capri

Cognitive Automation Platform for European PRocess Industry digital transformation

Deliverable

D4.3 Control Layer Reference Implementations

Deliverable Lead: CARTIF

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EXECUTIVE SUMMARY / ABSTRACT SCOPE

This deliverable of type OTHERS presents the implementation results of the Control Layer Reference Architecture for Cognitive Plants in the process industry, as developed in the CAPRI project. The implementation is based on Open-Source environments from bodies such as the APACHE Software Foundation or the FIWARE Foundation and aims to be easily reused by third parties. As such, the platform reference implementation has been published as Open-Source software as well. In addition, we provide guidance on how to realize innovative smart control applications on top of the platform, by releasing explanatory videos, accompanying text documents, datasets and partly even the applications itself that have been implemented in the CAPRI project.

The deliverable is part of a series of documents describing the different layers of the CAPRI Cognitive Application Platform (CAP). The other documents are

- D4.1: Sensors Layer Reference Implementations
- D4.5: Operation Layer Reference Implementations
- D4.6: Planning Layer Reference Implementations

1 Introduction

1.1 Scope of Deliverable

D4.3 – “Control Layer Reference Implementations”, is a deliverable of type OTHER aiming at describing the practical results and the implementation of the Control Layer Reference Architecture for Cognitive Plants in the process industry, as developed in the CAPRI project within the CAP (Cognitive Automation Platform).

The implementation is based on Open-Source environments from bodies such as the APACHE Software Foundation or the FIWARE foundation to be easily accessible, with a large software community available for maintenance and extensions, so aims to be easily reproducible by third parties with smart cognitive control loops, as designed in task T4.2 “Cognitive control solutions for process industries”. The CAPRI Reference Implementation, as described in D3.1, has been materialized supporting state of the art open standards such as OPC UA and MQTT for data ingestion and NGSI-LD for data representation. What will be presented in this deliverable, alongside D3.1 and D4.1, corresponds to achievement of milestone MS3, which is an “Alpha version of the final cognitive automation architecture and technology validation of cognitive solutions for control level in relevant industrial environment”.

Part of the outcomes will be provided in a zip file to be submitted together with the present deliverable. For each Control-Related Cognitive Solution and its integration within the CAP Architecture, some or all of the following details will be provided:

- Text document explaining the work done, introduction to the video (if any), user manual of the apps and the used architecture modules, interfaces within the platform, including the available links, data and metadata description and description of everything else in the ZIP file or files provided within D4.3.
- Executable of the program/app, if any
- Any kind of data that can be publicly shown (full data, sample data, metadata, surveys results, …)
- If available, video used to explain “physical” results and interfaces of the control solutions at Control Layer implementation within the CAP.

Finally, D4.3 aims at providing some recommendations related to the rest of the Layers of WP4 and WP5 integration. This includes suggestions on the best integration approach within the CAP in the Control Layer or features that could further be evaluated and improved in the upper and lower layers and that could be conceived as innovative aspects and to be followed in future research projects or moved to other process industry domains.

1.2 Audience

This deliverable target the Alpha release of the CAPRI implementation in the CAP platform. Practical details of the cognitive control loops are provided, with textual information explaining all related work.

Advanced and adaptive control services can be developed at different levels in the IT infrastructure supporting both the production and other auxiliary processes (e.g. maintenance). In such a context Artificial Intelligence and other cognitive approaches can be used to develop flexibility and optimization along all the control loops characterizing the different sectors taken into account the CAPRI pilots. The “Control Layer” Reference Implementation (CLRI) of the CAP has been here developed for the implementation of the three tailored instances of the CAP in the chosen domains. If needed, a specific class of control services has also been deployed to product/process quality control.

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For this reason, this D4.3 report is conceived to be accessible to all partners and it is addressed mainly to a reader with a technical background related to Control Technologies and Data Architecture and their integration within a Reference Architecture described in D3.1:

- For the three pilots, it is a technical description of the Smart Control cognitive components installed in their environment and integrated with existing assets and solutions;
- For technology providers involved in WP4 and WP5, it represents a reference to drive the control solutions integration with CAP implementation and verifying compliance with requirements as described in deliverable D2.2 and D3.1.

1.3 Relationship with other deliverables

D4.3 deliverable, concerning Cognitive Control Solutions and their integration within the corresponding Reference Architecture, is related with the following deliverables:

D3.3 – “CAPRI Industrial Analytics Platform and Data Space” traces a continuation line after D3.1 – “CAPRI Final Reference Architecture”. D3.1 describes the Reference Implementation of the Cognitive Application Platform (CAP) while D3.3 describes the standalone development of the control-based solutions. Then D4.3 describes their integration in the final plant for the different domains for the specific control layer.

On the other hand, final results in WP3 have fed the integration steps covered in WP4, paving the way to the final demonstration in WP5 tasks at plant level.

This way, D4.1 – “Sensors Layer Reference Implementations” allows analysing and integrating the interfaces defined for the Sensor Layer of the Reference Architecture (defined in task T4.1) with this Control Layer (task T4.2) and their interaction.

Also, D4.3 defines the integration of the different interfaces of the control layer with the higher layers of tasks T4.3&T4.4 as the final CAP platform and lays the foundation layers and interfaces for D4.5 – “Operation Layer Reference Implementations” and D4.6 – “Planning Layer Reference Implementations” for the corresponding operations and planning layers and their customizations needed for the implementation of the three tailored instances of the CAP in the three use cases.

All of these set the basics for the final D4.8 – “Cognitive Automation Platform Blueprints” and will be the starting point for the corresponding deliverables of WP5.

1.4 Document Structure

This document is organized with four main chapters (from Section 2 to Section 0), in addition to the introductive chapter (the current one, which describes the scope of the deliverable, its audience, the relationship with other deliverables and the description of its own structure) and the conclusive one, which summarizes main achievements, conclusions and shaping the next steps.

Section 2 - Attachment Structure Description This section explains the distribution of all files of type OTHER that are being part of this deliverable D4.3 with the corresponding links to access them all.

Section 3 - Control Layer Architecture explains and set the basics of the corresponding Reference Architecture Platform as a recapitulation of the platform architecture described in D3.1 and how it has evolved and been implemented for the corresponding Cognitive Control Solutions of the Control Layer of the platform.

Section 4 - Control Layer Platform Reference Implementations provides a summary view of how the different cognitive control solutions have been integrated at the control layer of the CAP platform, split by domain.

Section 5 - Information Modelling aims at describing the role of models (data models …) in the CAP in general and the specific domain implementations, in particular regarding those implemented for the control layer.

Section 0 - Control Layer Applications aims at reporting the detailed description of the control layer applications, in particular the material included in the zip file and, especially, regarding the updated work done to integrate those Cognitive Control Solutions described in D3.3 as standalone descriptions but integrated within the Reference Architecture. All those related files, links, interfaces, videos and so on to be included as part of this D4.3 for each domain are described in this section regarding the Control Layer Architecture.

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2 Attachment Structure Description

Since Deliverable D4.3 is of type OTHER, each Cognitive Solution integrated within the CAP platform is equipped with:

- A number of attachments of different nature (video, data, metadata, application, code, …), containing additional information that helps to better understand the final output of the different CS and how they are being integrated within the CAP platform and to provide a concrete evidence of what has been implemented in WP4;
- A textual part, available in Chapter 0 that complements the "physical" content in attachment, explaining what it is and how to exploit it.

The attachments are available in the corresponding Folder in Zenodo repository. Due to limitations of space (52Mb) in EC portal not all the assets could be included into 1 single file. That is the reason we have decided to include all files into CAPRI's Zenodo account and CAPRI YouTube channel video for the videos showing specific demonstrations. The table below lists all the links (Zenodo and, if applicable, YouTube) of the different files described in the present report.

Table 1 D4.3 – List of attachments

Cognitive Solution	Content	Type	Location
CAC1 - Control of the asphalt drum	CAC1_IO_DB.m	Input Data reading script	https://doi.org/10.5281/zenodo.6867476
	CAC1_IO_DB_OUTPUTS_v2.m	Output Data writing script	
	CAC1_curl_post_matlab_function_v3.m	POST request to Orion CB script	
	CAC1_DMP_ALL_DATA_dataset_v1.0.xlsx	DMP file	
CSS2 - Cognitive Sensor for Solidification	CSS2 video_2.mp4	Screencast explaining the data flow for cognitive temperature sensor for solidification	https://doi.org/10.5281/zenodo.6914668
CSS3 - Cognitive Sensor for Product Temperature	CSS3 video_2.mp4	Screencast explaining the data flow for cognitive temperature sensor	https://doi.org/10.5281/zenodo.6914729
CSS4 - Cognitive Sensor for Scale Build-Up	CSS4 video_2.mp4	Video with the data flow for cognitive scale sensor, estimating thickness and composition of steel	https://doi.org/10.5281/zenodo.6914764
CPC1 - Cognitive control concept (zip-	description.txt	Description of the contents of the data files A3_DOK_CPC1_CPS1.xlsx and A3_DOK_CPC1_CPS2.xlsx .	https://doi.org/10.5281/zenodo.6866069

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archive CPC1_Data_2.zip)	A3_DOK_CPC1_CPS1.xlsx	Sample dataset concentration control via CPC1 and CPS1.	https://doi.org/10.5281/zenodo.6866069
	A3_DOK_CPC1_CPS2.xlsx	Sample dataset granule size control via CPC1 and CPS2.	
	CPC1_DMP_CPC1_Data_2_V1.xlsx	DMP file	

It is worth to mention that each data file shared is accompanied by the corresponding data management plan file (DMP file) to comply with the F.A.I.R.[1] principles as CAPRI project is part of the open research data pilot of H2020[2].

Finally, an overview of each Cognitive Solution is available in the CAPRI website, at the “Use Cases” section[3].

[1] Under these principles, each data file must be Findable, Accessible, Interoperable and Reusable. http://ec.europa.eu/research/participants/data/ref/h2020/grants_manual/hi/oa_pilot/h2020-hi-oa-data-mgt_en.pdf
[2] https://www.openaire.eu/what-is-the-open-research-data-pilot
[3] https://www.capri-project.com/technology

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3 Control Layer Architecture

The CAP Reference Architecture (Figure 1) is structured for the development of an advanced cognitive software solution. Considered as a digital enabler toward the innovation of process industry, it is an Open-Source solution which is applicable to wide range of use cases, supporting at the same time a large variety of applications. The design becomes ever harder in the real industrial environment, for this reason it was done thanks to an iterative process started in D2.1 where as a first step there were a phase of functional and non-functional requirements collection followed by a continuous validation from the pilots with the common goal of introduce the cognitive automation processes in the process industry. In D3.1 is reported the improvements done in the Reference Architecture underlining the concept of edge and cloud cognitive computing with the aim of solving business challenges, creating new value from data and improving the product quality.

