Cognitive Automation Platform for European PRocess Industry digital transformation

Deliverable

D3.5 CAPRI Smart decision support

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Document Control Page	
Title	CAPRI Smart decision support
Lead Beneficiary	Nissatech
Description	This deliverable of type OTHER presents the implementation results of the data-driven Reference Architecture for Cognitive Plants in the process industry, with Smart Decision Support, as developed in T3.4. The Capri Reference Implementation, as described in D3.1, has been materialized by Open Source environments such as APACHE and FIWARE, and state of the art open standards such as OPC UA and MQTT. Part of the final outcomes will be provided in the zip file to be submitted together with the present deliverable. For each Cognitive solution the following details will be provided: **Text document** (Word/Pdf): explaining the work done and providing an introduction to video, to the user manual of the apps, including the available links, data and metadata description, if any, and the description of everything else in the ZIP; **Executable of the program/app**, if any; Any kind of **data** that can be publicly shown (full data, sample data, metadata, surveys results, …), if any; **Video** used to explain “physical” results, as sensors, if any.
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5.0	31/03/2022	CARTIF	Final review

List of Acronyms and Abbreviation	
Acronyms	**Description**
CS	Cognitive Solution
MQTT	Message Queuing Telemetry Transport
DMP	Data Management Plan

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EXECUTIVE SUMMARY / ABSTRACT SCOPE

D3.5 – "CAPRI Smart decision support", is a deliverable of type OTHER that, together with D3.2, D3.4 and D3.5, targets the so-called 'MS4' milestone, regarding technology validation of different cognitive solutions at M24, and describes the concrete achievements in the development of the Smart decision support cognitive solutions, leveraging on the Capri reference Implementation described in D3.1, and particularly on open standards such as OPC UA and MQTT for data ingestion and NGSI-LD for data representation.

After an introduction on the document's scope, audience and structure, for each domain a summary view of cognitive solutions at decision support level is proposed, then an extensive list of evidences will be detailed to better shape the achievement obtained. For each cognitive solution, they are provided a text to explain the work done until M24: an introduction to a video showing the cognitive solution in laboratory environment, data and metadata description, sample data used for testing, user manual of the applications, and any other element. Some of these contents cannot be included in this document, so they will be uploaded in a separate file.

It is provided also a section that describes the distribution of the various developed CSs in the D3.2, D3.3, D3.4 and D3.5 deliverables, with the used content structure to make easier to find the relevant information.

The final section offers some recommendations to further Work Packages (WP4 and WP5) on the best integration approaches with the CAP, or features to be evaluated in next phases that could bring improvements on the functional side, or can constitute innovative aspects to be followed up in future research projects.

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1 Introduction

1.1 Scope of Deliverable

D3.5 – "CAPRI Smart decision support", is a deliverable of type OTHER aiming at describing the practical results of the data-driven Reference Architecture for Cognitive Plants in the process industry, with smart decision support components, as designed in T3.4. The CAPRI Reference Implementation, as described in D3.1, has been materialized by Open Source environments such as APACHE and FIWARE, supporting the state of the art of open standards such as OPC UA and MQTT for data ingestion and NGSI-LD for data representation. What will be presented in this deliverable corresponds to achievement of milestone MS4 of technology validation of different cognitive solutions, with a focus on the decision support solution components.

Part of the final outcomes will be provided in the zip file to be submitted together with the present deliverable (uploaded in Zenodo).

1.2 Audience

D3.5 – "CAPRI Smart decision support", is a deliverable of type OTHER that presents the implementation results, targeting the Alpha release of the CAPRI implementation, that represents the standalone implementation of cognitive solution. In this deliverable the practical details of the decision support cognitive components will be provided, with textual information explaining the work done, introduction to videos or screenshots, user manual information on apps used to showcase results, data and metadata description, to better explain the zip file contents.

