Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes - REVaMP

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Lead Beneficiary: **BFI**

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<u>Dissemination level</u>

PU	public	☒
CO	Confidential, only for members of the consortium (incl. the Commission Services)	☐

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1. About REVaMP

The main objective of the project "Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes" (REVaMP) is to develop, adapt and apply novel retrofitting technologies to cope with the increasing variability and to ensure an efficient use of the feedstock in terms of materials and energy.

For this purpose, existing metal production plants shall be retrofitted with appropriate sensors for scrap analysis and furnace operation. Furthermore, the selection of the optimal feedstock in terms of material and energy efficiency shall be improved by application of appropriate process control and decision support tools. Also, a solid scrap preheating system operated with waste derived fuel shall increase the energy efficiency of the melting processes. To monitor and control the process behaviour in an optimal way, model-based software tools will be developed and applied.

The retrofitting solutions will be exemplarily demonstrated within three different use cases from the metal making industry, namely electric and oxygen steelmaking, aluminium refining and lead recycling. The performance of the different technologies will be assessed, and the benefits will be evaluated in terms of economic and ecological effects, as well as cross-sectorial applicability in other process industries.

2. Introduction and Summary

This deliverable D4.1, "On-line monitoring systems for process behaviour developed", is included in the work package WP 4 "Process Monitoring, Control and Decision Support Systems" of the project.

This report presents the development and adaptation of dynamic process monitoring tools developed in order to predict process quality outputs (composition, temperature) based on the input process data for the three different use cases:

- For the steelmaking use case: Integration of an analytical dynamic process model for the Electric Arc Furnace into the on-line plant monitoring system at Sidenor, to continuously calculate composition and temperature of the steel melt (BFI, SID)
- For the aluminium use cases: Dynamic process monitoring tools based on Data Science methods to improve process understanding by establishing hidden correlations between process data and process quality outputs (EUT, AZT, REF, GHI)
- For the lead use case: Dynamic process monitoring tools based on Data Science methods to improve process understanding by establishing hidden correlations between process data and process quality outputs (CAR, EXI)

3. Process on-line monitoring for steelmaking use case (BFI, SID)

This chapter describes the implementation of the dynamic EAF process model as on-line monitoring tool for the steelmaking use case at Sidenor. The model is based on energy and mass balances and was described in detail in Deliverable 2.2. Furthermore, the accuracy of the model calculations was improved and evaluated based on new data obtained from the implemented monitoring application.

3.1. Integration as on-line process monitoring tool at Sidenor

The model-based on-line monitoring solution with the dynamic process model is implemented at Sidenor according to the scheme in Figure 1. A model shell was developed that uses process data (e.g. electric energy, burner gas, oxygen flow rate, etc.) stored in a data base to initiate the heat state calculations in the model kernel via an interface class. The calculation results are returned to the model shell and written back into the data base in time intervals of one second. Simultaneously, logging files are created on the local machine that are used to evaluate the model's accuracy and to optimize the model parameters with the help of off-line tools. Prediction calculations for the heat state evolution in further treatment and control set-point calculations will be developed in the next step and will be described within Deliverable 4.2.

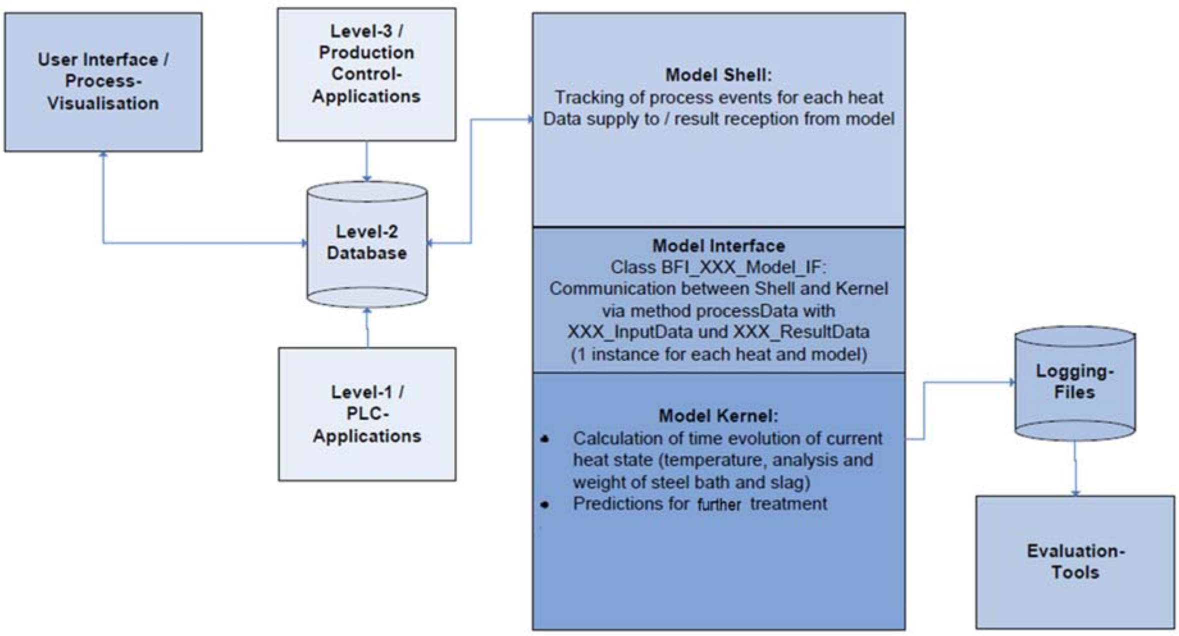


Figure 1: Deployment scheme of dynamic process model at Sidenor.

To provide the monitoring functionality to the plant operators, a user interface was developed that displays the model input and output data during EAF operation (Figure 2).

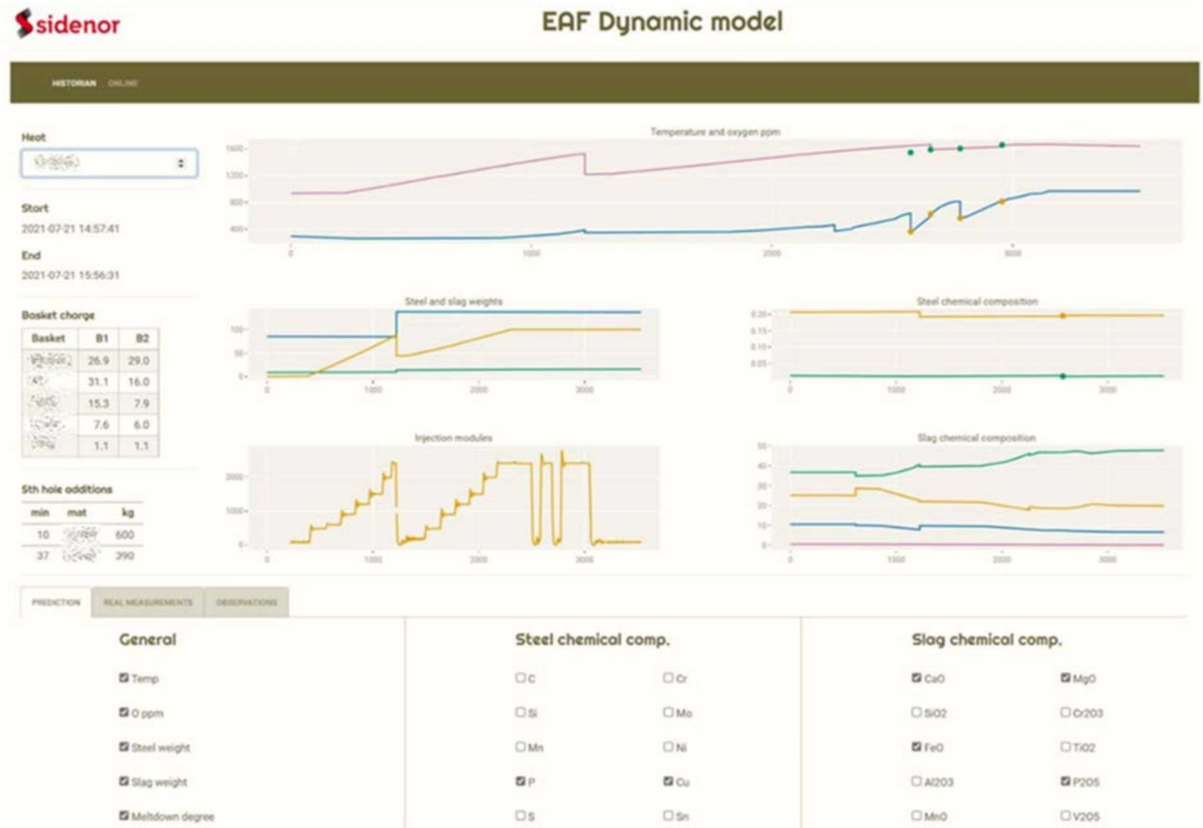


Figure 2: User interface for process monitoring with dynamic process model at Sidenor.

Charged materials, current operating conditions and the heat state in terms of melt temperature as well as steel and slag weight and composition are clearly visualised by trend lines. A checkbox menu lets the user decide on which information shall be displayed to improve clearness of the GUI. In addition to the live data, historical heats can also be loaded and visualised in order to analyse the process and model performance from past EAF operation.

3.2. Model parameter tuning and evaluation of calculation results at Sidenor

In Deliverable 2.2 the dynamic process model's parameters were fitted to the available data of roughly 150 heats. As this data set was not sufficiently representative, another tuning session was performed based on the data of 700 new heats (May/June) and validated against an additional data set of 700 heats (June/July) from the implemented background application.

Furthermore, improvements in the online data acquisition were performed, resulting in more (> 90 %) complete and representative data compared to the earlier stage (60 %). The modelling results and accuracies are shown exemplarily for temperature as well as phosphorus content as critical liquid steel quality indicators in Figure 3 and Figure 4. The accuracy of further considered steel and slag components is on a similar level. The accuracy evaluation is based on the metrics: mean error, mean absolute error (MAE) and standard deviation.

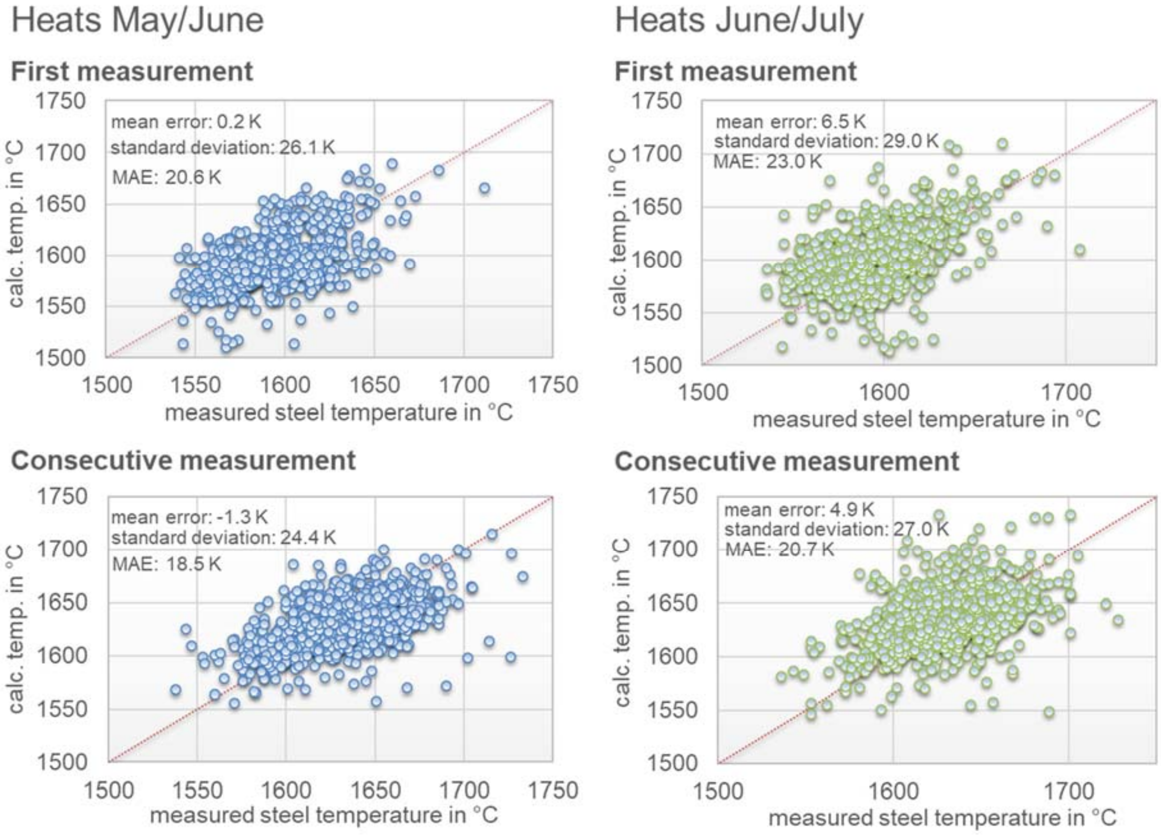


Figure 3: Calculated and measured steel temperatures for the fitting and validation data set. First and consecutive temperatures are depicted separately, and evaluation metrics are shown.