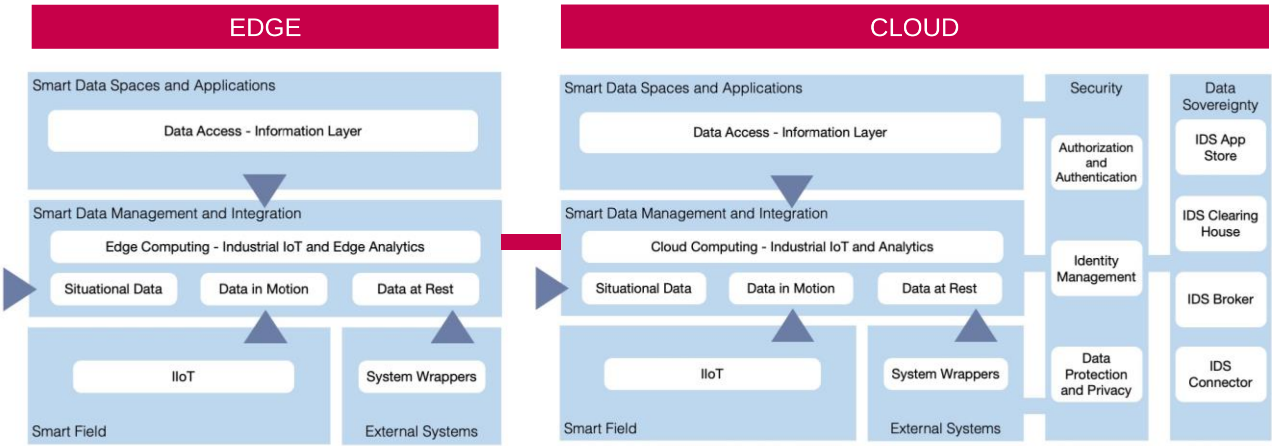

Figure 1 - CAP Reference Architecture

The CAP Reference Architecture is designed many horizontal layers able to guarantee the interoperability, privacy, protection and data sovereignty. In this section the focus will be on the control layer, represented by (details have been described in D3.3 and D3.6) the core of the architecture, since it contains the brokering, the storage and the data processing capabilities, including also cognitive process analytics and simulation systems. Data in Motion, Data at Rest and Situational Data are represented using standard information models and made available using standard APIs. As already reported in D4.1, the sensor layer and the control layer use open-source technologies from Apache (Livy, Spark, StreamPipes, Kafka) and FIWARE (Draco, Cosmos, Orion Context Broker, OPC UA Agent) foundations. This layer will feed the Smart Applications to do integrate BI & Analytics, AR/VR and other generic cognitive applications.

In the next sections will be described for each domain how the control layer is actually implemented to satisfy the requirements of the cognitive solutions integrated in the CAP Platform.

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4 Control Layer Platform Reference Implementations

4.1 Asphalt domain

CAC1- Cognitive control of Dryer Drum

The control solution objectives are to obtain a dry product (dry aggregates) at an optimum temperature for the next process (asphalt mix) and the corresponding combustion gases that go through the chimney through the baghouse filter, at the lowest possible temperature, on one hand not to damage the bag filter and on the other to minimize energy consumption, thus increasing the efficiency of the drying process. The main objective is to decrease the consumption of electricity, recycled fuel and diesel. This way knowing the different inputs of the rotary dryer drum, adjustments are made to obtain the best conditions of the outputs, avoiding overheating of aggregates.

This solution, based on a control algorithm where sensors and actuators are used to calculate the optimum values for the different variables that run the drum, has been integrated, at control layer, as part of the CAP Reference Architecture that has been deployed within CARTIF premises.

As Cognitive Control Solution, CAC1 detailed description can be found in the following deliverables: D2.2 Use Case Requirements and D3.3 CAPRI Industrial Analytics Platform and Data Space.

CAC1 has been implemented in the corresponding platform developed for the Asphalt domain and it is comprised of the following modules:

Based on **FIWARE** Reference Architecture, as described in D3.1, the asphalt domain platform has been implemented in a Linux **Ubuntu** distribution based **server** where the different modules communicate and interact among each other but deployed using the **Docker** platform (A docker is a container, a standard unit of software that packages up code and all its dependencies so the application runs quickly and reliably from one computing environment to another). Each and everyone of the different modules have been implemented through a Docker that interacts with the corresponding ones.

From the Gerena Asphalt Plant, real time data (with sample times as low as 1 or 5 seconds, depending on the data source) is received from a WAGO PLC datalogger using **MQTT** protocol. In the asphalt domain CAP platform, a **mosquitto**-based broker receives those data and it is redirected through an **IoT Agent for JSON** (a bridge between HTTP/MQTT messaging (with a JSON payload) and NGSI. This IoT Agent has been customized to meet the asphalt domain requirements.

This IoT Agent communicates and send the corresponding data to the **Orion Context Broker** module (Generic Enabler that provides the FIWARE NGSI v2 API, a simple yet powerful Restful API enabling to perform updates, queries, or subscribe to changes on context information). This Broker is the core of the whole FIWARE-based Reference Architecture implemented in the Asphalt domain.

From this broker, a **Draco** module has been set up, which is a Generic Enabler that is an alternative data persistence mechanism for managing the history of context. It is based on Apache NiFi and is a dataflow system based on the concepts of flow-based programming. In this case, it manages the data coming through the Orion Context Broker and sends them to a **MySQL** database which is used for data persistence within the CAP platform.

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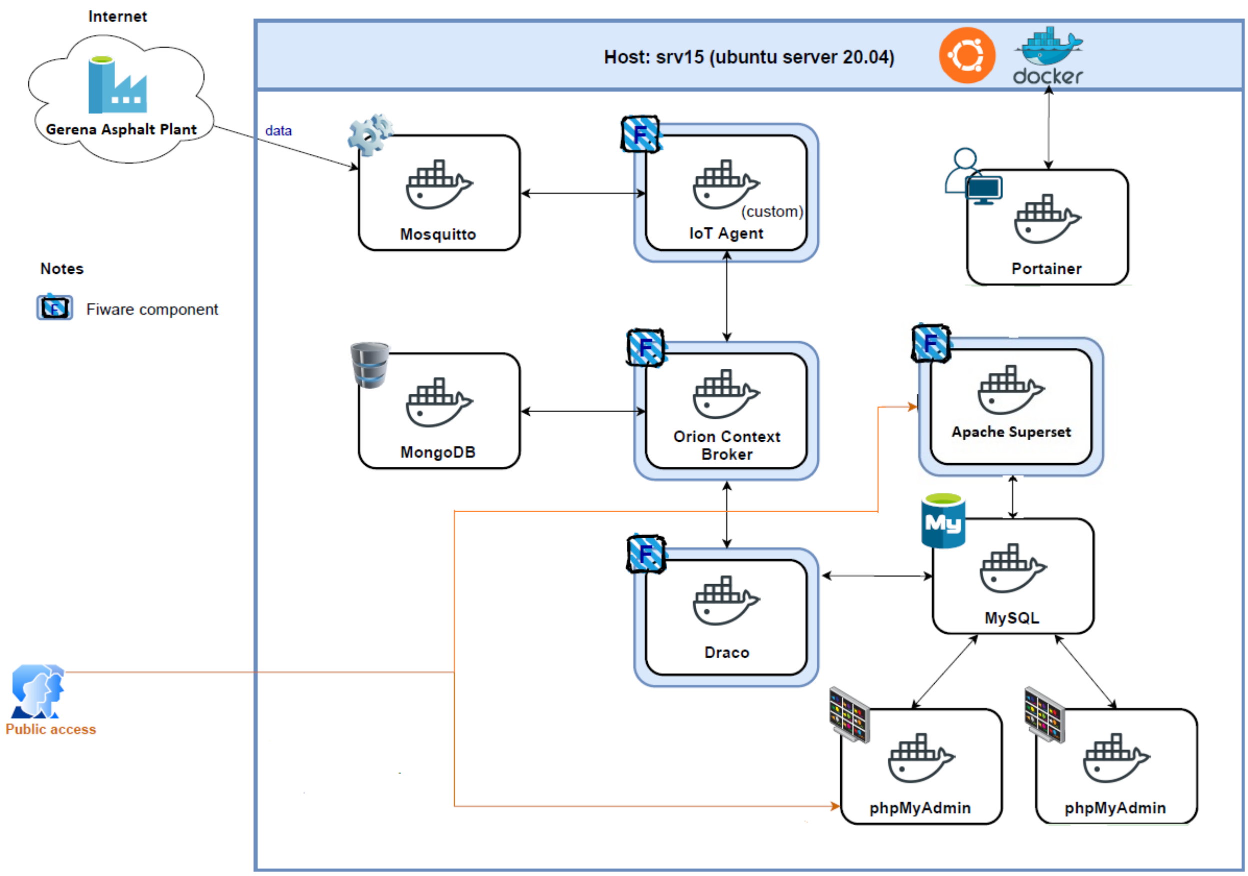

Figure 2: Basic CAP FIWARE-based platform implemented at Asphalt Use Case scenario

CAC1 cognitive control solution, based on MATLAB and Simulink tools, interacts with this MySQL database, where almost real time data and historical data are taken into account for its core algorithm (the identified model of the plant and the MPC-based control solution), sending its outputs to the same MySQL database, in a specific table.

In this way, CAC1 algorithm reads last data coming from Gerena asphalt plant from the DB itself and sends its outputs to the Orion Context Broker in a direct way using a MATLAB S-Function through the Simulink Environment.

This output data, which is received by the Orion Context Broker, is stored at the MySQL database through the **Draco** module and is also accessed through the visualization module based on **Apache Superset**, a lightweight module that connects to the **MySQL** database (see section 5.1) to be able to display the corresponding CAC1 outputs in both, as a trending graph and as output fields where latest values are displayed. This visualization platform has been chosen for being a plug-in architecture that makes it easy to build custom visualizations that drop directly into **Superset**. This module can be accessed through a web-based interface to be accessible from anywhere, and especially, from the plant where managers and operators can see the corresponding CAC1 outputs and take actions based on detected values.

Schematics of the described implementation and the different FIWARE-based Reference Architecture for the Asphalt Domain can be seen on Figure 2 and in a more detailed, CAC1 focused, on Figure 4.

