag/metal system and has been verified through significant testing at multiple plants in the Elkem system. This work was mostly carried out during the EU-funded project Recoba (2015-2018). The model is implemented in a free-standing software package (Raffsim) that can be run on a single laptop. Currently, this model is not used as decision support for operators but is an expert tool used for analysis and optimization.

As a part of Recoba, an earlier version of the Raffsim model for silicon refining was simplified and adapted for online use (digital twin). The main simplifications were that the detailed description of the reactions within the bubbles resulting from the bottom gas plug were replaced with a simpler description, and that the heat transfer through the ladle wall was simplified. The simplifications were made to increase the calculation speed while retaining sufficient accuracy for temperature and chemistry.

Raffsim has since then been extended to include iron and iron oxides so that simulations of ferrosilicon refining can be carried out. The digital twin will be extended to also account for iron, and it is assumed that the same simplifications that were done previously will still be valid.

The digital twin was originally developed for a different Elkem plant, and it is expected that it must be modified to Elkem Bremanger due to differences in the process between the two plants. E.g., stirring is achieved by rocking the ladle instead of using gas blowing. When the model has been adapted to Elkem Bremanger, parameter fitting and estimation will be performed using historical data in order to achieve the best possible match between the model and the plant.

## 3.7 Description of Data available

There are several process parameters that are recorded during the post taphole process (1.1-1.3). Some of these are immediately available through the plant database/storage system. A list of available parameters is given in Table 1.

*Table 1 – Measured process parameters and relevance for digital twin model.*

| Measurement | Method | On-line model |
|---|---|---|
| **Ladle weight before tapping** | In big truck | Required |
| **Ladle weight before tapping** | Tapping cart, scale on floor | Required |
| **Ladle weight during tapping (dynamic value)** | Load cells on tapping wagon | Useful |
| **Tapping rate(kg/min) - calculated** | Load cells on tapping wagon | |
| **Tapping time** | Manuaul | Useful |
| **Amount of gas through doghouse** | Pitot-pipe in off-gas channel | Not used |
| **Ladle weight after tapping** | In big truck | Required |
| **Ladle weight after tapping** | Tapping wagon, scale on floor | Required |
| **What furnace is being tapped?** | | Required |
| **Switching of ladles** | | Required |
| **Ladle weight before refining** | In big truck | Useful |
| **Metal temperature before refining** | Dip sampling | Required |
| **Chemical analysis before refining** | Dip sampling | Required |
| **Position of metal bath (height from reference)** | In probe for sampling | Useful |
| **Additions by silo system** | Silo load cells | Required |
| **Additions by plunging** | Manual registration | Required |
| **Metal temperature before casting** | Dip sampling | Required |
| **Ladle weight after refining** | In big truck | Required |
| **Lance position injection** | Lance manipulator position | Useful |
| **Average flow fines injection** | Load cells injector | Required |
| **Yield of alloying materials (calculated)** | Silo load cells, chemical analysis before and after alloying | Useful |
| **Refining effect (calculated)** | Silo load cells, chemical analysis before and after alloying | Useful |
| **Grade** | | Required |
| **Recipe** | | Required |
| **Amount cast on belt and delivered to dumper** | Floor scale under dumper | Useful |
| **Metal temperature before hot crushing** | Pyrometer | Useful |
| **Casting belt speed** | Encoder on engine | Not used |

| | | |
|---|---|---|
| **Opening 1.st crushers** | Manually | Not used |
| **Cooling water for belt** | Flowmeters | Not used |
| **Casting thickness in mm (calculated from weight increase truck, belt speed, mould dimensions)** | Floor scale under truck, encoder engine | Not used |
| **Mould temperature (under)** | Pyrometer | Not used |
| **Casting time** | Pyrometer (when hot metal is on the belt) | Not used |
| **Mould wash consumption** | Silo load cells | Not used |
| **Mould wash density** | Densimeter | Not used |
| **Weight increase truck (casting speed) kg/s** | Floor scale under dumper | Not used |
| **Number of sparks extinguished** | Switch on vent | Not used |
| **Pth yield(cast/tapped) (calculated)** | Floor scale | Not used |
| **Chemical analysis (end sample)** | Sampling at end of belt | Useful |
| **Ladle weight after casting** | Stortruck | Not used |
| **Ladle weight after refractory maintenance** | Stortruck | Not used |

## 3.8 Measurable KPIs and Final impact

The most important KPI`s are

1. Post-taphole yield (tonnage cast/tonnage tapped). These values are measured for each batch.
2. Hit-rate on chemical composition (intended product/actual product)
3. Specific energy use (kWh/tonnage cast). The energy is the electrical energy fed to the submerged arc-furnace.

As all these values are sensitive information, we will use a relative value set to 100 for the last 6 months of production for each of the variables. Improvements resulting from the project implementation will be calculated and normalized. Thus, the goal of the project is to

- Increase PTH yield from 100 to 102
- Increase hit rate on intended products from 100 to 102
- Reduced energy consumption from 100 to 99
- Increase lifetime of ladles from 100 to 105

As of today, there are no good dust measurements taken in the plant. Thus, there is no way for the project to properly evaluate the reduction of dust emissions. In addition, none of the actions described in the proposal are aiming to reduce dust emissions. Therefore, there will be no further attempts to quantify improvements in this area.

Similarly, there is no good way of measuring product quality variations (chemistry, microstructure, particle size) so this is not a convenient KPI for determining the success of the project. We will be focusing on KPI 1-3 as described above.

# 4 Summary

For the Hydro pilot challenges and opportunities have been discussed. The idea is, by support of COGNITWIN, to make the Gas Treatment Center an interactive operating extension of the electrolysis process. Hydro has already an IoT platform in operation but have not yet applied advanced data analytical models. The KPIs flagged for the Hydro pilot relates to a controlled and optimal distribution of HF in the secondary alumina feed to the cells, and at the same time HF emissions should remain well below the accepted limits and with a reduced energy consumption for the fans managing the flow of gas through of off-gas from the cells.

For the Elkem pilot plant, the current digitalisation level has been analysed. There are already several useful process measurements that are available for an on-line digital twin. The main output from this deliverable is a table listing all the relevant process measurements currently taken as well as process measurements needed to successfully develop and implement a digital twin of the refining/alloying/casting process during ferrosilicon production. In the following months, thermo cameras will be tested in pilot scale with the purpose of adding additional information to the digital twin. This work will go in parallel with the development of the digital twin and its launching to a "live" environment.