As already described in Deliverable 2.2 the first and consecutive temperature measurements are evaluated separately due to the model's adaptation to the measured value, compensating for uncertainties during the melting phase of the EAF process. With a MAE of around 20 K a good overall accuracy is achieved for the first data set (May/June) that was used for fitting the dynamic process model. Even for the validation data set (June/July) the MAE only drops by 2 – 2.5 K, indicating that the model is not overfit and suitable for robust and reliable process monitoring of future heats.

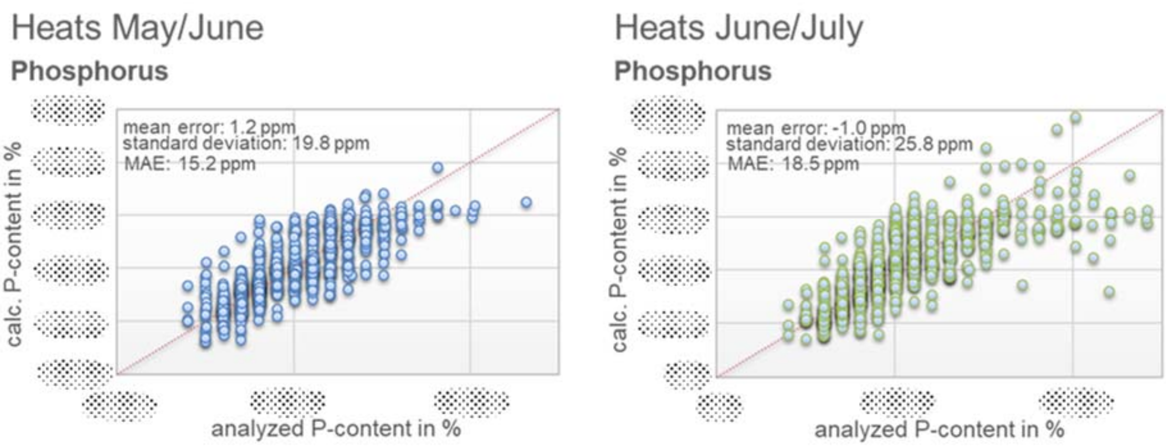


Figure 4: Calculated and measured phosphorus concentration in the liquid steel phase for the fitting and validation data set with evaluation metrics.

A new model extension developed within this project is the detailed phosphorus content modelling for the EAF process, which was described more precisely in Deliverable 2.2. With a MAE of 15.2 and 18.5 ppm for the two data sets it is concluded that the modelling was successful and captures the phosphorus behaviour very well. In the validation set higher phosphorus concentrations with increased deviations are observed, but these are of less interest for the phosphorus forecast application since the heats of high-quality steel grades should not reach those levels.

Overall, the accuracies suggest a reliable use of the dynamic model as process monitoring system and will serve as a solid foundation for the model predictions and decision support system to be developed within Deliverable 4.2.

4. Dynamic monitoring tools for aluminium use case (EUT, AZT, REF, GRU)

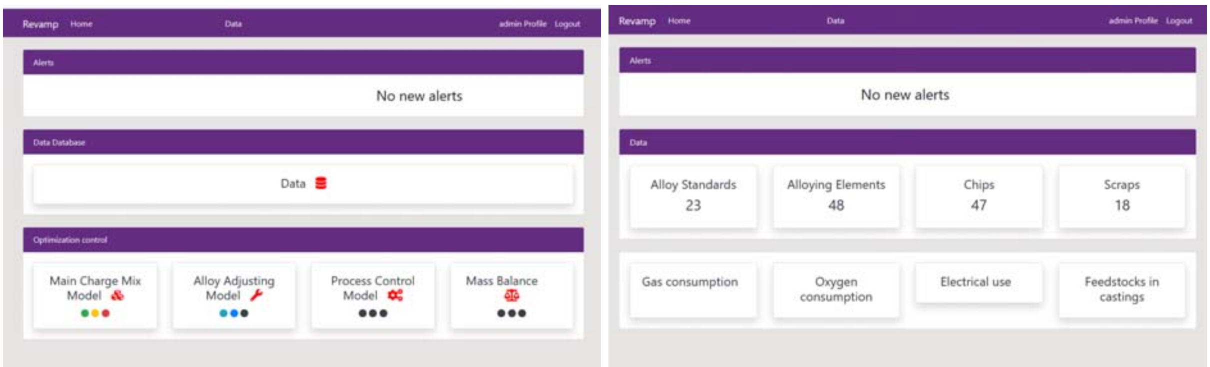
4.1. Description of the developed tools and applied methods

4.1.1. Data Processing and Modelling Dashboard (EUT)

In order to develop the monitoring and control tools that **Grupal Art** requires, EURECAT has been working into a robust and flexible framework that will allow the development of the different models and solutions in a Data Processing and Modelling Dashboard.

The dashboard stores and shows the historical data of the Grupal Art process, as well as the different analysis models developed during this project. It will be employed by the end-users in Grupal Art, so it should be a flexible, intuitive and user-friendly tool.

The dashboard is already operating using a web-based solution. For access, it is necessary to provide the user name and password information. The home page, shown in Figure 5(a), contains the 5 main services: the data storage, the first and second optimisation modules (Main Charge Mix model and Alloy Adjusting model), the Process Control model of the furnace and the Mass Balance.



(a) (b)

Figure 5: a). Home page of the dashboard. b). Secondary page with the information of the data available.

The secondary page with the different datasets is shown in Figure 5(b), where all the information of the data available in Grupal Art is stored. The first line contains the list of alloy standards and the feedstocks ready to use in the plant (Alloying elements, Chips and Scrap).

The second line includes the information related to castings already performed, gas and oxygen consumption, electrical use and the feedstock loaded for each case.

In the table of aluminium alloy standards, shown in Figure 6(a), the maximum and minimum percentage of each element permitted by the standard is established for each alloy. Figure 6(b), (c) and (d) exhibit the tables of the alloying elements, chips and scraps. All of them contain the metallic yield, price, minimum weight and composition. The dashboard allows to delete, edit and add new feedstock materials or alloys. In the case of the scrap, the table also contains the date when the material arrived in the workshop, the weight available and the location. In addition to the options of delete, edit and add new scraps, the dashboard allows to visualize the composition of the scrap by clicking the 'Plot' button. Figure 7 displays an example of it. The pie plot illustrates the composition of the selected scrap except for the aluminium.

(a) (b) (c) (d)

Figure 6: Page with the tables of (a) standards, (b) alloying elements, (c) chips and (d) scraps.

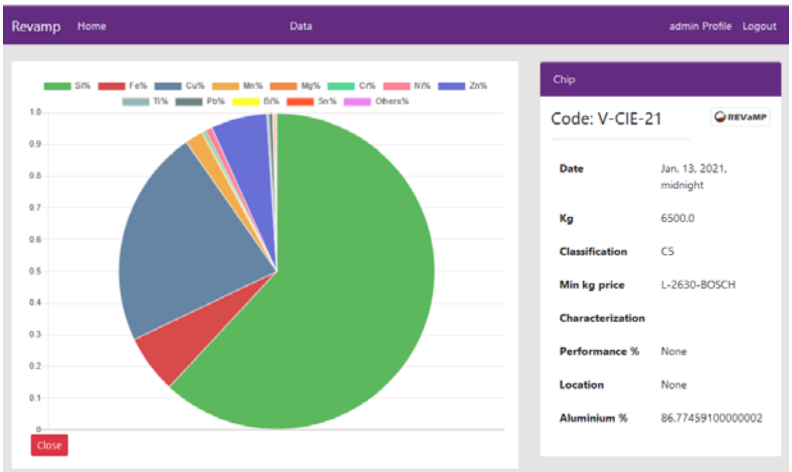


Figure 7: Visualisation of the V-CIE-21 chip.

In Figure 8 an example of the plots with information on the furnace consumption figures is presented. In this case, the plots show the maximum temperature, average temperature, max and minimum pressure of the gas used for a given batch. This information will be stored and visualised to feed the Process Control Model.

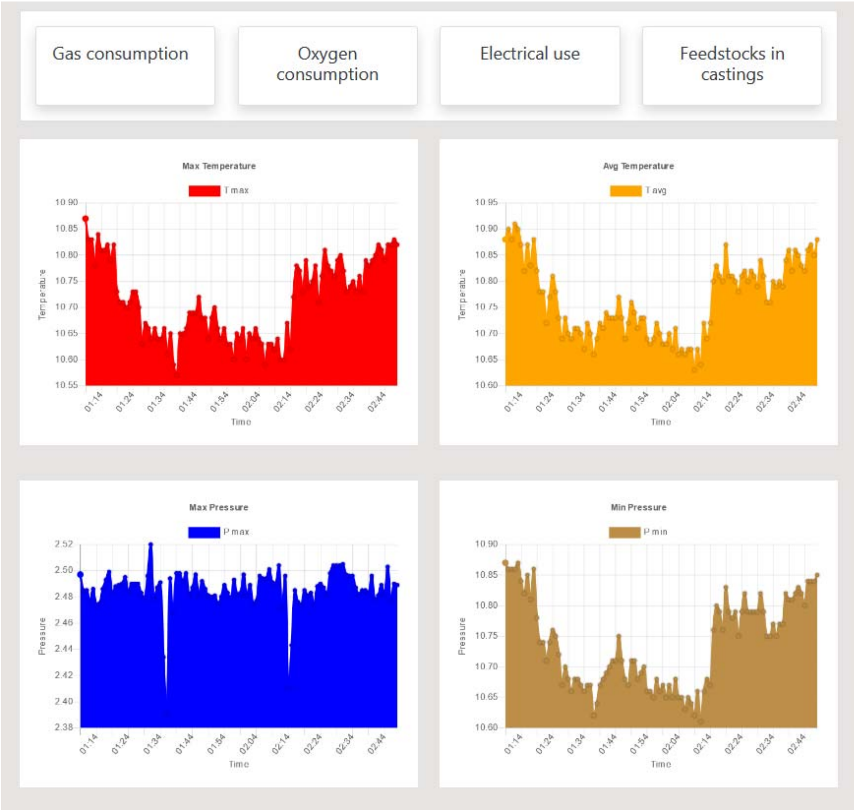


Figure 8: Visualisation of the parameters of the gas.

The dashboard will facilitate the use of the four models developed during the whole REVaMP project. The Main Charge Mix Model is being developed in WP2, the first version was introduced in Deliverable 2.1, and it will be upgraded in the following stages. The first version is accessible on the home page of the dashboard as shown in Figure 5. The input data that the user should introduce are the weight of the alloys and the security margins to apply to the standards. The model will create three .csv tables with the following results: the weight of each feedstock material, the unitarian weight of each feedstock material (taking into account the minimum weight available) and the composition of the final batch. The Alloy Adjusting model and the mass balance will be implemented during Task 4.2 and explained in Deliverable 4.3.

Finally, the Process Control Model pipeline is presented in Figure 9. The design of the algorithms required for the prediction of the performance of the furnace will be done in Task 4.3 and explained in Deliverable 4.4. In this model, the information acquired in the furnace for each batch (gas consumption, oxygen consumption, electrical use and feedstock materials added) will be processed to perform a feature engineering analysis. This analysis will acquire the most significant information to feed the different algorithms proposed to proceed with the final process control analysis.

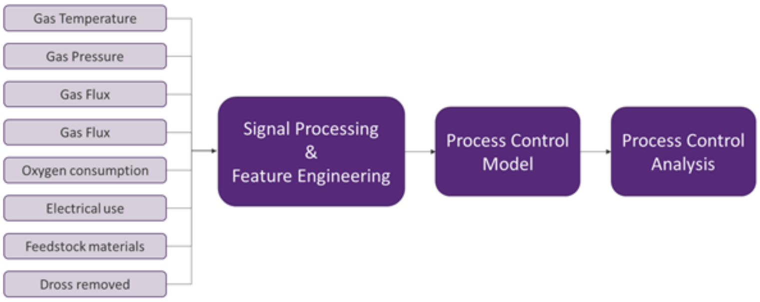


Figure 9: Pipeline of the Process Control Model.

The technical aspect of the dashboard and the infrastructure of the system

The products, technologies and tools used to build the dashboard are the following:

- Python, HTML5, CSS3, JQUERY
- Django: Django is a Python framework for web application development and will be the main framework for all the development of the application. This framework allows to develop or import independent modules with specific functionalities and interconnect them to build the functionalities.
- SQLite: is a relational database management system (RDBMS) contained in a C library. SQLite is not a client–server database engine. Rather, it is embedded into the end program.
- Chartjs: Django Chartjs helps to manage charts in the Django application. This is compatible with Chart.js and Highcharts JS libraries.
- AJAX: AJAX is a client-side technology used for making asynchronous requests to the server-side - i.e., requesting or submitting data - where the subsequent responses do not cause an entire page refresh.

The modules developed in this project are:

- Django module user: This module is used to handle both authentication and authorisation (authentication verifies that a user is who they claim to be, and authorisation determines what an authenticated user is allowed to do), It also handles user registration, login, and logout. The module is presented in Figure 10.
- Django module dashboard: This module is used to manage the dashboard views, to show tables (chips, scraps, alloy standards, alloying elements...), to draw graphics with Chartjs (gas and oxygen consumption) and to manage user orders (execute main charge mix model, alloy adjusting model, process control model, CRUD operations of stored data...). Figure 11 illustrates the module.