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The MySQL database is accessible from Apache Superset, currently selected as visualization tool able to read the data stored and process them in order to create the required dashboards. In the following picture (Figure 3) an example of dashboard produced with the outputs of CAC1, in which the burner power of the dryer drum and the rotary speed are depicted on a time-series chart.

Figure 3 – CAC1 Line charts

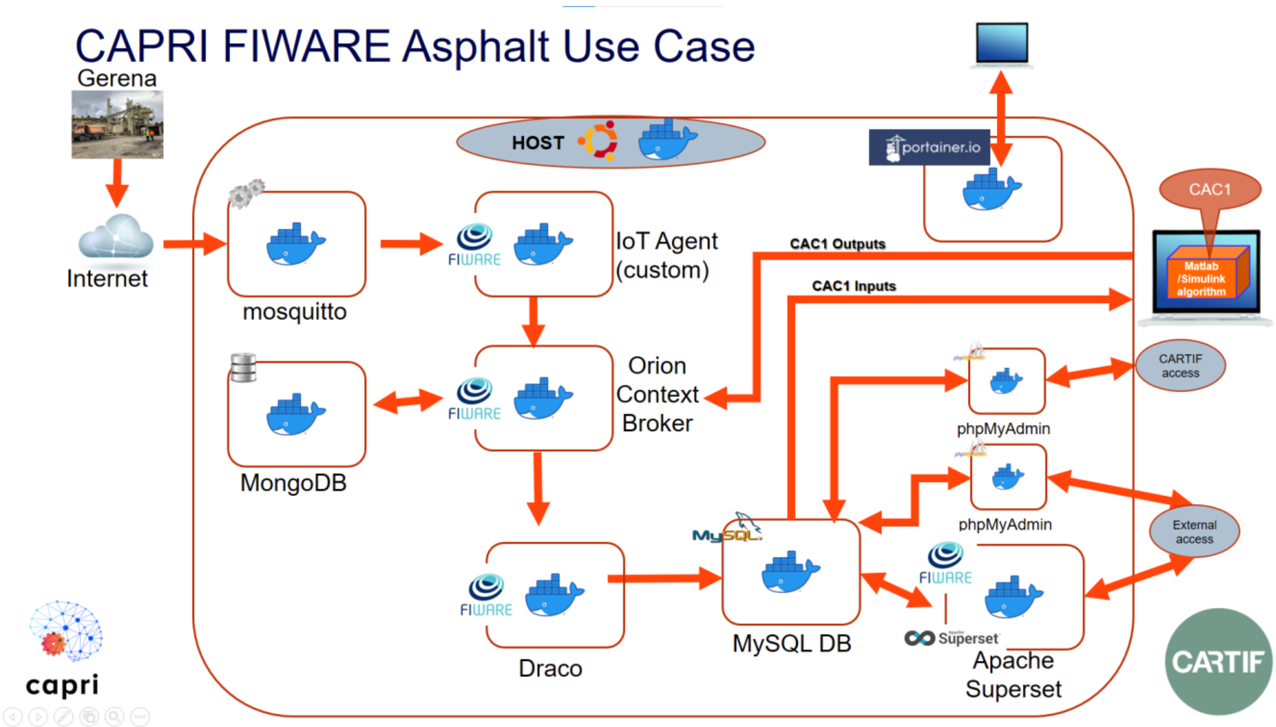

Figure 4: CAPRI FIWARE Asphalt domain schematics and CAC1 CS integration

4.2 Steel domain

An architectural view of the CAP in the steel use case is shown in Figure 5. It consists of three main parts:

- The agents, collecting data from the automation system and transferring it to the CAP
- The core cognitive automation platform (CAP), providing services such as persistence and a web interface, as well as a runtime for applications that need to work with low-latency data.
- The application runtime, which may or may not be integrated into the CAP. Applications deployed here access data from the CAP via the REST-based web interface.

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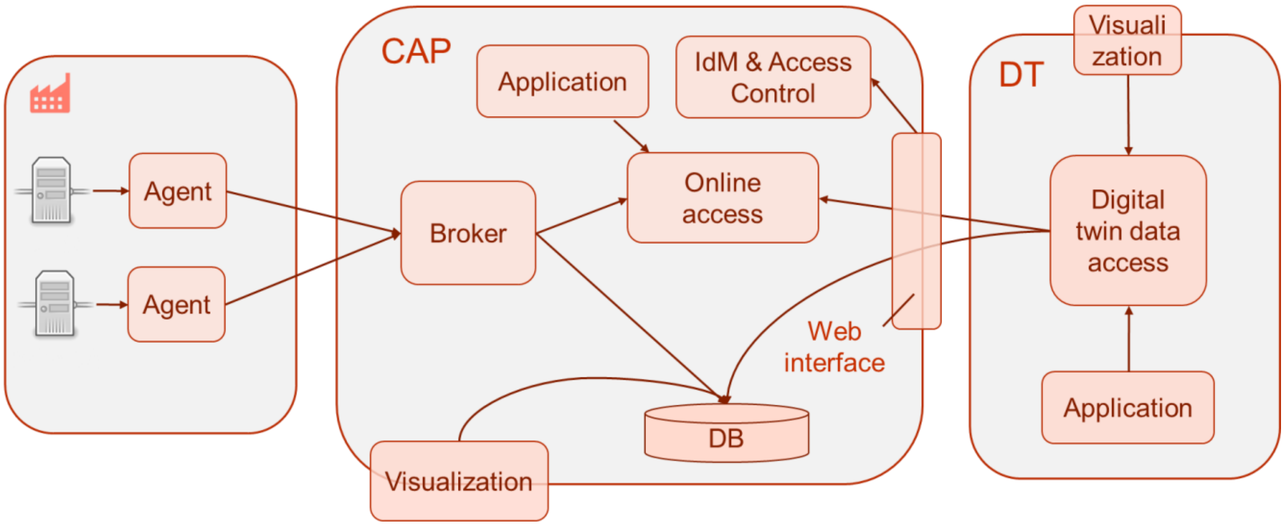

Figure 5: Architectural view of the CAP in the steel use case

The platform has been realized by means of open-source applications, see Figure 6. The data broker receiving process data from the agents is based on Node-RED (https://nodered.org/). The fast layer application runtime consists of a Kafka broker and Spark. The persistence layer has three types of databases, a timeseries database (InfluxDB), a SQL database for structured data (PostgreSQL), and a real-time database for instantaneous data access (REDIS Pub/sub).