For this reason, while D3.5 is conceived to be a report accessible to all partners, it is addressed mainly to a reader with a technical background related to Sensors Technologies and Data Architecture:

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

1.3 Relationship with other deliverables

D3.5, together with D3.2, D3.4 and D3.5, trace a continuation line after D3.1. While the latter D3.1 describes the Reference Implementation of the Cognitive Application Platform (CAP) to support the integrated implementation of the four cognitive layers, D3.5 describes in details the standalone development of the sensor based solutions support smart decisions, to be integrated in the final plants in the different domains.

At the same time D3.6 will describe the overall picture of activities performed within WP3, presenting the openness approach on cognitive solution and investigating the generation of Open Data, whose specific results at Sensors, Control, Operation and Planning level are documented respectively in D3.2, D3.3, D3.4 and D3.5.

On the other hand, final results in WP3 will feed the integration step to be covered in WP4, paving the way to the final demonstration in WP5 tasks at plant level.

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1.4 Document Structure

This document is organized with three main chapters (Section 2 – Section 4), in addition to the introductive chapter (the current one, which describes the scope of the deliverable, audience, relationship with other deliverables and the structure are described) and the conclusive one, which summarizes main achievements and shaping next steps.

Section 2 – Attachment Structure Description explains the distribution of all developed CSs in D3.2, D3.3, D3.4 and D3.5 deliverables, with the used content structure to make easier to find the relevant information. Besides the list of documents attached in the zip folder, this section will be the same in all four deliverables.

Section 3 – Smart Decision Support Cognitive Solution Overview provides a summary view of cognitive solutions at Smart decision support level, split by domain.

Section 4 – Smart Decision Support Cognitive Solutions Results aims at reporting the detailed description of what is going to be included in the zip file. Sample data and data format will be provided through .csv files, demonstrative screenshots will be .jpg file, videos will be .mp4 files, and Applications used to showcase particular features will be .exe files.

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2 Attachment Structure Description

The objective of the current chapter is twofold: first of all it aims to provide an overview of the structure of the four deliverables of type Other, including the current one; secondly to provide the list of the documents attached to the present report, including the Zip folder, the Zenodo folder and any other external link.

Actually, at month M24 (March 2022), WP3 is delivering four deliverables of type Other to summarise and provide evidence of what has been implemented so far; each deliverable consists in a textual part (the present document) and a set of attachment, which is the core of the deliverable.

This section aims at providing a summary picture of the structure of the four documents and of the attachments to make easier to find relevant information, since the subjects presented in each report may overlaps with the others and it is not straightforward for the reader to understand what he/she can find where. Hence, the objective of this chapter is to provide support in orientating inside them.

Since it deals with the four deliverables, it will be replicated almost the same in all of them:

- Deliverable D3.2 – “CAPRI Industrial IoT Platform and Data Space” as output of Task 3.1;
- Deliverable D3.3 – “CAPRI Industrial Analytics Platform and Data Space” as output of Task 3.2;
- Deliverable D3.4 – “CAPRI Smart Knowledge and Semantic Data Models” as output of Task 3.3;
- Deliverable D3.5 – “CAPRI Smart Decision Support” as output of Task 3.4, the current one.

As mentioned above, each deliverable is related to a specific Task, but the activities performed in WP3 can’t be siloed per Task since they involve more than one at the same time. Actually, the CAPRI Cognitive Solutions are 19 assets implemented at laboratory level, split by the three domains (Asphalt, Steel and Pharma) and encompassing the four layers of WP3 (Sensor, Control, Operation and Planning, corresponding to the four Tasks). It means that each CS is developed within one specific use case, but it presents features that cross more than a layer, so practically, it is part of more than one Task.

To overcome this situation and the fact that each CS should be described in more than a deliverable, it has been agreed to include in the report a section (Chapter 3) to describe the activities associated to the Task. So, Chapter 3 is at Task level and takes care only of the CS’s component related to the task, even if it means to depict it only partially.