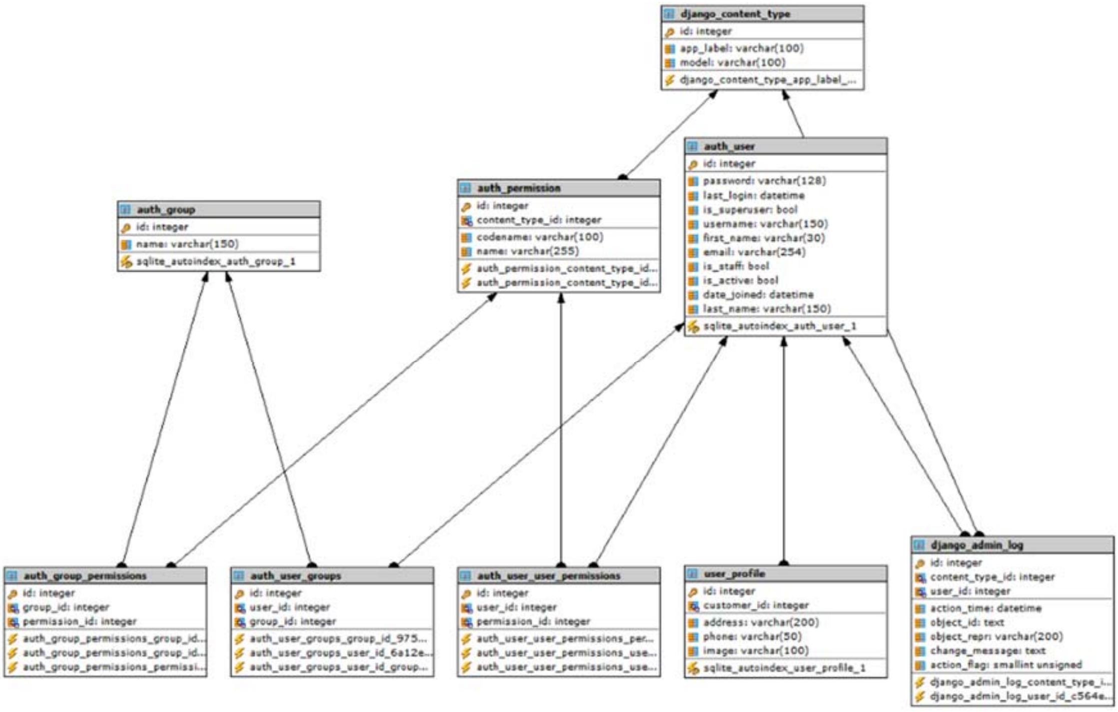


Figure 10: Data model of the user module.

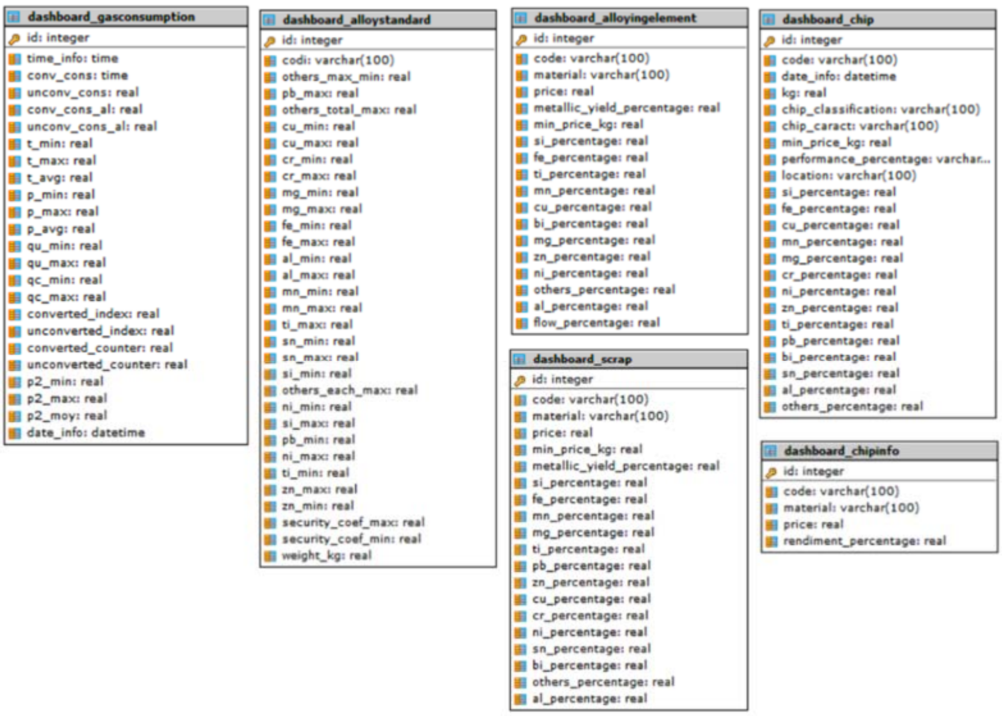


Figure 11: Data model of the dashboard module.

4.1.2. Sentinel Manager for on-line monitoring (AZT)

In case that a prediction of the quality of the manufacturing process is needed to make the right decisions at the right time, Sentinel is the tool needed in the manufacturing process. Sentinel can provide the following features:

- **Monitoring.** Those people responsible for making decisions will obtain data collected from each area of the manufacturing plant in a friendly way. In addition, new information could be created by combining all data gathered into a new one, which will provide an added value when it will be employed for following prediction and control tasks.

- **Analysing.** Based on data gathered in real time and the aggregated information generated, Sentinel works in control tasks thanks to the ability to make predictions and gives alerts regarding the defined targets. In order to carry out this work, Sentinel uses a multivariable analysis based on Artificial Intelligence techniques.

- **Managing and improving.** Working as a guard, Sentinel is able to detect when a problem could appear, being responsible for calculating the best corrective actions that will be transformed into recommendations to solve and prevent the appearance of problems during the manufacturing process.

This solution or system was developed by AZT as the result of the research in technological solutions than can be applied to the manufacturing processes. Although Sentinel is a big tool for optimisation and control, the work developed for this deliverable is just focused on the monitoring tasks. Hence, for this purpose it is used with the capability of working as a data distribution system. More accurately, Sentinel provides the right data, in the right hands and at the right time, being a powerful tool for developing monitoring tasks in the plant.

The defined architecture provides an easy way to adjust this development to the specific goals or objectives defined by the final user. In this way, a new version of this software was developed to be adapted to the new aluminium use case. Specifically, dashboards and data gathering tools were created to meet the requirements of the **Refial aluminium** use case.

In the same way, the advanced design of this tool allows to be connected to already deployed systems in the final use case. This is possible because Sentinel includes several drivers or agents for data gathering and managing for the most extended databases and storages. These small agents, which standardise the data to flow through the system, have been adjusted and adapted to be able to deal with the Refial use case.

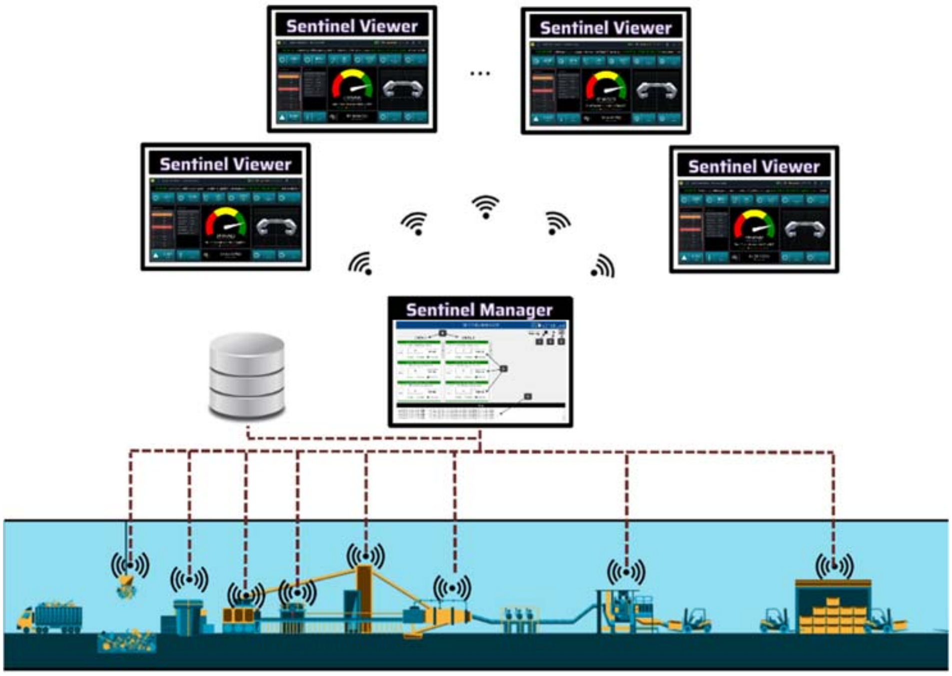


Figure 12: Overview of Sentinel monitoring tasks.

Despite of the fact that the current version of Sentinel for the Refial use case is new and it has been never designed and developed before, this software was successfully deployed in previous usage scenarios such as it is shown in Figure 13.

Figure 13: Examples of Sentinel deployments for other different metallurgical processes.

Specifically, the previous examples are from:

- *Fagor Ederlan Markulete*: Iron foundry / Automotive - Sentinel application demonstrator for process monitoring and prediction of several critical defects in brake disc production.
- *Alcorta Forging* - Forging Steel - Predictive application deployment as a demonstrator focused on avoiding defects associated with the wear of components needed in the manufacturing process.

4.1.2.1. Sentinel Architecture

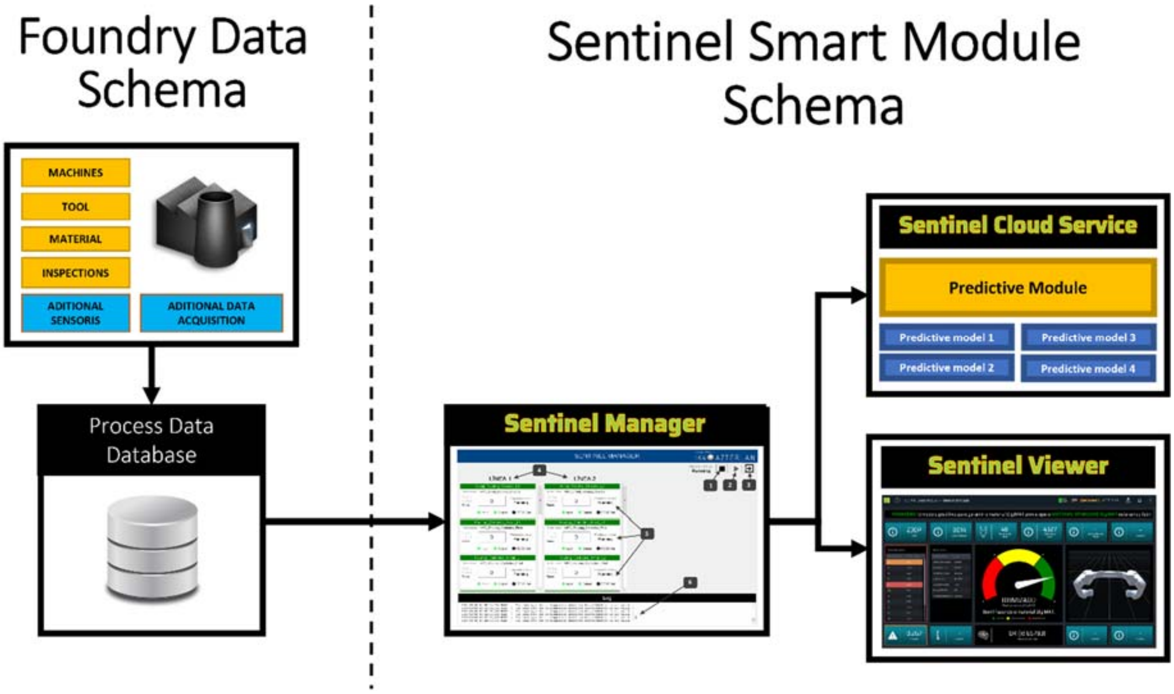


Figure 14: Sentinel architecture.

Sentinel Modules

The Sentinel system consists of the following applications or components that work collaboratively to achieve a common optimisation goal. Please, take into account that not all parts will be developed for monitoring tasks, nevertheless, they all are described in this document. Later, the final development will be included in further deliverables.

Sentinel Manager:

The manager is a desktop application that is responsible for managing the information and making the predictions (in other words, it decides when something must be done) of the installed predictive models. The version for the Refial use case is shown in Figure 15.