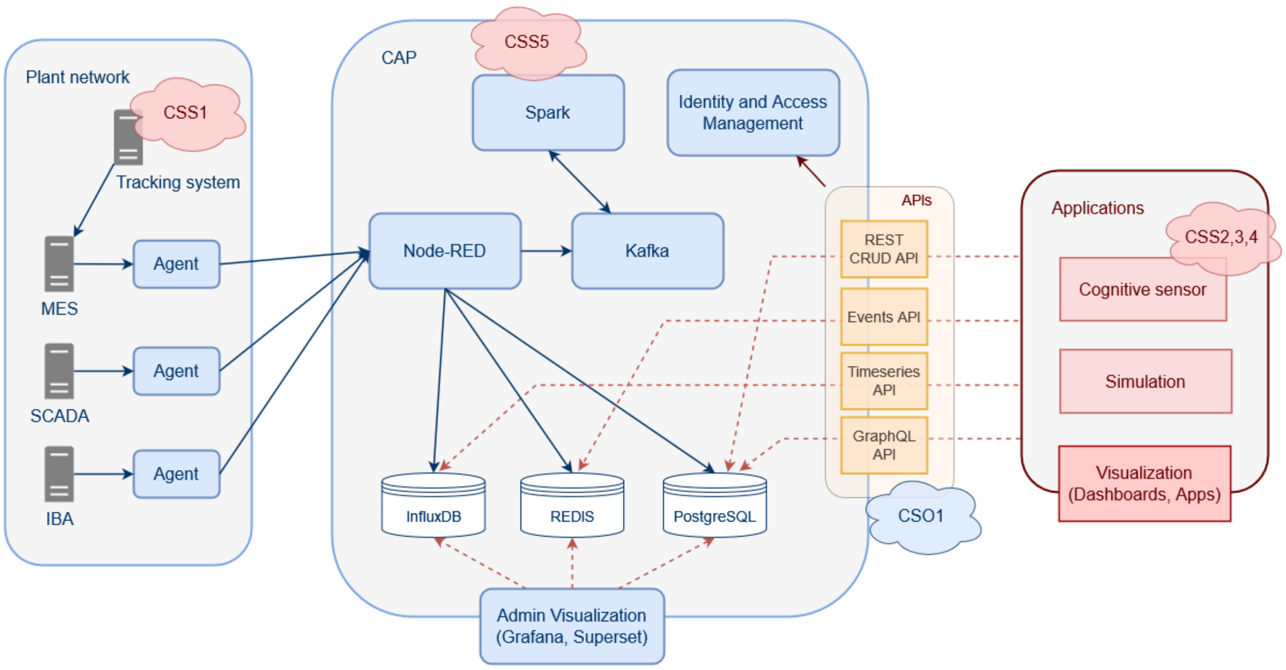

Figure 6: Components of the CAP in the steel use case

4.3 Pharma domain

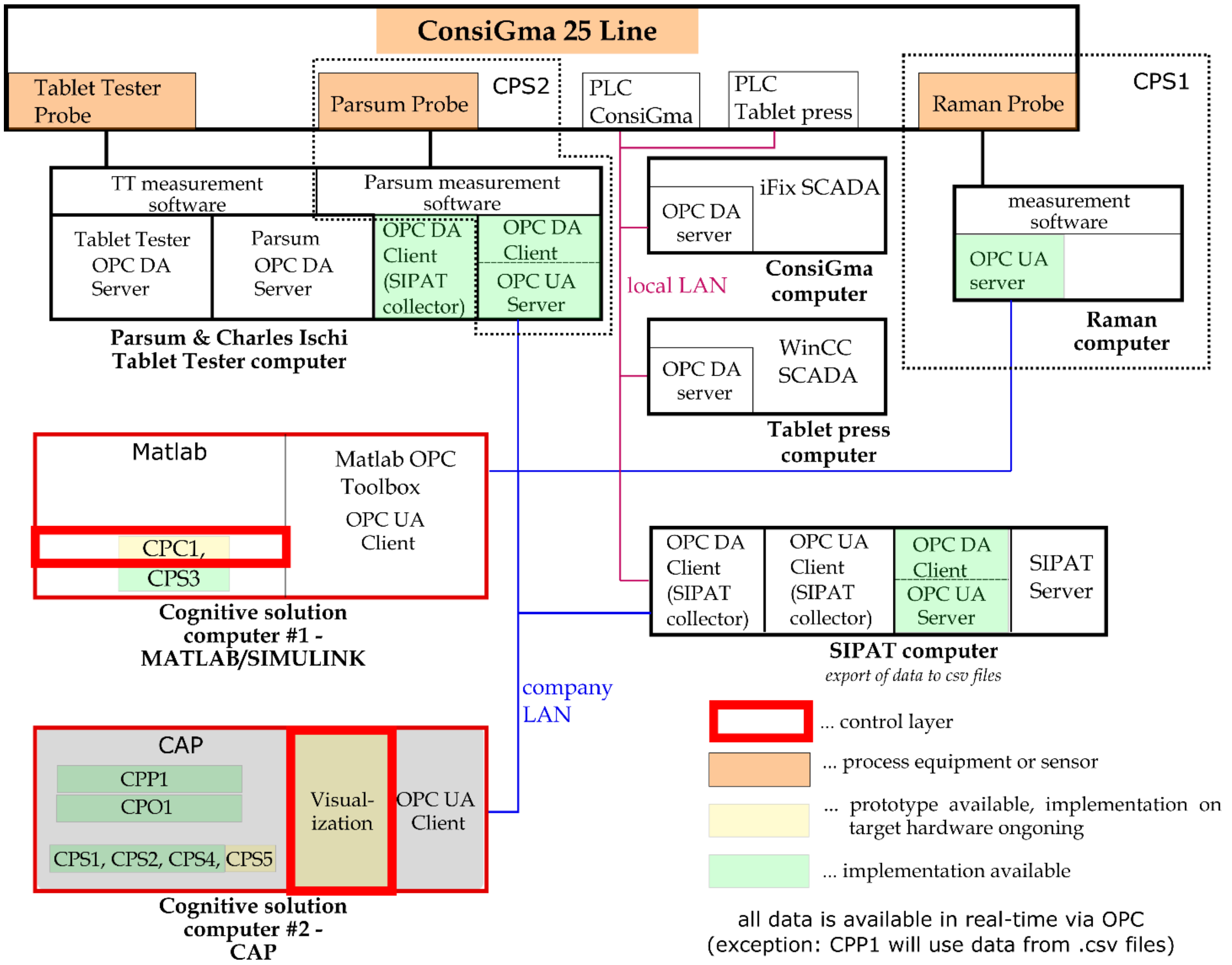

Figure 7: Control layer reference implementation

Figure 7 shows the topology of the pharma solutions. The control layer components are highlighted in red. CPC1 is implemented using Matlab/Simulink, which is connected to the CAP via OPC UA. In terms of the control layer implementation in CAP, its visualization capabilities are being used: trends of controlled variables are visualized. Further, simple user interaction will be implemented, allowing to switch on or off dedicated parts of CPC1. The information needed by CPC1 is collected via the Matlab/Simulink OPC UA-Client from the respective OPC UA-Servers. Information that is needed covers:

i) process data from the ConsiGma 25 manufacturing line (read by OPCDA-client on the SIPAT computer, provided via the OPCUA server on SIPAT computer),

ii) ii) results of CPS1, CPS2 (provided via the respective OPC UA servers on the Raman computer and the Parsum and Charles Ischi tablet test computer) and CPS3 (directly available in Matlab/Simulink).

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5 Information Modelling

5.1 Asphalt domain

In the Asphalt domain, the whole dataset coming from the actual asphalt plant located at Gerena (Spain) is received using MQTT protocol. Two different types of datastreams are sent from the plant:

- Production dataframes: These datasets are received following the following conventions:
    - STOP DRYING PROCESS PATTERNS (Short RPA + RPD + RPE): The codes short RPA + RPD+ RPE are concatenated to form a single frame and are sent every 5 seconds, when the drying process is stopped (no formula and batch during the drying process).
    - DRYING SETPOINT FRAMES (SP): The SPA+SPB+SPC codes are concatenated into a single frame and sent once when the formula for drying is selected.
    - DRYING FRAME (RP): The codes RPA+RPB+RPC+RPD+RPD+RPE are concatenated to form a single frame and are sent every 5 seconds when the plant is in production (current formula and batch).
    - MIX TOWER SETPOINT FRAMES (ST): The STA+STB codes are concatenated to form a single frame and are sent once when the formula is selected in the tower.
    - MIX TOWER PRODUCTION FRAMES (RT): The RTA+RTB+RTF codes are concatenated to form a single frame and are sent at the end of the mixer emptying, when the plant is in wrapper or mixer blending production (formula and batch already selected at the hot tower level).
- IoT dataframes: These datasets are sent every 1 second and they send data from all those sensors and equipment which have been directly connected to the asphalt WAGO PLC, responsible for sending all data coming from the plant. This comprises the different data coming from different temperature, flow, weather station, etc coming from the plant. More information can be found at deliverable D2.2 and the different D3. X.

As explained in section 4.1, the data, through the CAP platform based on FIWARE modules, is stored in a MySQL database with the structure that can be seen on Figure 8.

The different data coming from IoT dataframes is stored in different tables with self-explanatory names (temperature, amperage, etc).

All production related dataframes have been stored in different tables depending on the data as explained in the previous paragraphs (RP, RT, SP, ST, etc) (see Figure 8).

The tables whose names start with 'ThingsXXX' are the raw dataframes as they are received from the plant, without any classification (see Figure 8).

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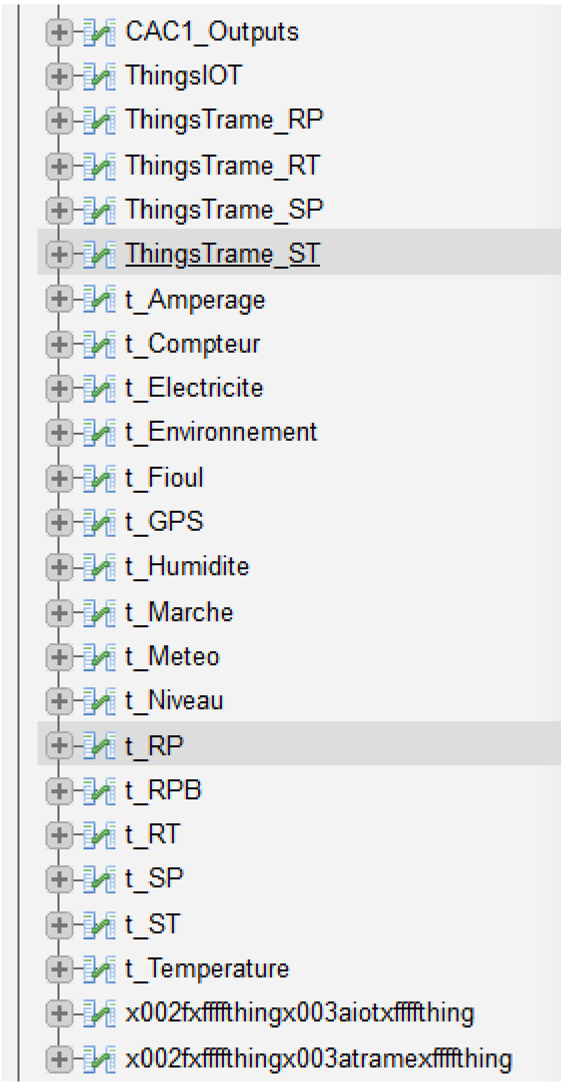

Figure 8: MySQL database structure (tables) for Asphalt Use Case data persistence.

Specifically, for the CAC1 CS algorithm, the following **input data** is read from the database (in a last received data basis) using the different available tables at DB:

- 'rcvTime' – Time stamp of the received data at the CAP platform (format yyyy-MM-dd'T'HH:mm:ss,SSSZ) – Datetime data type
- 'Cburner_RPA1300' – Rotary Dryer Drum Burner Power (%) – Numeric Data Type
- 'Fproduction_RPA0700' – Production Flow Rate (Tn/h) – Numeric Data Type
- 'Pdryer_RPA2000' – Pressure drop at rotary dryer drum (Pa) – Numeric Data Type
- 'Pfilter_aggr_RPA2100' – Pressure drop at baghouse filter (Pa) – Numeric Data Type
- 'Crotating_dryer_RPA1900' – Rotary dryer drum speed (%)– Numeric Data Type
- 'DrumFuelVal' - Consumed fuel at dryer drum burner (kg) – Numeric Data Type
- 'TemperatureDoseur1' - Cold Aggregates Hopper 1 (sands) Temperature (ºC) – Numeric Data Type
- 'TemperatureDoseur2' - Cold Aggregates Hopper 2 (sands) Temperature (ºC) – Numeric Data Type
- 'Tmixture_RTA1300' - Mixture temperature (ºC) – Numeric Data Type

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- 'MetTemperatureExt' - Weather Station External Temperature (ºC) – Numeric Data Type
- 'HumiditeDoseur1' - Cold Aggregates Hopper 1 (sands) Humidity (%) – Numeric Data Type
- 'HumiditeDoseur2' - Cold Aggregates Hopper 2 (sands) Humidity (%) – Numeric Data Type
- 'MetHygrometrie' - Weather Station Humidity (%) – Numeric Data Type
- 'O2' - O2 concentration at baghouse filter (chimney) (%) – Numeric Data Type
- 'PPMPrefitre' – Particles Concentration at baghouse filter inlet (ppm) – Numeric Data Type
- 'Tout_dryer_RPA1000' - Outlet Rotating Dryer Temperature (ºC) – Numeric Data Type
- 'Tfilter_in_aggr_RPA1400' - Inlet aggregates filter temperature (ºC) – Numeric Data Type

The CAC1 **output data,** received, managed and distributed by the Orion Context Broker, is then written to the CAC1_Outputs table of the database with the corresponding timestamp:

- 'C_Burner_SP' – Rotary Dryer Drum Burner Power Setpoint (%) – Numeric Data Type
- 'C_Drum_SP' – Rotary Dryer Drum Rotation Speed Setpoint (%) – Numeric Data Type

The exhaust damper opening as a setpoint has been discarded due to the fact that the integrated control loop for pressure control (negative) at the baghouse filter is already optimum.

5.2 Steel domain

The modelling approach used in the steel domain follows the FIWARE modelling guidelines. Model classes are specified in terms of JSON schema and try to adhere to the NGSI-LD cross domain ontology, extending it with a domain-specific model for the steel production. The latter is based on the SAREF extension for industry and manufacturing (SAREF4INMA, https://saref.etsi.org/saref4inma), with certain adaptations. The model has been described to some extent in the CAPRI deliverable D3.4 already, and a standalone publication on the topic is planned. See Figure 9 for a high-level overview.