Conversely, Chapter 4, that is the core of the deliverable together with the set of attachment, provides the overview at CS level, in order to avoid jumping from a document to another to find information. Each Chapter 4 (of the four deliverables) contains only a subset of CSs but they are fully described: for each cognitive solution, the main achievements are presented.

The following table shows in which way the 19 Cognitive Solutions encompass the four WP3 layers and so, also the four WP3 Tasks (in bold, the percentage that drove the choice of the deliverable where the CS has been assigned).

Table 1 CAPRI CSs encompassing the four layers/tasks

DOMAIN	CS'S NAME	CS'S CODE	T3.1 Sensor	T3.2 Control	T3.3 Operation	T3.4 Planning
ASPHALT	Sensor for bitumen content	CAS1	**50%**	50%		
	Sensor for particle size	CAS2	**80%**	10%		10%
	Control of the asphalt drum	CAC1		**85%**	15%	
	Predictive Maintenance of baghouse	CAO1	10%		**30%**	60%
	Planning and control of asphalt production	CAP1		10%	10%	**80%**
STEEL	Sensor for product tracking	CSS1	**70%**	30%		
	Sensor for Solidification	CSS2	20%	**80%**		
	Sensor for Product temperature	CSS3	20%	**80%**		
	Scale sensor for scale build-up	CSS4	20%	**80%**		
	Sensor for risk and anomalies	CSS5			30%	**70%**
	Digital twin architecture	CSO1		10%	**60%**	30%
PHARMA	Sensor for blend uniformity	CPS1	**80%**	20%		
	Sensor for granule quality	CPS2	**80%**	20%		
	Sensor for product moisture	CPS3	10%	30%	**60%**	
	Sensor for prediction of dissolution	CPS4		40%	**60%**	
	Sensor for fault detection	CPS5		10%	**60%**	30%
	Cognitive Control Concept	CPC1		**70%**	30%	
	Cognitive Operation Concept	CPO1		10%	**70%**	20%
	Cognitive Planning Concept	CPP1		10%	10%	**80%**

We agreed to assign each CS to a specific deliverable, even if it encompasses more than a layer (and so, more than a Task) to ease and speed-up the reading of the document and to show all the information related to a Cognitive Solution in a single report.

Hence, the 19 CSs have been split in the four deliverables as follow, according to the most relevant layer:

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Figure 1: The 19 CSs into the deliverables D3.2, D3.3, D3.4, D3.5

In this way, the four deliverables are well balanced: 5 CSs are described in D3.2 and D3.3, whose main component is the Sensor and the Control, respectively; 6 CSs are described in D3.4, focused on Operation and finally, 3 CSs are described in D3.5, about Planning. In each deliverable, Asphalt, Steel and Pharma domains are always represented.

Namely, the current deliverable contains the following 3 Cognitive Solutions:

- CAP1 – Planning and control of asphalt production [Asphalt]
- CSS5 – Sensor for risk and anomalies [Steel]
- CPP1 – Cognitive Planning Concept [Pharma]

Since we are talking of deliverables of type Other, each Cognitive Solution listed above is equipped with:

- A number of attachments of different nature (video, data, metadata, …), containing additional information that helps to better understand the final output of the CS and to provide a concrete evidence of what has been implemented in WP3;
- A textual part, available in Chapter 4, that complements the "physical" content in attachment, explaining what it is and how to exploit it.

The attachments are available in the Zip Folder, in Zenodo system. 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 youtube) of the different files described in the present report.