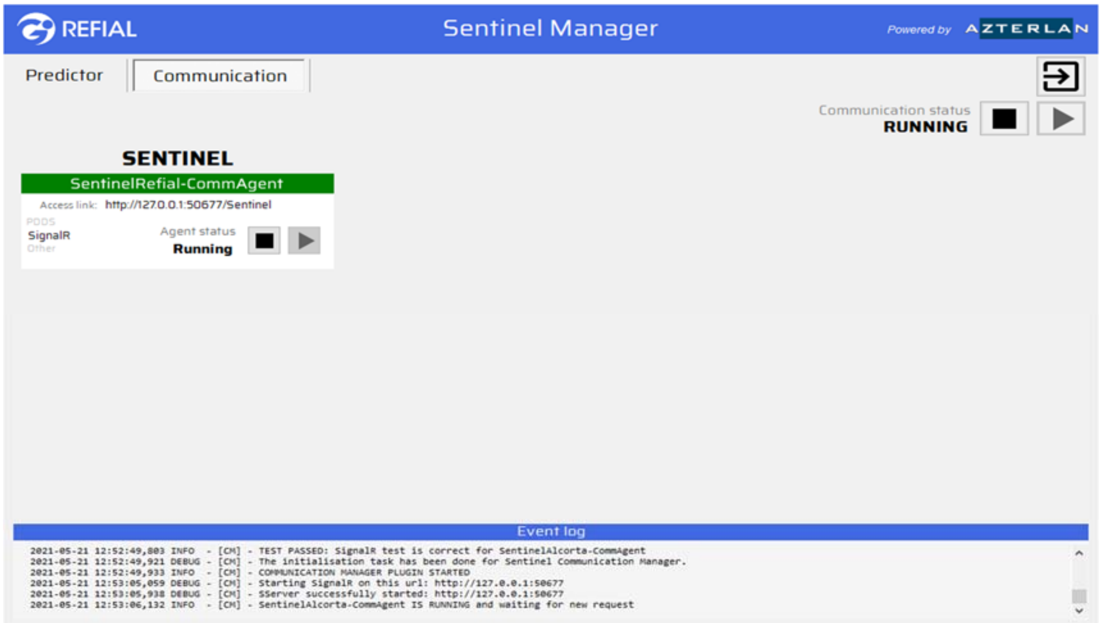


Figure 15: Sentinel Manager Developed for the Refial Use Case.

Regarding *Predictive Functions,* Sentinel Manager is responsible for making artificial intelligence predictions. Sentinel Core retrieves the data located in the process databases in the correct moment and sends them to the Sentinel Prediction Service via WCF (Windows Communication Foundation). When it finishes the prediction, it returns the result to the Sentinel Manager, and it stores the result in the internal Sentinel database. Moreover, this data will be used to be shown in the visualisation. This part will be more accurately discussed in Deliverable 4.2 that is totally focused on controlling the manufacturing process.

This module or component also handles monitoring tasks and information management functions. Hence, with the aim of having clients with an updated information in real time, Sentinel Manager is responsible for retrieving the data from data gathering agents, sending it to the client via SignalR (explained later in *Sentinel Communication* section), preventing clients from directly accessing the database or other data sources and guaranteeing its security. SignalR technology allows information to be sent to all clients without having to wait for the client to make the request. This information is only sent if the value has changed, which minimises network traffic comparing it to other systems that make queries frequently.

The minimum requirements for this software are the following ones:

- Operating system: Windows 8 or higher. Windows Server 2012 or higher.
- .NET Framework 4.5
- DDS access
- Microsoft SQL Server
- Use port 45000 to advertise SignalR services. This port is configurable.
- A license file is generated for each installation

Sentinel Cloud Service

This is an application that is installed in different ways, for instance, as Windows service or in a Web Server, so it does not have a visual interface. It has a warehouse with the predictive models implemented. Communication between both parts is done through the REST API prepared, allowing to communicate through different implementations, programming languages or ways. This last part will be improved in Task 4.5, creating a new and more powerful service that can be easily integrated with third-party models developed by other REVaMP Partners.

The expected requirements are the following ones:

- Operating system: Windows 7 or higher. Windows Server 2008 or higher.
- .NET Framework 4.5
- Access to the computer where the Sentinel Core application is located.
- Recommended 2-core processor and 8 GB of RAM
- Use port 80 to publish REST services. This port is configurable.

Please, note that to optimise the performance of predictions, it is recommended to install them on the same computer as Sentinel Manager, reducing the communication delays between them.

Sentinel Viewer

The core of the Sentinel Viewer Application is developed in Unity that, through different widgets, shows the data from the database or network in real time. The data is provided by the Sentinel Core server through SignalR technology. As many dashboards as necessary can be developed, such as it is displayed in Figure 16, Figure 17, and Figure 18 for the Refial use case.

The requirements of the PC are the following:

- Operating system: Windows 7 or higher. Windows Server 2008 or higher.
- .NET Framework 4.5
- Access to the computer and port where the Sentinel Manager application is located.
- Recommended 2-core processor and 4 GB of RAM

Figure 16: General visualisation for the Refial use case via Sentinel Viewer.

Figure 17: Metal Alloy Quality visualisation via Sentinel Viewer.

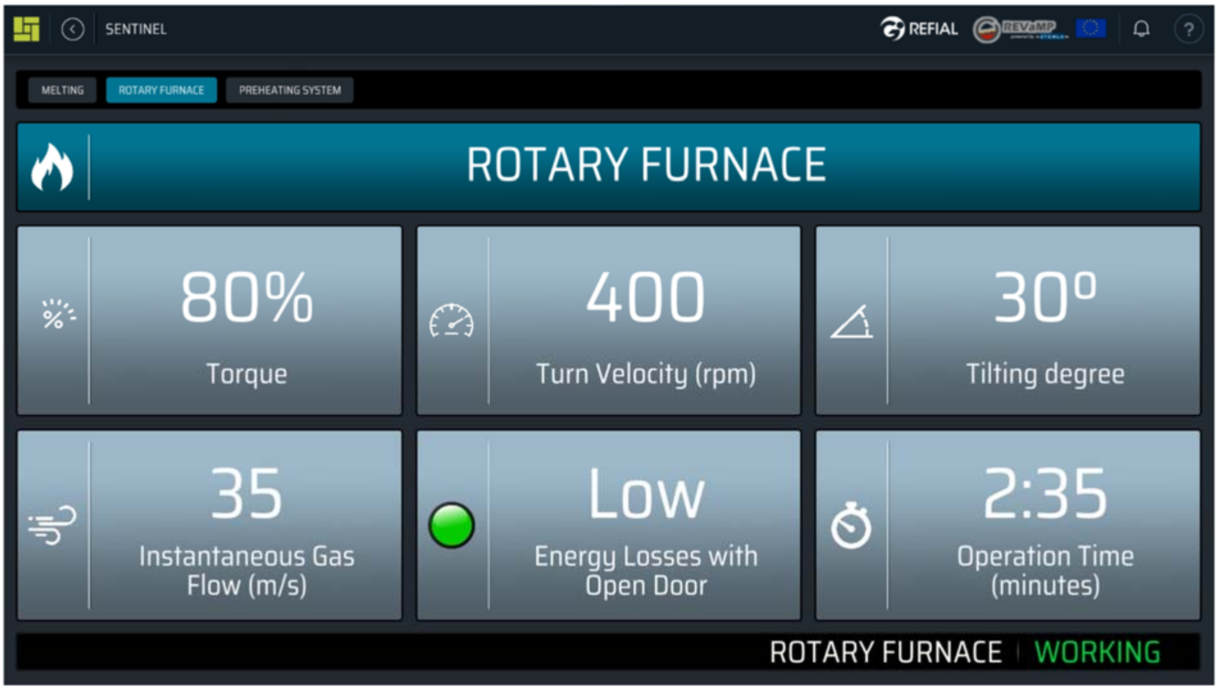


Figure 18: Rotary Furnace visualisation via Sentinel Viewer.

Sentinel Communications

Given the initial architecture of the Sentinel system, different ways of communication are used between the different entities that were shown before. Specifically, it uses (i) a real-time data distribution system, which includes information security, for transferring information between the data gathering agents and the Sentinel Manager, (ii) direct access to Databases for reading and storing data from data gathering agents and Sentinel Manager, and (iii) SignalR for the distribution of monitoring information between Sentinel Manager and defined visualisations.

All these communication methods will be described below.

Data Distribution System (DDS):

The real-time monitoring and processing platform for the use case of Refial will work with different technologies: (i) Data Distribution System (DDS) and (ii) Information Capture and Management System; thus, allowing all possible options to facilitate tasks of correlations and communications of information in real time. Using a system similar to the following would greatly facilitate the addition and removal of systems or agents that have to process data of this type.

Specifically, the ad-hoc platform developed is called PDDS (Production Data Distribution System), which allows to use the characteristics of quality of service (Quality of Service), information security and allowing the architecture of publishers/subscribers.

The current PDDS implementation makes use of the .Net Framework, therefore, the agents that are developed and want to use it, for now, must have been developed also using this platform.

A DDS is an API specification that defines the protocol or form that allows to retrieve information and communicate it from one point to another. Specifically, it is a *wire-protocol* since what is expected is that it can interoperate between more than one application. The use of this type of communication allows defining the data-centric architecture for the publisher/subscriber architecture, connecting anonymous information providers with also anonymous consumers.

Like Service Oriented Architectures (SOA), DDS promotes the loss of matches between the components of a system. Thus, a distributed application consists of only two types of profiles, on the one hand, the consumer of information and, on the other hand, the generator or publisher of information. It should be noted that entities can assume both roles, but within the only pair of roles that are counted on in this communication; and even, each one of the entities can be totally separated from the other, for example, working in different address spaces or even being located in two different computers.

In DDS, data providers publish typed data streams that allow them to be identified through a Channel ID or a Name for that channel. This name is what will be called communication topics. Thanks to the use of these communication topics, the entities that want to receive this information will be able to indicate what they want to subscribe to. For a specific application, a DDS is represented as data-bus software in its architecture.

A DDS system focused on data with publisher/subscriber architecture allows that the components are decoupled in space (i.e., providers and consumers can be anywhere), in time (i.e., the delivery of data can be done immediately after publication or later), in flow (i.e., quality of service (QoS) can be specifically controlled), on platform (i.e., providers and consumers can rely on different implementation platforms and programming languages based on .Net API provided), and in multiplicity (i.e., there may be multiple providers and consumers within the same communication topic).

Figure 19: Data Distributions System (DDS) diagram.

Entities of a DDS

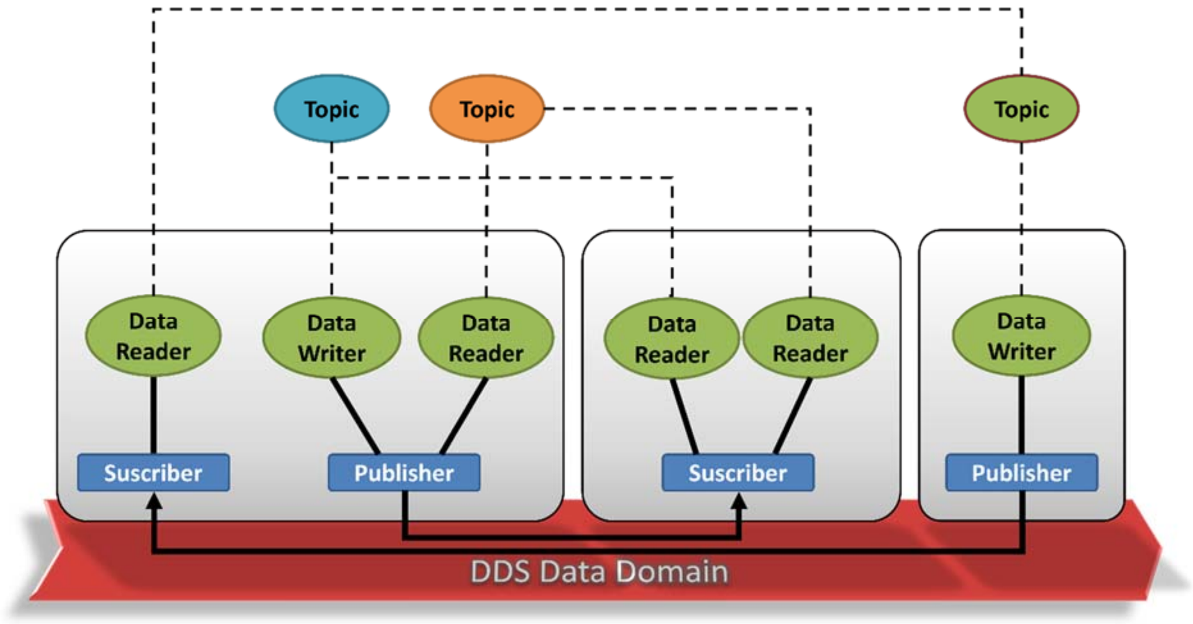


Figure 20: DDS Data Domain Management Diagram.

- *Domain:* The domain is the basic construction that allows joining each of the individual applications for communication. A distributed application can choose to use a single domain for its data-centric communications or define multiple domains, providing developers with an easily extensible and scalable way of communication over time or segregating it to simplify it across different systems. Everything that is published within one domain will not be received by the subscribers of the other domain, thus keeping them separate.
- *Participant:* an application uses an object called “Domain Participant” to represent its activity with the interested domain.
- *Data Writer (DW):* it is the main access point for an application that wants to publish information in a DDS data domain. Once it has been created and configured with all the communication information, the application only needs to make a call to publish the data.
- *Publisher:* this entity is a virtual container that groups together all the individual Data Writers. In more complex systems it would allow us to modify all the writers simultaneously.
- *Data Reader:* in this case, it is the main access point to retrieve the data that the subscriber is receiving.
- *Subscriber:* like the publisher, it is a virtual entity that allows all individual data readers to be grouped together. In the most complex cases, it could be generated and configured to allow all these data readers to be configured in a centralised way.
- *Topic:* provides the basic connection point between publishers and subscribers. The topic given by a publisher in a node must completely match the topic that the subscriber has associated with; otherwise, the message would not reach that subscriber and communication would not take place.