The model is a core component of the digital twin platform realized in the steel use case and as such it shall be reflected by the CAP REST interface, although at the time of writing some harmonization work is still pending, with the interface following more closely the naming conventions of the data sources/agents than the green field model. Although the FIWARE software is not used in the steel use case, the model could be deployed to a FIWARE-based platform as well.

Examples of the classes used for modelling billets and heats, pertaining mainly to CSS2, are illustrated in Figure 9 and Figure 10.

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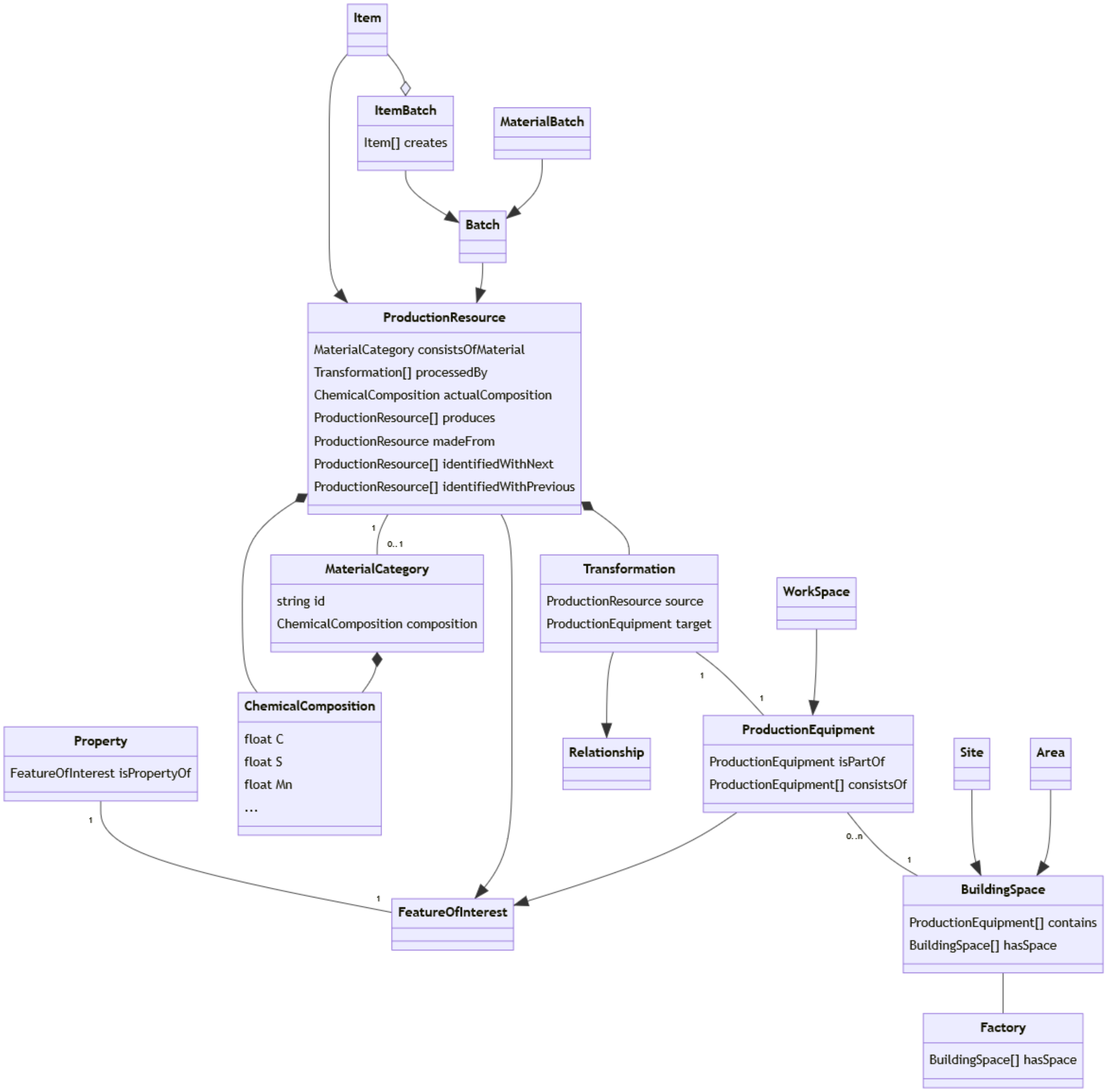

Figure 9: High-level class structure for the steel domain, based on the SAREF4INMA model

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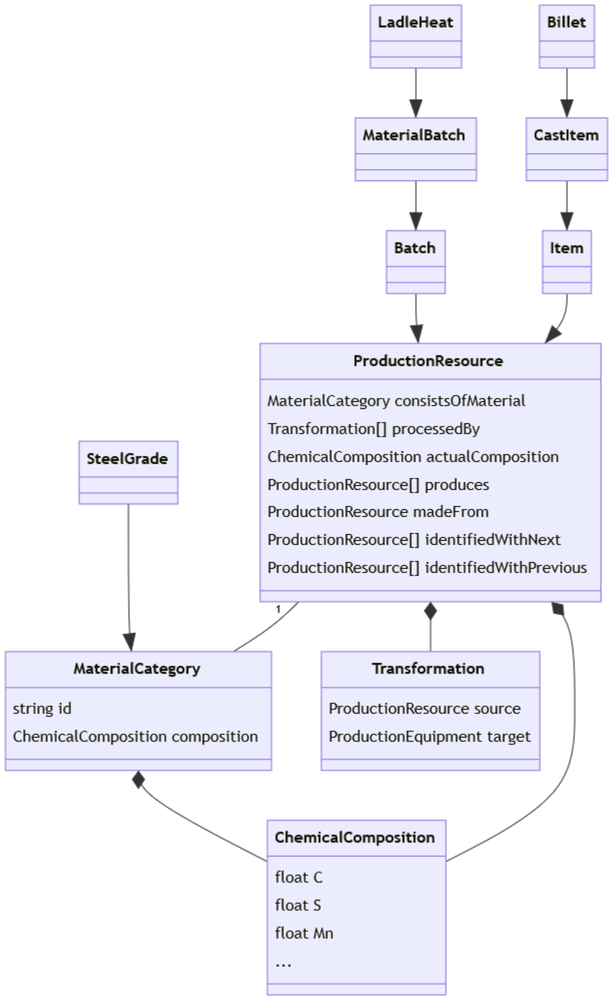

Figure 10: Class hierarchy for the LadleHeat and Billet classes, relevant to CSS2.

5.3 Pharma domain

The control solution CPC1 covers two main parts: i) a process control concept that uses real-time process data and data computed by CPS1, CPS2 and CPS3 in order to execute model based control algorithms; ii) a quality control concept that relies on information that is related to the product quality (so called critical quality attributes, CQAs) and performs discharge of out-of-specification (OOS) – material.

i) Process control concept

The process control involves three control concepts, each relevant for one of the intermediate critical quality attributes (CQAs), i.e., the particle size distribution (PSD) of wet granules, API concentration of wet granules, and residual moisture (LOD) of dry granules. The first control concept utilizes the first moment of granule size (M_1, monitored via CPS2) as a controlled variable. The model predictive controller (MPC) adjusts the granulation parameters, i.e., liquid-to-solid ratio (LS), in order to keep M_1 close to the specified reference value. The second developed control concept considers the API concentration of wet granules as a controlled variable (monitored via CPS1). This quantity is kept within the specified boundaries by means of solid feed rate adjustments. Additionally, the controller adjusts the liquid feed rate in order to keep LS close to the reference value. The third control concept involves the drying time adjustments based on the CPS3 prediction of LOD in individual cells. As

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soon as the predicted LOD reaches the specified target value, drying is stopped and the respective cell is emptied.

ii) Quality control concept

The quality control-part of CPC1 is shown in Figure 11 . Aim of the quality control concept is to discharge OOS material either after the ribbon blender or after the tablet press. The discharge-decision is based on CPSx data and on process data originating from the manufacturing line. From the manufacturing line-data, information on the current location of specific material is derived. This information is fed into a material tracking model (which is implemented as part of CPC1). The information provided by that material tracking model is then used (in combination with the CPSx data) to trigger potential discharge decisions after the ribbon blender or after the tablet press at the correct time.