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Table 2 D3.5 – List of attachments

Cognitive Solution	Content	Type	Location
CAP1 – Planning and control of asphalt production	CAP1.R	R file	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
	RP.csv	Data sample	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
	RT.csv	Data sample	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
	Ingredients.html	Bar chart	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
	Production.html	Line chart	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
	Summary.xlsx	xlsx	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
	nombresRP.Rdata	R data	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
	nombresRT.Rdata	R data	Zenodo link: https://doi.org/10.5281/zenodo.6397453 Zip folder: “CAP1”
CSS5 – Sensor for risk and anomalies	CSS5 video_1	Video	Zenodo link: https://doi.org/10.5281/zenodo.6397467
CPP1 – Cognitive Planning Concept	TSG_E.xlsx	Excel file	Zenodo link: https://doi.org/10.5281/zenodo.6397455 Zip folder: “CPP1/CPP1_Data_1”
	TSG_t.xlsx	Excel file	Zenodo link: https://doi.org/10.5281/zenodo.6397455 Zip folder: “CPP1/CPP1_Data_1”
	CPP1_App1.py	Python script	Zenodo link: https://doi.org/10.5281/zenodo.6397455 Zip folder: “CPP1/CPP1_App_1”

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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].

If you are interested in the details other CSs different from the three associated to the current deliverable, please refer to another deliverable according to the structure shown in Figure 1.

[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 Smart Decision Support Cognitive Solutions Overview

This chapter aims at providing a summary view of cognitive solutions at Smart Decision Support level, split by domain.

3.1 Asphalt smart planning solutions

Detailed scheduling using predictions of dynamic process models can optimise the production along the complete process chain in agreement with the requirements of the underlying local control systems. One of the main problems in the production of asphalt is to know the correct composition of the raw materials as well as their properties such as viscosity, humidity and temperature. The availability of a tool to help decision making will optimize the production and logistics processes.

That is the cognitive solution that has been developed to deal with some of these issues in the asphalt use case:

- *Cognitive solution of Planning and Optimization of Asphalt Production (CAP1)*

The cognitive planning solution for asphalt production consists of a planning decision tool that, from the sensors data installed in the plant and contributing to the planning reference implementation layer of the CAP, allows to decide the right moment to start the production and the necessary adjustments to get the asphalt mix to leave the production plant to the asphalt application area in the optimal conditions (temperature mainly). It takes into account the industrial data streams coming from both the local control system located at the asphalt use case and the data coming from the new different sensors that have been connected to the local datalogger also available at the asphalt production plant and as part of this project development.

The implementation of the cognitive system of production planning and optimization gathers all the data coming from the cognitive sensors developed in the project (as the content of bitumen or filler present in the asphalt mix) and any other sensors already installed alongside, with data coming from the laboratory if needed. After that, an advanced calculation of the mass balance throughout all the production chain is performed, including the continuous part of it (aggregates drying process) and the batch one (mix tower). This mass balance is made up of the different calculations that can be performed using all the available data and taking into consideration both, stationary and dynamic (transitory) mass balances like mass balance of aggregates in the dryer, mass balance in the baghouse filter and the corresponding gases in the dryer, mass balance in the bucket elevator to the mixing tower, mass balance in the upper sieves and in the hot aggregates hoppers and eventually the mass balance in the mixer taking into account the different additives (including RAP, bitumen, etc.). Also, the different recipes production historical data is used as a basis for the calculations of this tool.

In addition, a thermal balance taking into account the set of temperatures available throughout the plant and their disturbances can yield optimal temperature setpoints that can feed the ones corresponding to the cognitive control solution of the asphalt use case.

The extraction of knowledge with all these calculations sets up an algorithm or expert system that generates, among other data, the settings of the set points of the controllers, the amounts of material to be incorporated into the processes such as the mixer and other data that allow the control and the optimization of the production process. In this way, the goal of this cognitive solution is to ensure the optimum temperature of the asphalt mix and minimize excess material in the hot aggregates bins at the end of the production schedule.

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3.2 Steel smart planning solutions

In Steel domain, the Smart decision support component has been developed in CSS5 – "Sensor for risk and anomalies".