How DDS works

Regarding the structure of the DDS the following can be explained:

- All DDS communications are related to a specific communication domain.
- A domain can be organised into partitions.
- Partitions can be used as elements of organisation of data flows.
- Topics can be published or subscribed through one or more partitions.

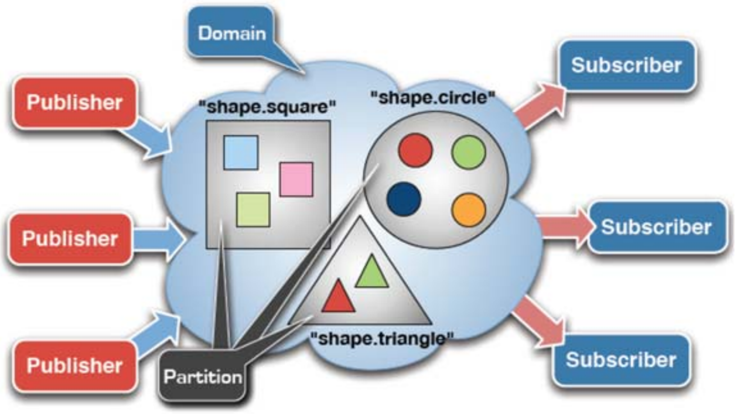


Figure 21: DDS Example.

SignalR:

Creating an application using the usual tools that mixes the Internet, asynchrony, and multiple users collaborating and interacting at the same time can cause us some headaches. This is because mainly the protocols that support the web are based on a synchronous client-server model: one or more clients make a connection to the server and transmit an action to be carried out, it processes it and returns the response, closing connection immediately.

A priori, there is no way for the server to be the one that notifies clients about state changes, unless they use a polling mechanism. This fact means that they are continuously establishing connections with the server to see if there are any new events to follow. Consider: the ideal would be to use a persistent connection, always open, between client and server, which would allow sending and receiving messages and events in a bidirectional way.

Today there are multiple solutions that allow solving the limitations of the protocol, those included under the name Server Push notifications or Comet. In them, taking advantage of the existing resources in the protocols used to create, or at least simulate, this continuous open channel between client and server using polling, long polling, HTTP streaming, and other devices.

Thus, SignalR appears as an abstraction offering the vision and advantages of a connected environment in which we can communicate client and server bidirectionally, asynchronously, and with simplicity. SignalR makes it seem as if client and server are connected continuously and facilitates sending of bidirectional asynchronous messages between both ends.

With SignalR, a virtually always-open connection is established. In this way, on the server we are able to detect (i) when a new client is connected, (ii) when it is disconnected, (iii)receive messages from them, (iv) send messages to connected client, and so on. In summary, everything we may need to create multi-user asynchronous applications.

4.2. Application at Grupal Art

4.2.1. Data provided by Grupal Art

In order to optimize the performance of the aluminium casting process, Grupal Art has provided several data sets, all of them in Excel format.

- Alloys: The list of alloys that are used to cast with adequate standards.
- Alloying elements: List of alloying elements available in the workshop, where the composition, price, performance and minimum weight is specified.
- Scrap: List of scraps available in the workshop, where the composition, price, performance and minimum weight is defined.
- Chip: List of different chips that Grupal Art have acquired in the last month. Unlike the alloying elements and scrap, the types of chips available in the workshop differs every month, so this list has to be updated. The date of acquisition, the weight, the classification of the chip, the minimum weight, the performance and the composition are described in the provided tables.
- Casting: Grupal Art recorded different parameters during the casting of a batch: the name of the final alloy, the feedstock materials introduced in the furnace and the weight, the amount of dross removed and the composition of the mixture in the furnace in every filling step.
- Furnace: During the casting process, the temperature, pressure and flux of the gas are recorded.

4.2.2. Integration of tools

The Data Processing and Modelling Dashboard will be deployed in Grupal Art facilities by means of a Software Container to guarantee an easy deployment and maintenance. Docker is a well-known set of platform as a service product that uses OS-level virtualisation to deliver software in packages called containers. These containers are isolated from one another and can incorporate different software, libraries and configuration files; they can easily communicate with each other through well-defined channels.

4.3. Application at Refial

4.3.1. Data provided by Refial

The system to communicate information based on a DDS development is different to usually employed systems, therefore, due to its data-based approach and not an entities-based one, the strict definition of the information must be carried out.

Currently, for the implementation of the communication platform based on a real-time data distribution system, a single domain will be taken into account. This domain is what is known as the real world. However, there remains the possibility of launching a second domain that focuses on the field of simulation of what happens in the plant (thinking in AI and Control tasks). Despite the possibility, the current scope of this deliverable will focus only on the part associated with the real world. Thus, in this domain, all measurements and values will be collected from the plant.

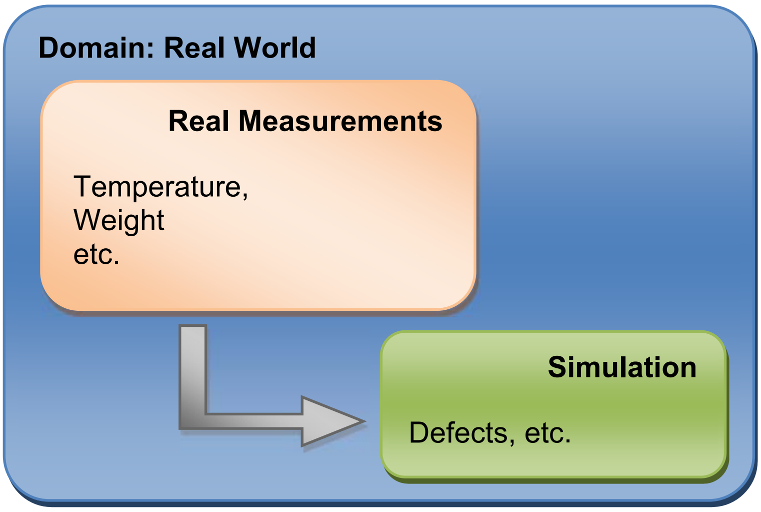


Figure 22: Diagram of implementation of RealTime Data Distribution Platform.

Domain, Topics, Information Sources and their Relationship

The different domains to be taken into account are shown below. In the same way, a summary is made of the different topics or channels for the Refial use case. Moreover, several data sources are shown. Finally, it will be necessary to illustrate the way in which the different entities are related, defining the way in which these should work as publishers as Sentinel Manager is currently the only subscriber.

Table 1: List of available domains.

Available Domains	
REFIAL-REVAMP-RTD	Message space defined for the development of real-time communications about what is happening in the Refial Use Case. The space or domain is defined by the addressing of the messages. Thus, the address of this domain is 224.1.1.1:5002

The approach of defining a single message space or domain does not avoid expanding it if needed, for example, with that second group of managements associated with the simulation. In the case that an isolation of different entities is needed, in order words, making entities disconnected, avoiding listening one to each other; the number of domains can be expanded. However, it should be noted that there may be situations in which it is interesting that some applications could access all known domains. For this purpose, applications must make a subscription to all of them with all the necessary addresses.

The topics available for the current domain are shown below.

Table 2: List of designed messages and their information.

Available Topics in REFIAL-REVAMP-RTD			Publisher
T001	MT_INITIAL_CONDITIONS_H01	Publish/Subscribe messages about START information of a MELTING for the first ROTARY FURNACE. In this case, the message has the basic information of scrap percentages, weights and salt	PDAgent Data Extractor
T002	MT_INITIAL_CHEM_COMPOSITION_H01	Publish/Subscribe messages of INITIAL CHEMICAL ANALYSIS of MELTING for the first ROTARY FURNACE. In this case, the basic information of the chemical composition with its elements and the percentage is transferred.	PDAgent XRT Equipment
T003	MT_FINAL_CONDITIONS_H01	Publish/Subscribe messages about FINISH information of a MELT for the first ROTARY FURNACE. In this case, the message has the basic information of temperatures weight and performance	PDAgent Data Extractor
T004	MT_FINAL_CHEM_COMPOSITION_H01	Publish/Subscribe messages of FINAL CHEMICAL ANALYSIS of MELTING for the first ROTARY FURNACE. In this case, the basic information of the chemical composition with its elements and the percentage is transferred	PDAgent XRT Equipment

Available Topics in REFIAL-REVAMP-RTD			Publisher
T005	AQ_TEMPERATURE_H01	Publish/Subscribe messages of ALLOY QUALITY of MELTING for the first ROTARY FURNACE. In this case, it transmits a remarkable temperature of the analysis.	PDAgent Metal Quality
T006	AQ_DENSITY_H01	Publish/Subscribe messages of ALLOY QUALITY of MELTING for the first ROTARY FURNACE. In this case, it is used to distribute the value of density analysis.	PDAgent Metal Quality
T007	AQ_OXIDE_H01	Publish/Subscribe messages of ALLOY QUALITY of MELTING for the first ROTARY FURNACE. In this case, this message contains the value of oxide analysis.	PDAgent Metal Quality
T008	RF_INFO_H01	Publish/Subscribe messages of OPERATION INFORMATION for the first ROTARY FURNACE. The information included in this messaged is the following: percentage of torque, instantaneous gas flow, turn velocity, energy losses with open door, tilting degree and operation time	PDAgent Rotary Furnace
T009	PH_INFO_H01	To be defined when the pre-heating system will be done.	PDAgent Pre-Heater

All designed messages have been created including a number or id of the furnace they refer to. The fundamental reason is to leave the system ready for the scalability of adding new units (furnaces) of analysis.

4.3.2. Integration of tools

First of all, when talking about system integration on the Refial use case, we must focus on the general structure of elements and their communication. In this way, Figure 23 shows how all the elements in the Refial infrastructure should be deployed and connected.

In this way, the following elements become part of the monitoring mechanism of the Sentinel platform:

- *PDAgents.* Small developments focused on making the data gathering process, being in charge of recovering the necessary information for this monitoring task, sending it. In the end, they are working as publishers in the communication architecture already presented in previous sections.
- *Main Storage – DB.* Main storage where data can be stored. This storage, although possible, is outside the scope of Sentinel monitoring. Although this database exists, the way to interconnect all the ecosystem is through Refial internal network as shown in the figure.
- *Sentinel Manager.* Software belonging to the Sentinel ecosystem that will receive the information distributed by the PDAgents and will determine notification and monitoring operations. Finally, it will distribute information to the different views (dashboards) displayed on the plant.
- *Sentinel Dashboards.* Final elements of the ecosystem that are in charge of painting and drawing the monitoring information, providing the correct data, at the right time, in the right place.

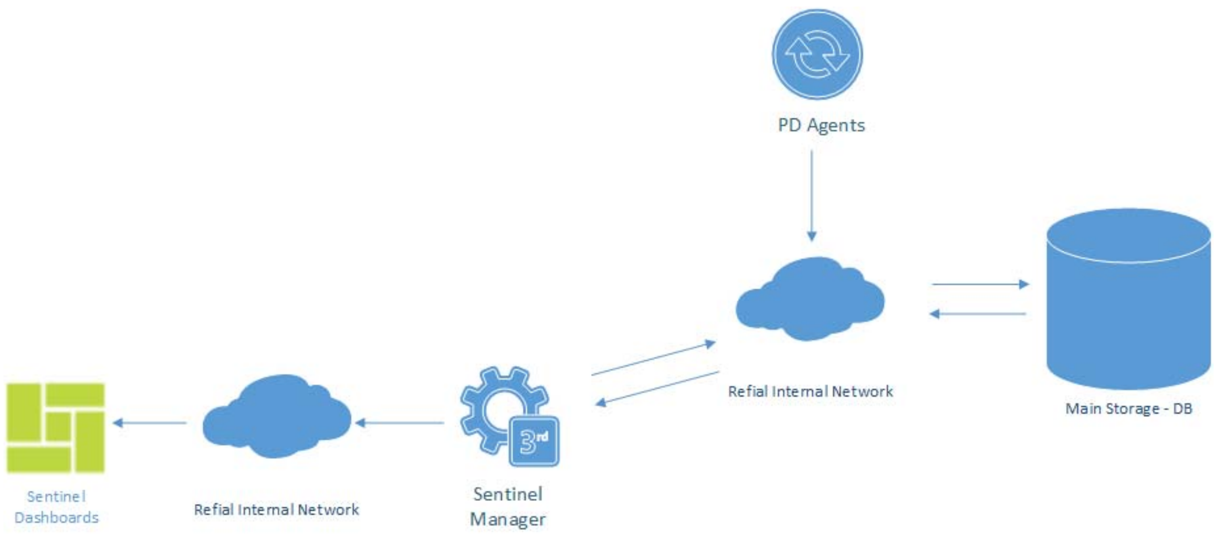


Figure 23: Refial use case overview.