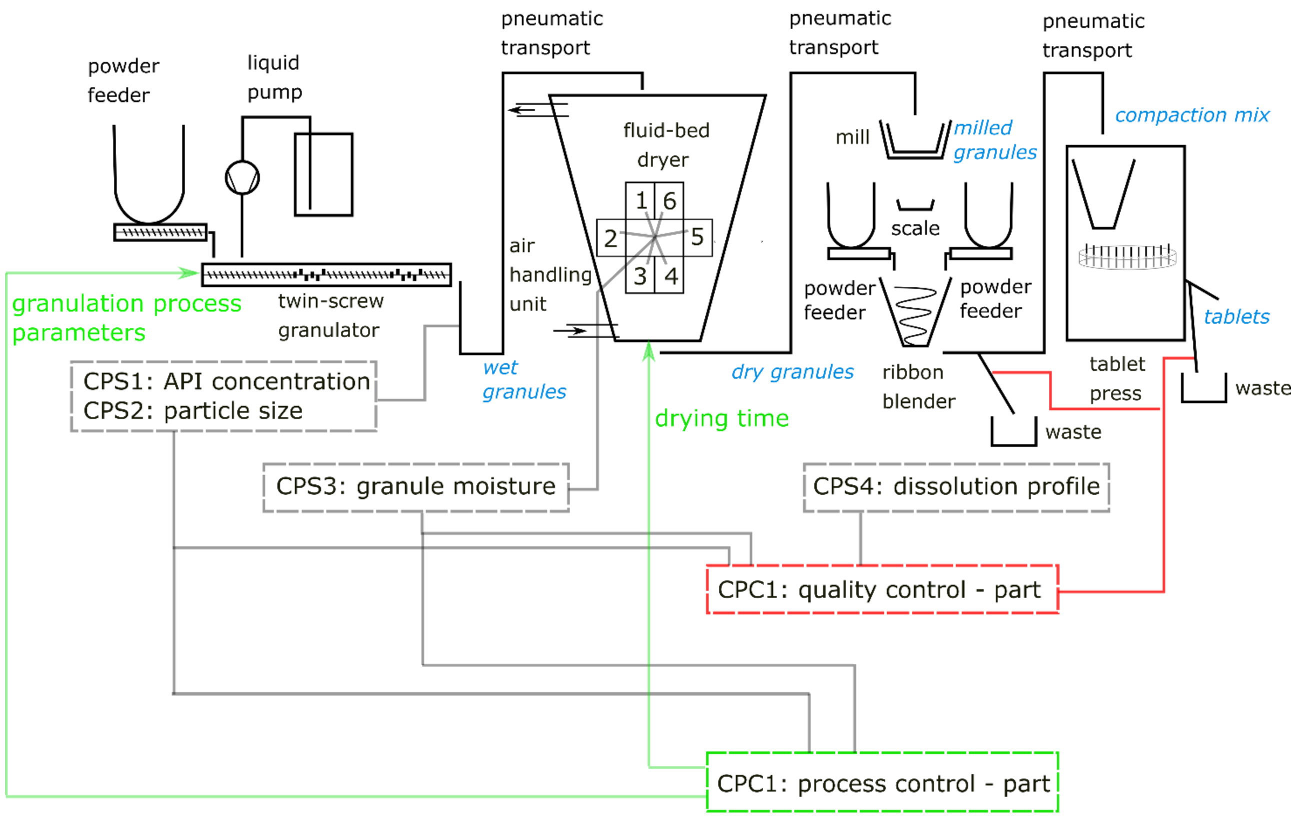

Figure 11: Process- and quality control concept

In Figure 12, the relation between product keys (PKs) and tablets is shown. A PK is a defined portion of material (granules) that propagates through the ConsiGma25™ manufacturing line. At the tablet press, neighboring PKs are being intermixed. Consequently, a single tablet can contain material from multiple PKs, and it is also possible that more than one tablets are typically related to one PK. From the attributes of the PK (together with the compute_press_RTD – function used for material tracking) and the tableting main compaction force the tablet attributes are computed (c_API, dissolution_time).

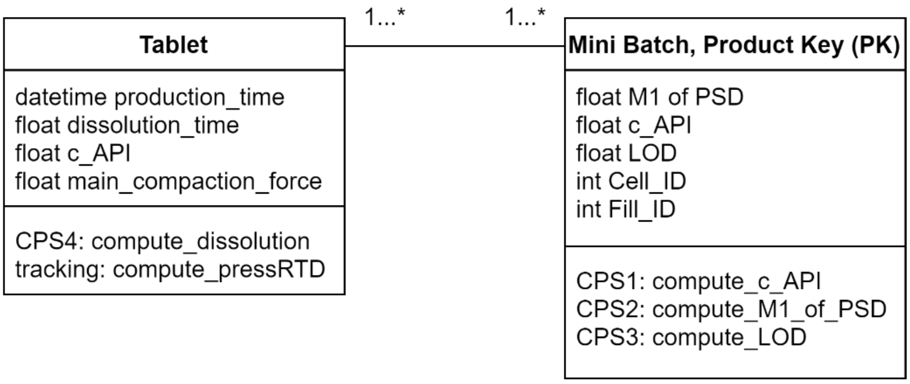

Figure 12: Class structure for material tracking

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6 Control Layer Applications

6.1 Asphalt domain

6.1.1 Cognitive control of the asphalt drum [CAC1]

FILES concerning CAC1 Cognitive solution

CAC1 CS development is based on the MATLAB development and simulation environment where it has been integrated into the CAP FIWARE-based platform as described in section 4.1.

- CAC1_ALL_DATA.mat

Preload of this MATLAB data file, which concerns the memory load of the corresponding variables used by this cognitive solution, is a mandatory first step to be performed before running this CS:

  - ss3: idss Matlab data type that refers to the N4SID identified data-based model that simulates the model of the rotary dryer drum using the System Identification Toolbox of the MATLAB environment. This model is based on the data used in the different experiments and tests performed at the actual Gerena asphalt plant.
  - mpc1: MPC model-based predictive control that has been setup and tuned using the MPC Designer Toolbox of the MATLAB environment.

- CAC1_IO_DB.m
  - MATLAB script file used by the main Simulink-based environment to run the CS. This file reads as they are received from the plant, all the corresponding data inputs needed by this CS from the MySQL database used at the FIWARE-based persistence data module as described in section 4.1
- CAC1_IO_DB_OUTPUTS_v2.m
  - MATLAB script file used by the main Simulink-based environment to run the CS. This file sends the corresponding outputs as they are calculated by the CAC1 algorithm to the Orion Context Broker using POST method through curl embedded function at MATLAB. From there, the data is distributed using Draco module at the FIWARE-based persistence data module as described in section 4.1 to show the corresponding set-points to be shown at the actual plant.
- CAC1_curl_post_matlab_function_v3.m
  - Auxiliary function used by the previous script to send the CAC1 output data directly to the Orion Context Broker using POST request via curl (see section 4.1).
- CAC1_IDSS_MODEL_MPC_CONTROLLER_v10.slx
  - Simulink model simulation, with the corresponding identified model block and the MPC control block previously fine-tuned with experimental data..

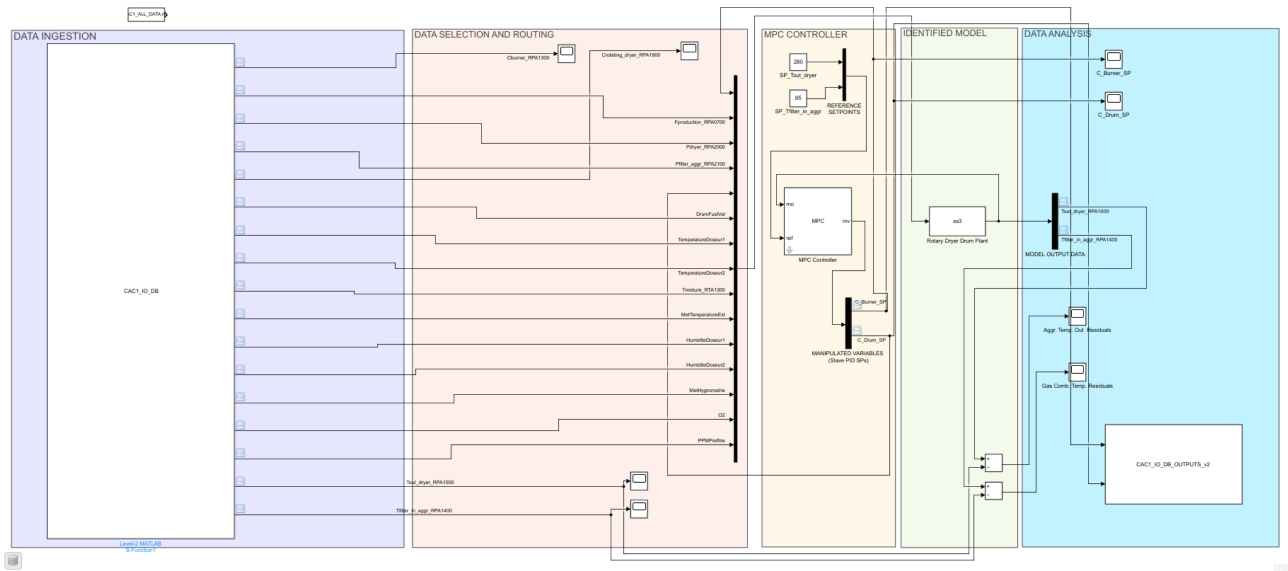

Figure 13: CAC1 Simulink algorithm implementation

DATA model

The I/O data model of the CAC1 algorithm is the one described at section 5.1.

CAP FIWARE integration

As described in section 4.1, **CAC1** algorithm reads the corresponding data coming from the plant directly from the **MySQL** database, reading the last data set received from the asphalt plant. The calculated outputs are then sent to the **Orion Context Broker** through a *MATLAB* S-function used at the *Simulink* environment. For this, it is used a library function that, through https, make a POST request to update the corresponding entity via curl. From this point and then through the Broker and, using the **Draco** module, written to the *CAC_Outputs table* of the same database. Then again, from this point, it is used by the corresponding visualization module to be shown at the actual asphalt plant. The Visualization Module, based on **Apache Superset**, can be then accessed through a web-based interface by the plant operators to see CAC1 output data, the corresponding Optimized Set-Points of the Burner Power and the Rotary Speed of the plant Rotary Dryer Drum. The web-based dashboard showcases some trending graphics and outputs fields that show the latest calculated value by the CAC1 algorithm. At this step, it is the plant managers/operators responsibility to apply the displayed value or ignore it based on their experience.

Connecting **Apache Superset** to the **CAC1_Outputs** table stored in MySQL database, the burner power of the dryer drum and the rotary speed are plotted on a time-series chart alongside two numeric fields showing the last current value (see Figure 14 and Figure 15).

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Figure 14 - C_Drum and C_burner linecharts (1)

Figure 15 - C_Drum and C_burner linecharts (2)

Requirements to run CAC1 algorithm

In order to run CAC1 algorithm, integrated within the CAP FIWARE-based platform, the following requirements must be fulfilled:

- The corresponding CAP FIWARE-based platform, as described in section 4.1, must be up and running.
- For the time being, MATLAB R2021b or above must be installed on a computer where the previous platform can be reached:
  - The following applications / toolboxes are needed:
    - Simulink
    - Database Toolbox
    - System Identification Toolbox

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  - Control System Toolbox
  - MPC (Model Predictive Control) Designer Toolbox

- Connection to the MySQL Database used by the platform for database persistence must be setup. The corresponding previously described I/O Matlab scripts have the corresponding access data. This connection is configured as a JDBC Data Source, although it can be setup as a Native Data Source within the Database Toolbox.
- Preloading of the file CAC1_ALL_DATA.mat in the Matlab workspace must be performed as a first step (although this step is automatically done if the next described file is loaded into Simulink environment).
- Then, loading of the Simulink CAC1_IDSS_MODEL_MPC_CONTROLLER_v10.slx and running it must be done. The CAC1 algorithm will then read the most recent data coming from the Gerena asphalt plant and calculate the corresponding setpoints for the burner power and rotary speed of the rotary dryer drum to control both, aggregates temperature and exhaust gases temperature of the same machine.

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6.2 Steel domain

6.2.1 Cognitive Sensor for Solidification [CSS2]

CSS2_video_2.mp4

The attached screencast explains the data flow for the steel solidification sensor. The latter retrieves the required input process data via the REST interface of the CAP and writes its results to the platform via the same API. The following data sources are relevant, both coming from the MES of the steel plant:

- Chemical composition of the heats (batches of liquid steel) and secondary metallurgy treatment (structured records)
- Casting timeseries, including continuous temperature measurements, casting speed, cooling water flow, etc

As a result, the sensor generates the following data:

- Billet twins: at the end of the casting machine the solid steel is cut into individual items, the so-called billets. The digital twin of these billets is created by the CSS2 and fed with the casting and secondary metallurgy data.
- Billet section data: as input for the risk sensor CSS5 aggregated data for billet cross sections of roughly 30cm length is generated.