Secondly, another very important point to talk about integration is the plant layout for the monitoring system. Specifically, and given the use case of Refial, monitoring is stablished at the furnace level. It monitors all the information related to the fusion elements (for example, rotary furnace and pre-heater, among others), as well as the metallurgical quality measures and future predictions to be made.

Please note that the deployment of a couple of servers is depicted in the architecture shown in Figure 24. The first of them will be placed at the plant. Currently, this server will take care of everything necessary for accessing data or information produced there. This server will be called *Data Server* and, in addition to having installed the PDAgents for capturing tasks; it can be used by other partners for operations focused also on data gathering. The second one will run in the offices and will be the place where the core of the Sentinel system will be running.

Specifically, it is indicated as a server, nevertheless, it could be deployed using the already existing infrastructure in Refial.

Moreover, in order to facilitate decision-making, it is proposed to carry out monitoring in the Refial/Inatec offices or facilities. Thus, the same system will be deployed too, allowing access to the data of what currently happens in the plant, giving real time information. Likewise, alerts, out-of-limits controls and future predictions and suggestions may be also sent to this new entity.

It should be noted that during the adjustment process, which is expected to be carried out in the following WPs, everything can be tuned and improved due to the easy way of changes and scalability of the Sentinel System.

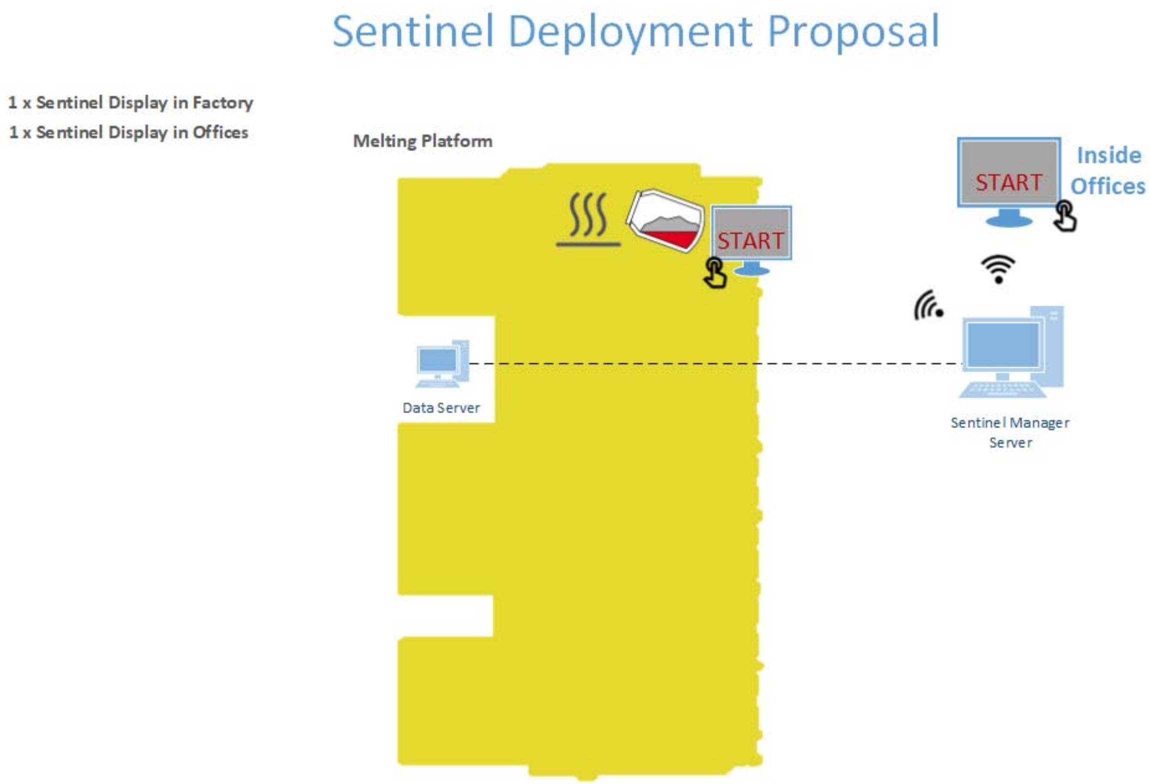


Figure 24: Sentinel Deployment Proposal in the Refial use case.

Thirdly, also considering the integration of tools, it is needed to comment how the data is extracted and transferred to carry out the required monitoring. In order to achieve this objective, different implementations of PDAgents are used that are focused on each data source that the Refial use case has.

PDAgents are usually independent software artifacts that coexist in the Sentinel ecosystem. Moreover, each one of them is in charge of managing a concrete and specific data source. Subsequently, once the information has been retrieved, the PDAgent is able to store the data in a centralised database or, as in the case of Refial scenario, send it through the real-time Data Distribution System (DDS) explained above.

All capturing agents are based on a basic template. This structure is illustrated in Figure 25. The basic structure provides the service functionalities, as well as the DDS communication infrastructure (this communication feature includes both sending and receiving operations in case they are needed) and the methods that allow querying about the current status of the service and its version.

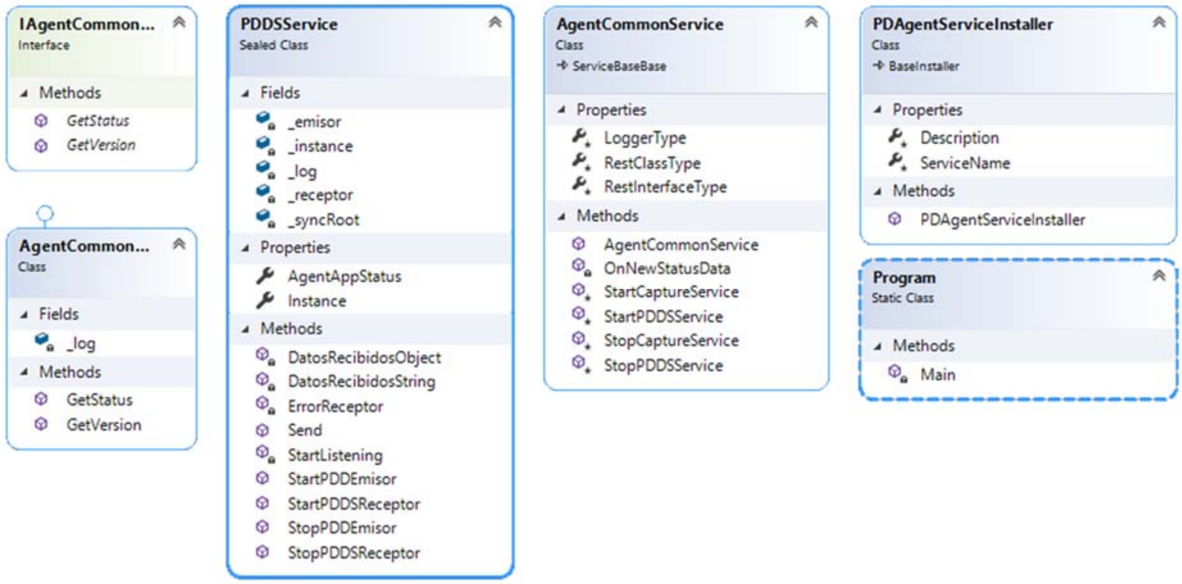


Figure 25: Class Diagram of a PDAgent Template.

The aforementioned template has to be adapted for each specific data source. This architecture makes the developed generalisation easily extensible. Thanks to this design, the creation of a new PDAgent that has to manage a different data source only needs the development of a data access layer that focuses on the database, file or data source from which to retrieve it.

The list of tasks that PDAgents perform are very basic. Each of them is created with the specific goal of reading and writing data. Reading from the original and unique data source. Writing to a centralised database, over the network or both. PDAgents will be able to validate the reading and apply a first layer of intelligence. Notwithstanding, they will never perform another type of complex processing, this will be done by other entities of the ecosystem, such as the Sentinel Manager.

Each of the PDAgents developed for the Refial use case has been configured to have high availability upon failure. In this way, the Microsoft Windows service has been configured with a restart of it in case any malfunction appears (see Figure 26). Internally, before a restart, the software recovers and manages everything that has been generated during this process, hence, no information is lost.

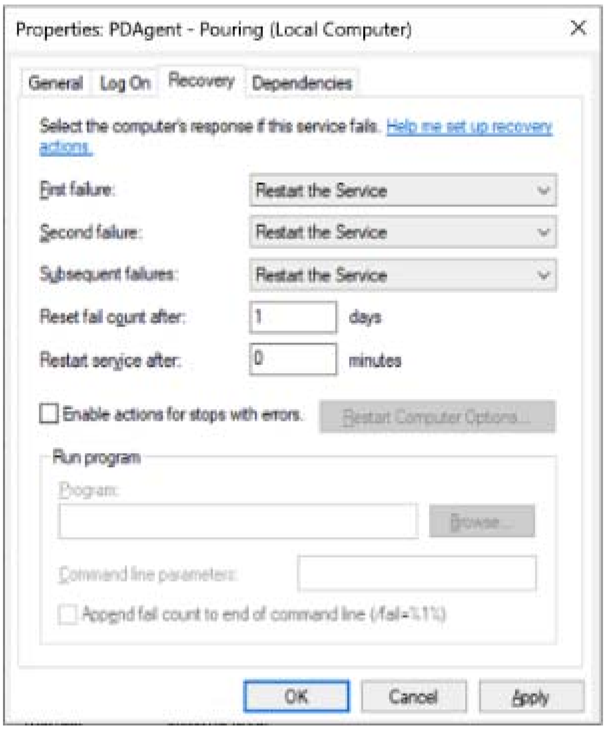


Figure 26: Example of PDAgent running as a Microsoft Windows Service with Recovery Properties Activated.

In the design of the Refial use case the PDAgents listed below were identified (shown in Figure 27). All of them will focus on reading and sending information through the DDS.

- PDAgent XRT Equipment. Agent that will be in charge of reading the chemical composition from the text file with delimited fields generated by the equipment.
- PDAgent Rotary Furnace. Agent that will oversee reading the rotary furnace information from the database deployed in the GHI Cloud.
- PDAgent Pre-Heater. Agent that will manage the process of data gathering from the pre-heater and, although it is not currently developed, it is expected to be stored in the GHI Cloud, the same location in which the information from the furnace sensors is stored.
- PDAgent Metal Quality. Agent that will supervise how to obtain the information from the two databases that the AluQ, the device developed during this project, has.
- PDAgent Data Extractor. Agent that must retrieve some information about the batches that are registered in the database of the Refial MES.

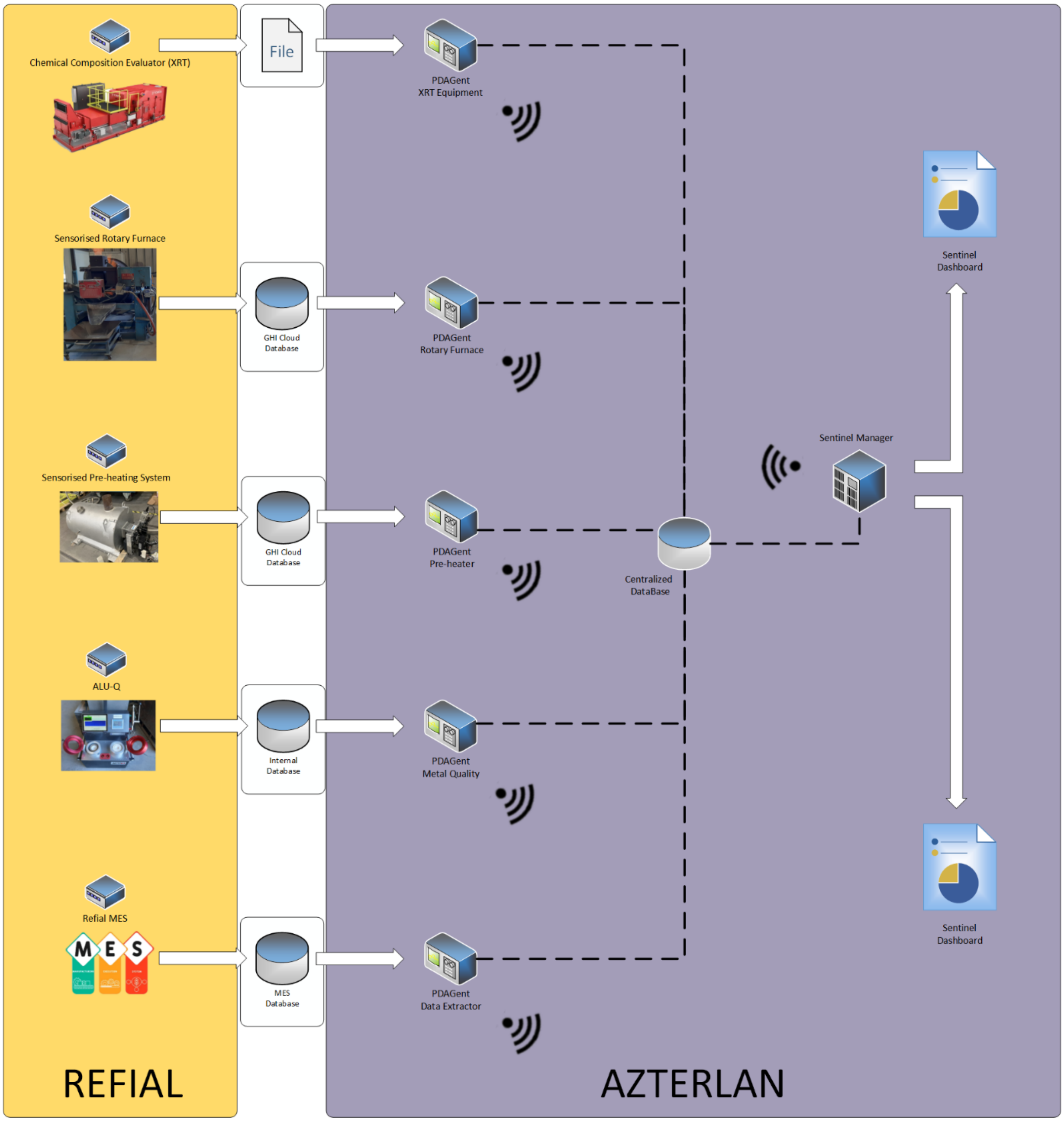


Figure 27: Data Gathering and Distribution using PDAgents and Sentinel Architecture.