The video explains the data flow and the use of a simulation tool for generating test data, based on historical data. The visualization of input and output data by means of dedicated dashboards is shown, as well, cf. Figure 16 and Figure 17. This visualization is based on Grafana.

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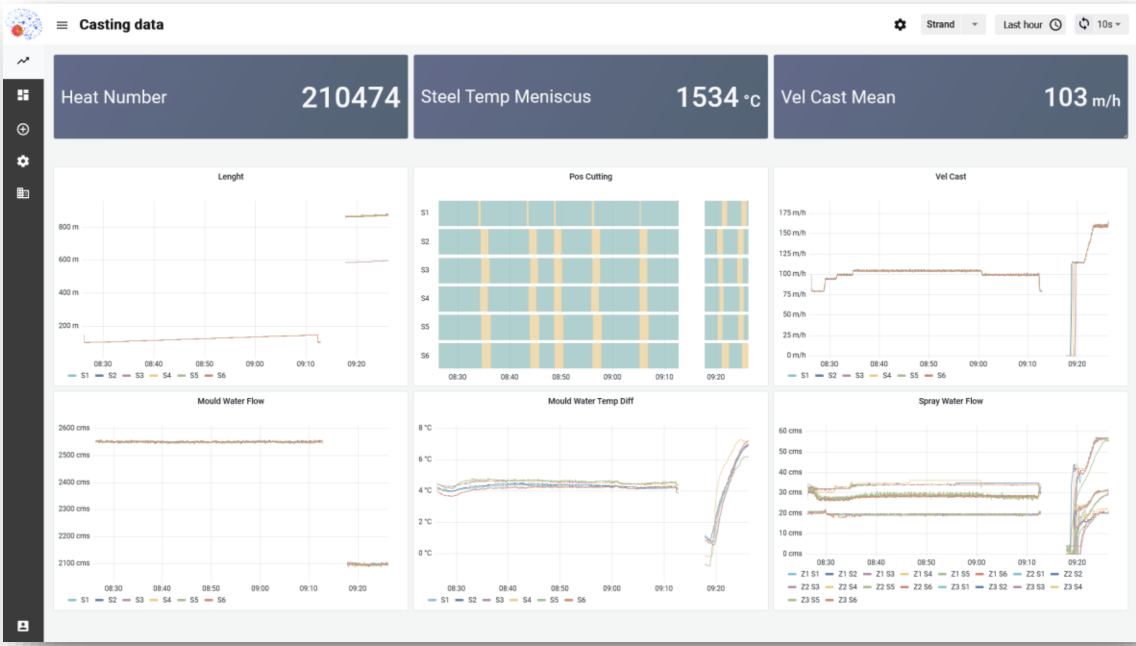

Figure 16: Visualization of casting timeseries data in the steel CAP

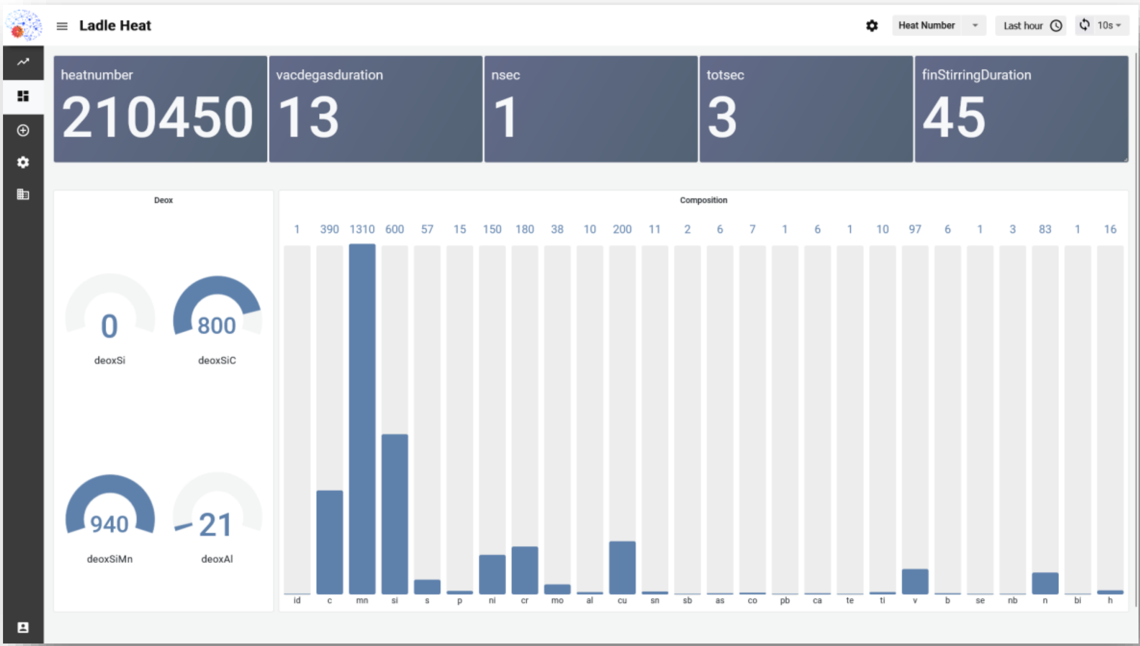

Figure 17: Visualization of structured data in the steel CAP

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6.2.2 Cognitive Sensor for Product Temperature [CSS3]

<u>CSS3 video_2.mp4</u>

The attached screencast explains the data flow for the cognitive temperature sensor. Its input data is received from the IBA system for the hot rolling mill, consisting of temperature measurements at three specific points in the mill, as shown at the bottom of Figure 18. Additionally, information on the diameter of the bars produced in the hot rolling mill is extracted from the MES and made available to the sensor. The cognitive temperature sensor derives product-centric dataset per steel billet (and the derived bars) and extrapolates the temperature evolution of the steel bars to the following cooling bed. This data is then written as a timeseries to the CAP, see Figure 19

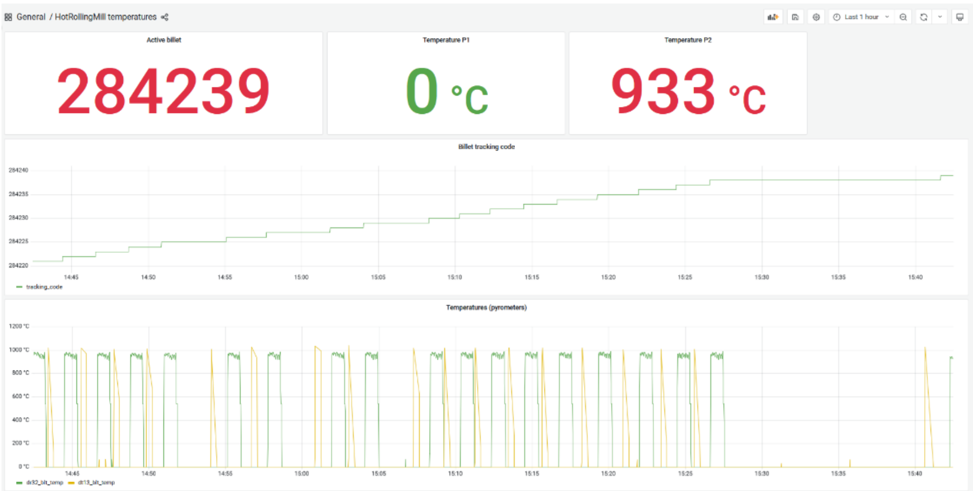

Figure 18: Dashboard showing the process data used by CSS3, in particular the temperature measurements from pyrometers installed in the hot rolling mill shown at the bottom.

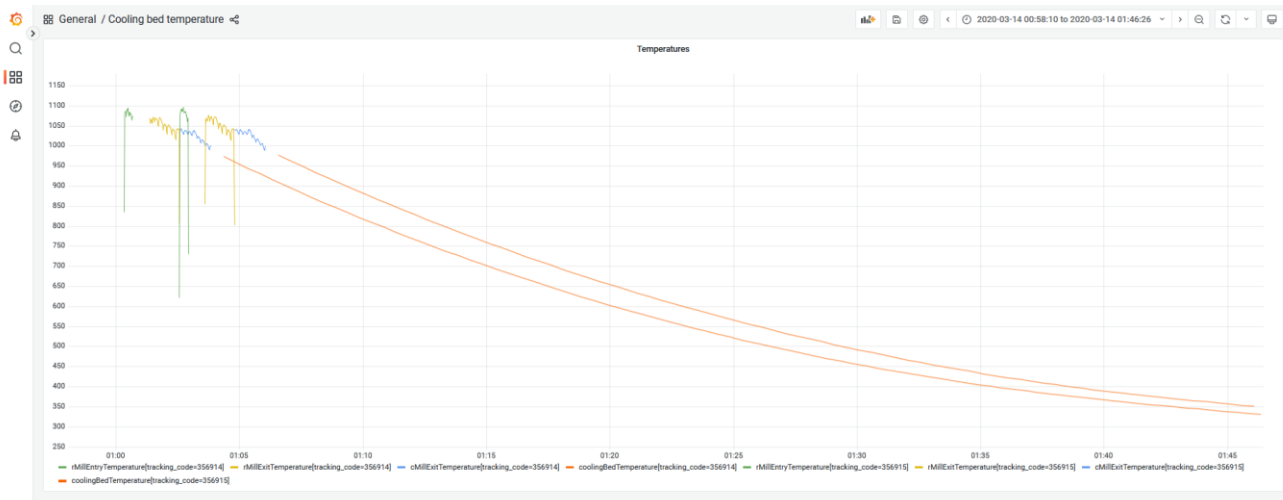

Figure 19: A dashboard presenting the temperature measurements from Figure 18 in a product-centric way, per steel bar, along with the interpolation for the temperature evolution of the bars on the cooling bed, as generated by CSS3.

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6.2.3 Cognitive Sensor for Scale Build-Up [CSS4]

CSS4 video_2.mp4

The presentation explains the data flow for the cognitive scale sensor, which estimates the thickness and composition of mill scale on the surface of steel bars after leaving the hot rolling mill. Mill scale consists of oxides that form on the surface of hot steel. Once the bars have cooled down below a temperature of roughly 500°C after leaving the hot rolling mill, the formation of scale ends.