Finally, all information previously explained has the aim of displaying the information for monitoring. In this use case, different dashboards are created. All of them have been generated to bring the information to the end user. Specifically, the windows that have been generated have navigation between them and are the ones shown in Figure 28. The UI starts in an initial display of Melting Information. This visualisation allows to navigate in depth to specific information regarding the quality of the metallic alloy. Horizontal navigation between different displays focused on the rotary furnace and the pre-heating system is also possible. Everything is better illustrated in the following image.

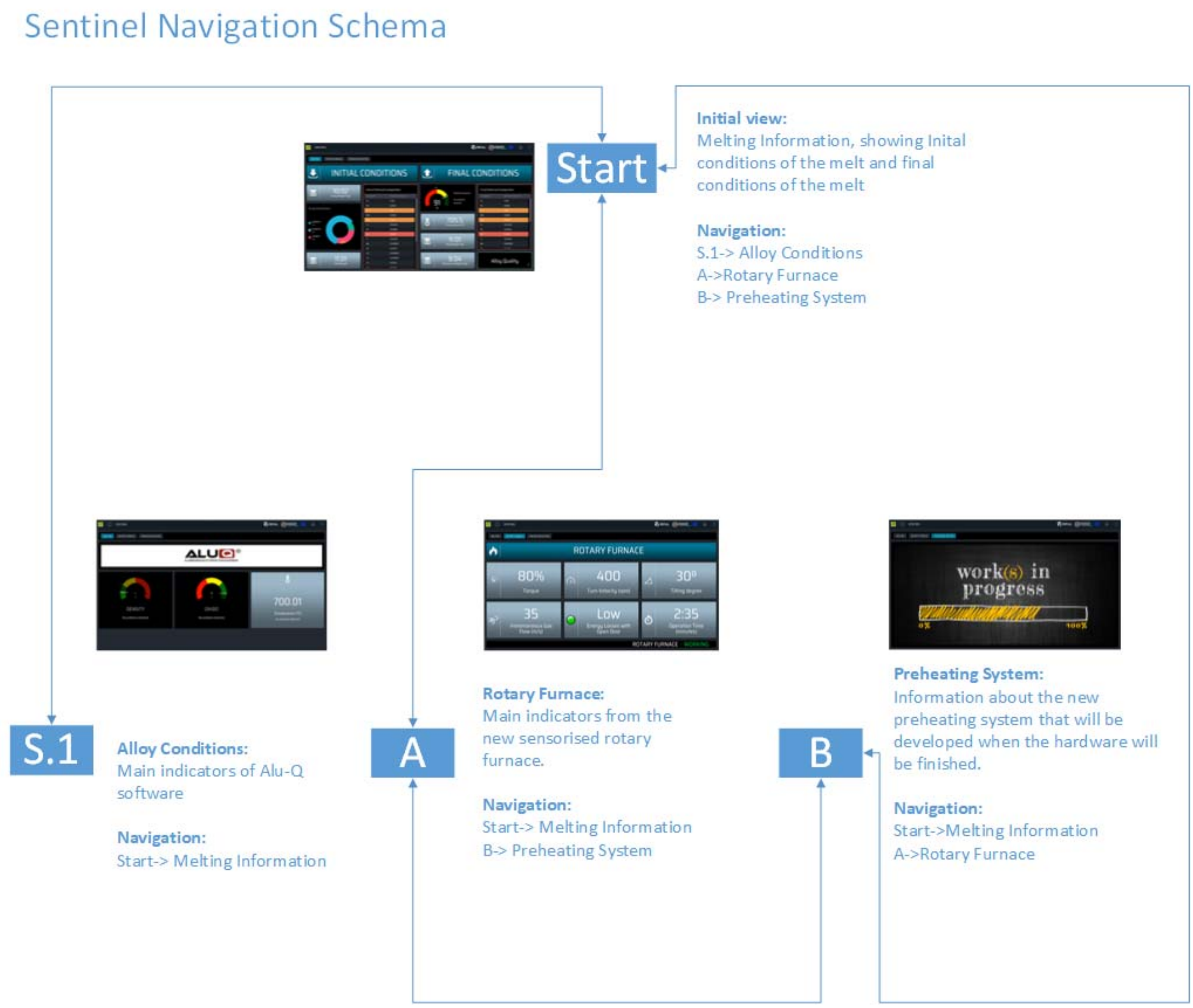


Figure 28: Diagram to define Sentinel navigation in the Refial use case.

5. Dynamic monitoring tools for lead use case (CAR, EXI)

5.1. Description of the developed tools and applied methods

The aim of this section is to describe the monitoring and control platform that has been developed in Task 4.1, in order to incorporate the models and algorithms obtained in WP2 for the lead use case. As initial approach, the platform includes a “Smart Data Visualisation” tool which can be used for analysis of the furnace performance, based on statistical data from raw material charged in the furnace and smelting process variables in a time slot. Subsequently, an algorithm for furnace yield prediction and a supervision and control system of temperature will be incorporated to the platform. In this deliverable the Smart Visualisation tool will be explained.

The Smart Visualisation tool designed in this Task 4.1 allows users to select and display data from the four rotatory furnaces in EXIDE plant using different data sources, with interactive visual exploration and suggested visualisations without the need for technical skill or training. The tool lets users identify relationships, patterns and trends to make much smarter decisions based on data. The program provides more options for display, going beyond basic bar and pie charts. Statistical graphs and charts as box plots, violin charts, histogram and interactive graphs have been incorporated to the software.

Retrofitting monitoring system

The first step for the development of the tool is to collect the data and transform it into a format that enables users to better use the information. In the case of EXIDE plant, it has been necessary to do a retrofitting of the monitoring system to ensure a proper development of the application. The data from the combustion and aspiration processes in the furnaces have been collected through the connectivity platform “KEPServerEX” that connects, manages, monitors, and controls the automation devices and software applications via OPC through a user interface.

The real-time data from PLC´s are stored in an ODBC-compliant database. In this case, Microsoft SQL Server has been chosen as database. Both, the connectivity platform and the database have been installed on a PC server where the historical data of the different smelting processes are stored.

On the other hand, the production data, including raw materials, fluxes, productivity and the laboratory analyses of the different castings, have been incorporated into the database. This data is recorded by EXIDE in Excel sheets that will later be uploaded to the database using the visualisation tool. Both production and process data are the input data that “the Smart Visualisation Tool” will use.

Smart Visualisation Tool

Once the different data that the tool will need for each of the applications were defined, the different requirements were designed for each of the applications of the visualisation tool. These applications will be explained in section 5.2.2.

The visualisation tool has been programmed in R, a free programming language for statistical computing and graphics. Specifically, the visualisation tool has been designed by Rstudio, an Integrated Development Environment (IDE) for *R* and by Shiny Server, a server to build interactive web apps straight from *R.*

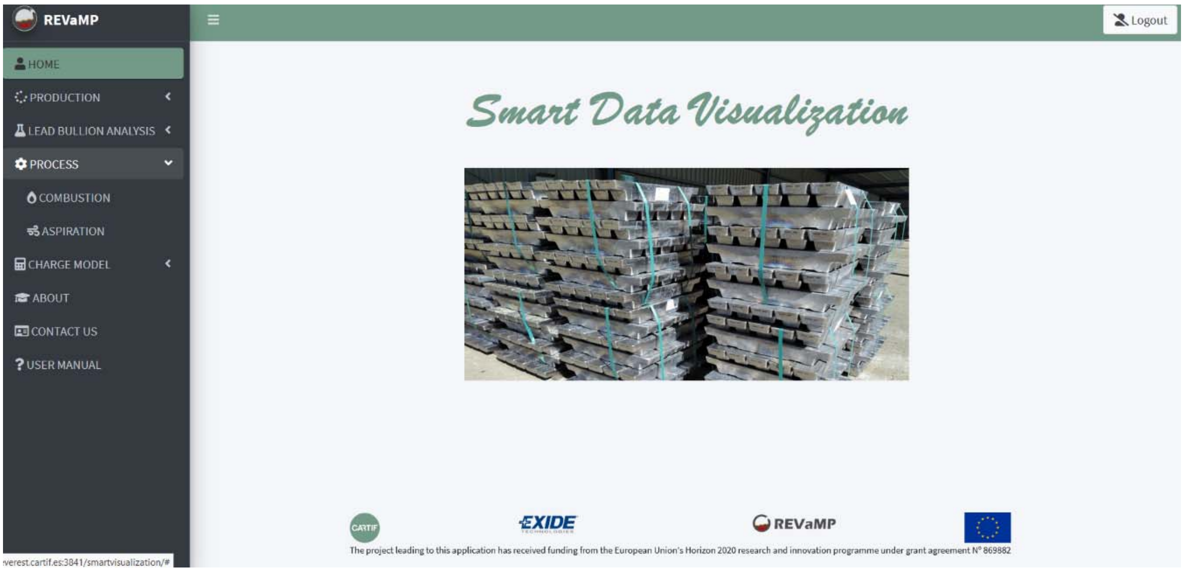


Figure 29: Smart Visualisation tool home screen.

5.2. Application at EXIDE

5.2.1. Data provided by EXIDE

The data that has been incorporated into the database corresponds to the production carried out in the EXIDE plant during the years 2019 and 2020. The tool has a function to incorporate new data by importing it to the database. The data can be classified into 4 groups depending on its origin. Each of them is defined below:

- **Production data**. The raw materials and fluxes loaded in the furnace, the production date, the furnace used and the type and quantity of lead bullion produced are some of the data that are collected by the operator and that will be used by the application for statistical analysis.
- **Process data**. This data corresponds to the main variables of combustion and aspiration processes that take place in the furnaces. In the combustion process, gas and oxygen flows are supplied in the proportions necessary for the chemical reactions to take place in the furnaces. On the other hand, in the aspiration process, the fumes outlet temperature and the depression in the furnaces are regulated to control the gas evacuation process. The analysis of this information will allow the decision-making to vary the conditions of both processes, optimizing them, at the same time that it allows detecting their malfunction.
- **Laboratory data.** The percentage of metallic elements in lead bullion such as Sb, As, Sn, Ag, Se and Te, are measured and recorded for each casting that is produced in the rotary furnaces. These values are transferred to the database in order to be managed by the smart monitoring tool.
- **Charging data.** The application for the optimisation of the charging in the furnaces developed in WP 2.1 needs to be fed by not only the value of the raw materials mass charged in the furnaces, but also by the costs of the raw materials and the lead percentages of each raw material and slag estimated in the equation regression obtained in WP 2.1.

5.2.2. Integration of tools

Among the main applications that have been incorporated into the smart visualisation tool, the following should be highlighted:

Furnace Productivity and Historical Castings Monitoring

Productivity Data: Using this utility, each of the four furnaces that EXIDE has in its plant can be chosen to view the raw materials and fluxes of the different castings that have been carried out on a specific day. The programmed graphics are dynamic so that the casts to be displayed can be chosen.

Figure 30: Visualisation of the raw materials and fluxes charged in a furnace for the castings obtained on a day.

Also, in this application, the yield of the different casting produced in a chosen day in the furnace and the average yield of this day are also represented. Normally, 4-5 casts are produced per day in each furnace, taking into account that the duration of a cast is estimated at four and a half hours.

The yield of a casting is defined as the weight ratio between the raw material charged in the furnace and the lead bullion obtained. The yields have been represented by gauge charts, with different colours red or yellow depending on whether the yield is higher or lower than the standard defined.

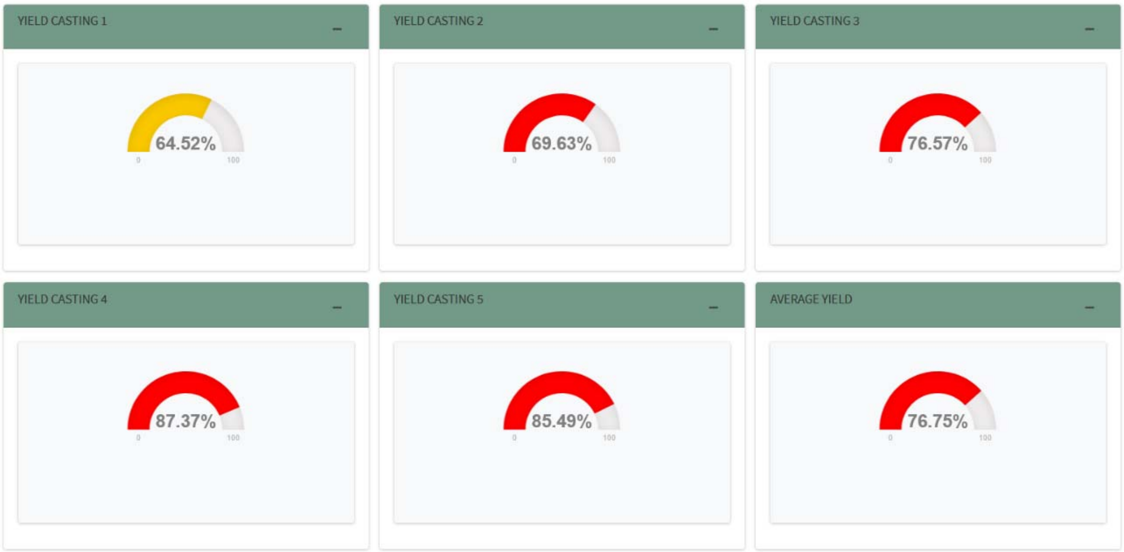


Figure 31: Visualisation of the productivity in a furnace for the different castings obtained on a day.

Historical data: Another function of the application is the visualisation of the raw materials and fluxes in the four furnaces in a time horizon that the user chooses through dynamic graphs. Initially, the 4 furnaces are represented on a screen, which allows the user to compare trends of the charge in the furnaces.

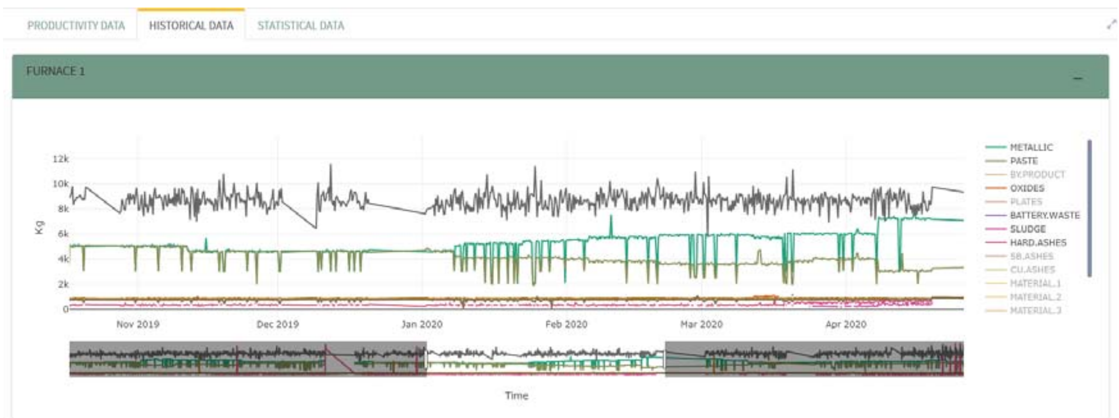


Figure 32: Visualisation of raw materials and fluxes in a furnace in a chosen time range.

Statistical data: The data of the raw materials and fluxes of the different charges in the furnaces incorporated in the database are statistically treated using this utility. The statistical parameters can be represented by means of box plots to know how the data is distributed for each variable and the date range chosen.

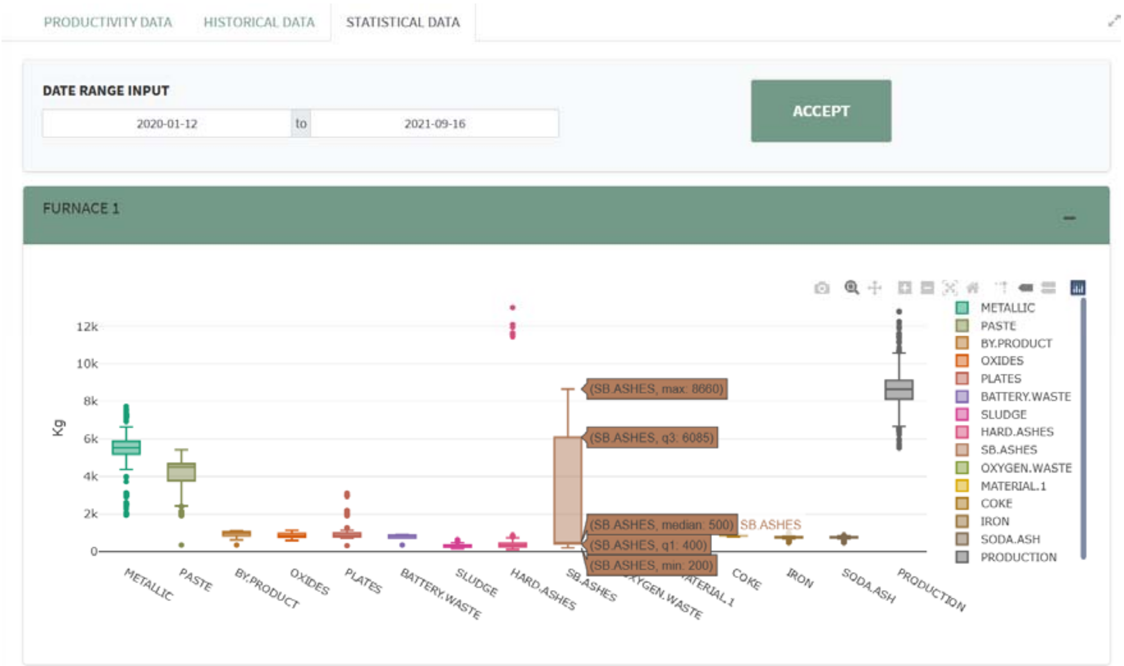


Figure 33: Visualisation of raw materials and fluxes in a furnace through boxplots.

Lead bullion analysis in laboratory

The percentage of metallic elements contained in the lead bullion is measured each time a casting is finished. The data obtained are stored in an Excel sheet. Through this application it is possible to transfer the information to the database. After importing the data, the user can view the percentage by mass of the main metallic elements of the selected cast by means of a bar chart.

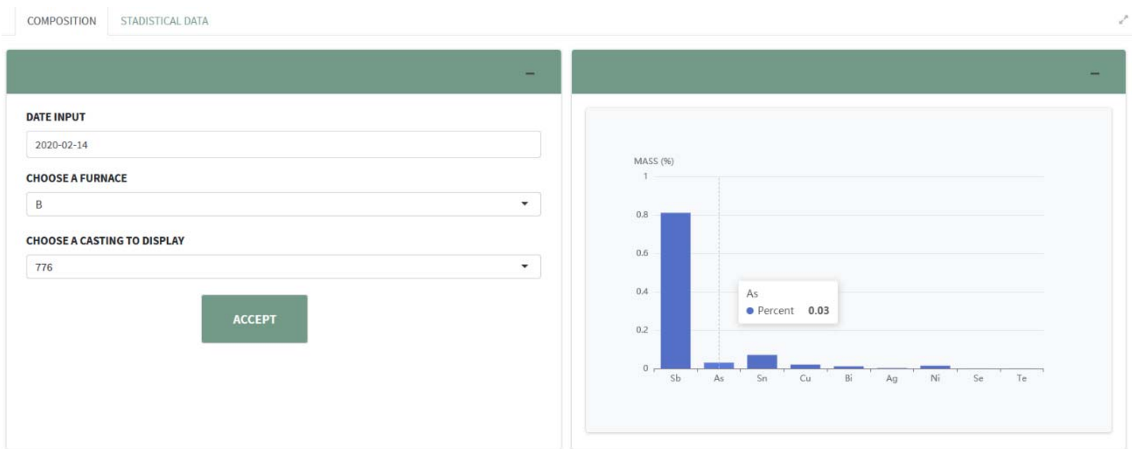


Figure 34: Visualisation of the mass proportion of the metallic elements contained in the lead bullion.

This application also has as functionality the statistical treatment of the lead bullion composition data. In this way, different parameters can be displayed for each metallic element in a set date range. Statistical values are represented in different graphs depending on the type of lead bullion produced, mainly determined by the Sb content. According to the EXIDE denomination, the produced leads are classified as blue, yellow and red leads.

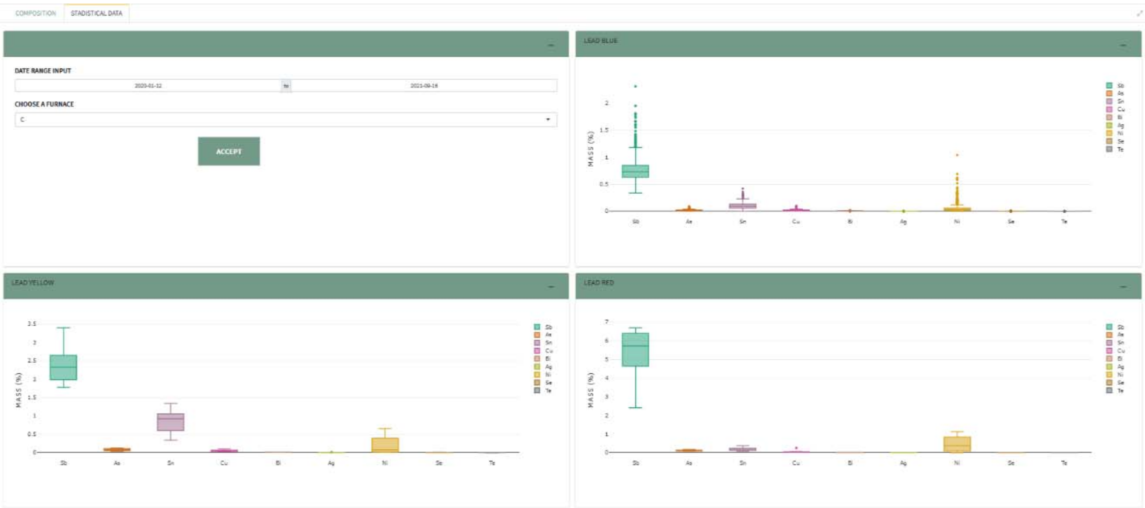


Figure 35: Visualisation of the mass proportion of the metallic elements contained in the lead bullion through boxplots.

Visualisation of the Combustion and Aspiration Processes in the Furnaces

The different data from PLC, which are registered in the database with the implementation of the new monitoring system, allow visualizing the different variables of the combustion and aspiration systems in the rotary smelting furnaces. The following graphs represent the oxygen and gas flows, as well as the temperature that occurs during the combustion process in the furnaces. The analysis of these variables will facilitate the development of decision tools developed in this task 4.1 (D4.2), such as the detection of bad behaviour in the smelting and reduction phases that take place in the furnaces. One of the first results has been to reduce the times of some of these phases with the consequent reduction of energy consumed in the furnaces.

Figure 36: Visualisation of oxygen, gas and temperature in a rotary furnace at the EXIDE plant.

Currently, it is pending to incorporate new variables of the aspiration process in two furnaces of the EXIDE plant whose automation systems have been retrofitted in the last months.

Furnace Charging Model

Another application that is under development is the implementation of the furnace charging model developed in Task 2.1.

The input data to the application are the different quantities and costs of the raw materials and fluxes charged into the furnace, as well as the estimated proportion of lead in each of the raw materials and slag. The outputs would be the mass of raw materials and fluxes, the total charge and its cost and the estimated productivity and yield of the cast to be produced.

The implementation of this application and those described previously included in the smart data visualisation will be carried out throughout WP 7 that will start in October 2021.

6. Conclusions

For the steelmaking use case at Sidenor the dynamic process model has been successfully deployed as monitoring tool and its accuracy has been validated. The utilisation of the model to perform predictions regarding the heat state development and to provide optimised set-point suggestions will be described in Deliverable 4.2. A continuous improvement of the deployed tools will be ensured within the work of WP5.

At Grupal Art the Data Processing and Modelling Dashboard is already operative as a data storage, data visualisation platform and also to compute the Main Charge Mix model, developed in WP2. The requirements for the following models that will be designed in REVaMP are defined, and the pipeline of the 'Process Control Model' has been introduced.

For the Refial use case, an easily scalable real-time monitoring system, called Sentinel, has been provided. Specifically, this system allows to share the right information, in the right place and at the right moment. In addition, this software, making use of the monitoring developed, creates the basis to start the work of developments for controlling the manufacturing process.

The retrofitting of the data acquisition systems and the implementation of a database has made it possible to centralize all the information from the smelting furnaces at the EXIDE plant. The development of a software platform for the integration of all the applications developed, among which the smart visualisation tool stands out, will allow the monitoring and statistical treatment of the data collected from production in the furnaces, facilitating decision-making for the operator of the plant. Future applications developed in WP2 and WP4 will be included in this software platform and will be implemented and validated during the execution of WP7.

7. Abbreviations

DDS Data Distribution System

EAF Electric Arc Furnace

GUI Graphical User Interface

MAE Mean Absolute Error

ODBC Open DataBase Connectivity

OPC OLE for Process Control

OS Operating System

PLC Programmable Logic Controller

RDBMS Relational DataBase Management System

REST API Representational State Transfer Application Programming Interface