Relevant input data for the scale estimation are the steel composition or steel grade and the temperature evolution over time. The latter is obtained from the temperature sensor CSS3, the former information is obtained from the secondary metallurgy raw data (source: MES), using the hot rolling tracking information (CSS1) to identify the relevant heat the bars are made from. The output of the sensor is a timeseries of the scale thickness, which is again written to the CAP, see Figure 20.

Figure 20: Visualization of the scale thickness (lower plot).

6.3 Pharma domain

6.3.1 Cognitive control concept [CPC1]

In order to realize the variations of API concentration, two solid feeders, the first one filled with a pre-blend containing 8% API, and the second one filled with the a pre-blend containing 0% API, are placed at the granulator inlet. An artificial feed rate disturbance of the second feeder is introduced to the system (approximately at 310s of the experiment shown in Figure 21, see $SFR2_{dist}$ in the third subplot). This disturbance results in a deviation of API concentration and L/S. CPS1 detects these deviations and provides them in real-time to the CPC1. CPC1 copes with the disturbance by decreasing the feed rate of the first feeder $SFR1_{ctrl}$ and the liquid feed rate of the pump LFR_{ctrl}. In such a way, both, API concentration and LS are brought back to the reference value. After the disturbance disappears (approximately at 650s of the experiment, see subplot 3 in Figure 21), the controller increases the solid- and liquid feed rate, $SFR1_{ctrl}$ and LFR_{ctrl}, respectively, and brings the API concentration and LS back to the reference values.

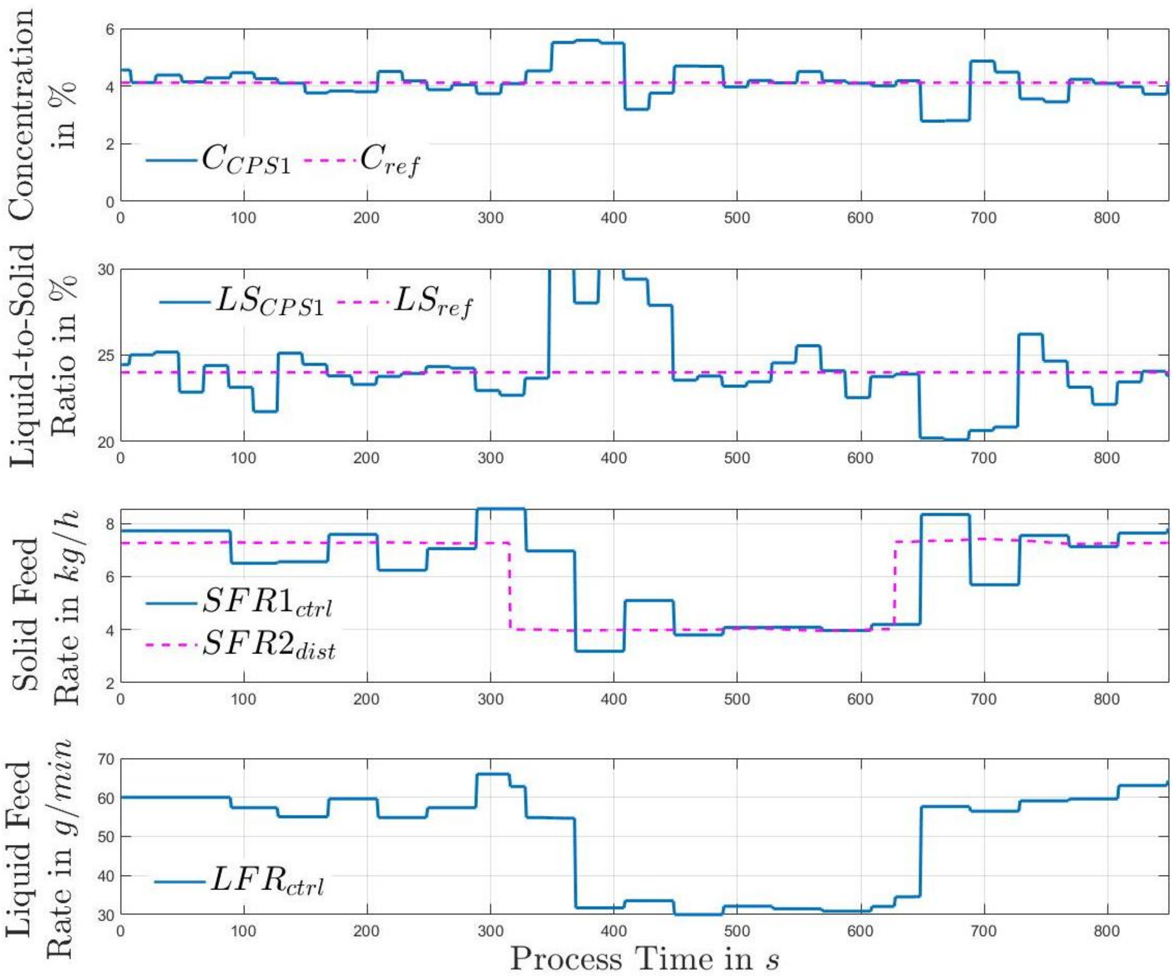

Figure 21: Investigation of concentration control concept performance on the ConsiGma line.

In order to investigate the performance of the granule size control concept, an artificial feed rate disturbance is introduced to the system. This disturbance is reflected in the M_1 deviation from the reference value approximately at 310s of the experiment (see top plot in Figure 22). CPC1 reacts to this deviation by increasing the liquid feed rate, bringing M_1 back to the specified reference value. After the introduced disturbance disappears, M_1 increases. Consequently, CPC1 decreases the liquid feed rate accordingly, and brings M_1 back to the reference value again.

Note: The controller performance was tested with an updated version of CPS2. The characteristic moment M_1 was calculated using the real size axis instead of a logarithmically scaled one and a pre-processing via the signal processing concept described in D4.1 was performed.

The attached zip-archive CPC1_Data_2.zip contains the datasets shown in Figure 21 and Figure 22. A3_DOK_CPC1_CPS1.xlsx is related to the concentration control approach shown in Figure 21 and A3_DOK_CPC1_CPS2.xlsx is related to the particle size control approach shown in Figure 22.

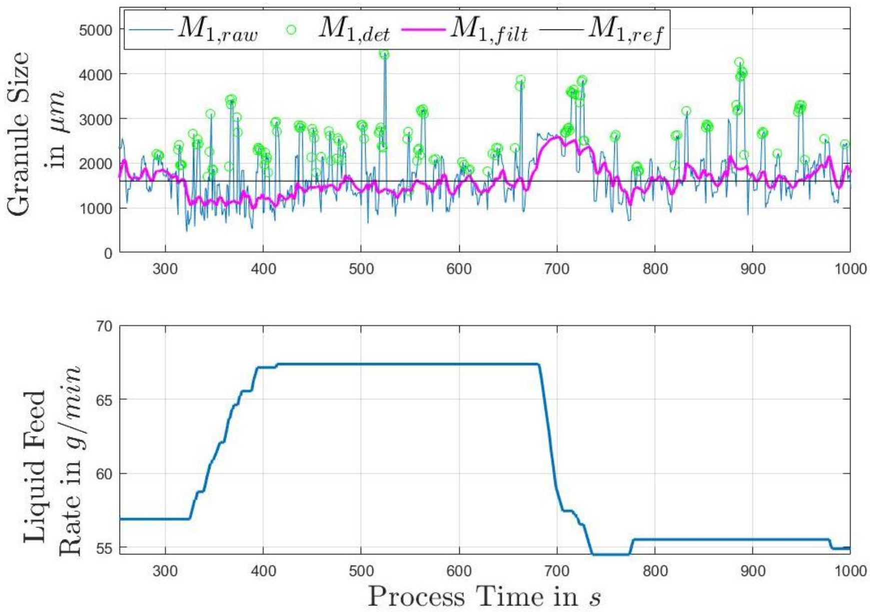

Figure 22: Investigation of granule size control concept performance on the ConsiGma line.

The top plot shows the moment M1 computed from raw data M1,raw, as well as a filtered version M1,filt and its reference value M1,ref. The values M1,det highlighted in green show raw-data points that were considered corrupted and consequently discarded.

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7 Conclusions and Next Steps

As a brief summary, the control layer developed for the CAPRI project, is specified per use case, and per cognitive solution, but all of them have a common part integrated, the FIWARE framework which is the central of communications of all the information transferred in to the project.

In general, the output of WP4 and more specifically, this deliverable D4.3 (of type OTHER) focused on the control based cognitive solutions and their integration into the Reference Architecture, is being integrated within the CAP platform in order to satisfy the needs of the three CAPRI domains (i.e., Asphalt, Steel, and Pharma) supporting all use cases and covering the entire life data cycle from the data ingestion to the data presentation.

The different control algorithms, already analysed in as outputs of WP3 as stand-alone solutions at lab level, have been integrated into the CAP platform for implementing the control layer.

WP4 is showing the quality, flexibility and performance of the different control solutions being integrated within the corresponding CAP platform which is mainly based on the FIWARE framework as Reference Architecture as described in section 3.

On the other hand, as it can be seen, it is shown a toolbox of control cognitive solutions for assisting process control to help the adoption of the CAP for batch, continuous and hybrid process industry plants.

The cognitive control solutions with the CAP following a modular and iterative approach provide a holistic solution, managing the cognitive functions embedded in cognitive control. At the same time, the integration of this layer enables a higher level of intelligence exploiting the vertical integration of such control solutions with other processing modules, at both edge and cloud level, delivering the cognitive applications towards the appropriate user role (e.g. planners, managers, workers).

The “Control Layer” Reference Implementation of the CAP is being developed and enables further customizations for the implementation of the three tailored instances of the CAP for the three pilots.

According to the different integrations within each domain, although maintaining the FIWARE framework as central core of the whole CAP platform, specific needs and implementations based on different modules have been selected, setup and commission to run all the different CS which are within the control layer. Sometimes, as described in the different sections, customizations of the different modules have had to be dealt with to allow the implementation of the corresponding application / tool.

Next steps involve the final integration of the rest of the “layers” of the reference architecture and the final validation to be developed at WP5, addressing manufacturing challenges in industrial operational environments of the three chosen process sectors, and providing useful feedbacks and lessons learnt.

Different KPI’s will be calculated and deployed to see if initial target objectives are met with an evaluation period (6-month minimum) of the performance improvements thanks to the different implemented cognitive solutions. This will provide effective background basis for replication purposes and dissemination. Results will be able to be replicated in other sectors with similar challenges from the point of view of control cognitive solutions applied to similar unitary processes.

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