The CAPRI risk and anomalies sensor for the steel production aims to provide an estimation of the processing risk for intermediate products at different stages of the processing chain. This risk estimation will be the basis for a decision support system, which will provide recommendations regarding the further processing of a semi-product. For instance, if an item will likely fail to meet the quality specification for its original customer order, the support system could recommend changing the target order the product will be assigned to, or it could recommend to immediately recycle the item or to do some reprocessing. The earlier we identify a problematic item, the less energy and time needs be wasted in its further processing, therefore the solution can lead to substantial savings both in cost and CO_2 emissions.

A decision to change the foreseen processing or target order for some semi-product impacts the planning of the upcoming production, which will need to be adapted accordingly.

Figure 2: Steel processing chain with the logical position of the two risk estimators.

In the Steel demo site, there is a particular interest in the continuous casting of steel billets and the hot rolling of billets, and the soft sensor will evaluate the data associated to these processes to identify high risk products regarding the development of surface defects. It will take into account both the process data coming from the automation system and the results of other soft sensors that will be deployed in the CAPRI project (CSS2-CSS4) and the tracking system (CSS1). The goal is to reduce the number of surface defects in the final products of the processing chain, which are round steel bars in this case.

3.3 Pharma smart planning solutions

The planning solution CPP1 aims at scheduling a set of trial runs in an optimal manner. The energy and/or time required to execute a set of trials on a continuous manufacturing line should be minimized by the proposed solution. Typically, before running a manufacturing process, experiments planned by so called "design of experiments" approaches are executed. The scheduling of these trial runs often does not consider the time (and energy) required for transitioning from one point to another. CPP1 offers this functionality.

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Strongly simplified models were created to quantify the time and energy needed for transitions from one trial run to another one. Based on that information, a scheduling problem has been formulated and solved.

The proposed concept is applicable to dedicated unit operations in a continuous manufacturing line, as well as to the entire process. The ConsiGma CTL25 was the use case considered during the development of CPP1. The deliverable at hand focuses on the twin screw granulation step of the manufacturing line.

Details on the modelling approach and on the scheduling problem are given in section 4.3.1.

4 Smart Decision Support Cognitive Solutions Results

4.1 Asphalt domain

4.1.1 CAP1 Planning and control of asphalt production

File **CAP1.zip**

The data set needed to perform the algorithm is a sample of production data from the EIFFAGE Gerena asphalt plant. These data are divided into different files. The sample data set can be run and tested on the current version of the CAP1 solution.

Input data for the CAP1 CS:

- RP.csv-- wrapped production line-mixer
- RT.csv-- hot tower production line
- nombresRP.Rdata--name of variables
- nombresRT.Rdata--name of variables

Output data generated by the CAC1 solution:

- Ingredients.png – stacked bar graph with the quantity of materials and additives used for asphalt processing.
- Production.png – time series with the amount of asphalt produced over time and the total amount of material used for this production.
- Summary.xlsx – summary table

CAP1 Data Model and Algorithm

The CAP1 algorithm (CAP1.R) consists of an algorithm programmed in the R environment. This algorithm is composed of different functions which perform a selection of variables for the large variety of variables received, a treatment of these variables and a processing and visualization of these variables.

To run the CAP1 algorithm that is included in the .zip file, the following instructions must be followed:

- Install the R (free software).
- Unzip the CAP1.zip file in one folder. Leave all the files that have been unzipped in the same folder.
- Open the script with the name CAP1.R
- Load the CAP1 function by activating the Source button of the R console.
- Type in the console the following action “CAP1(RP.csv, RT.csv)”
- The above-mentioned script outputs will be saved in the directory

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4.2 Steel domain

4.2.1 CSS5 Sensor for risk and anomalies

Physical sensor, introduction to the video

The risk and anomalies sensor for the steel domain is a data-driven software solution aimed at identifying anomalies in the process data (and derived data) and at estimating the processing risk for semi-products after the continuous casting and the hot rolling processes, referring mainly to surface defects. Due to the large amount of process data generated in the steel production powerful numerical tools are required for the analysis. Furthermore, the sensor depends on other solutions developed in CAPRI, foremost the steel product tracking sensor (CSS1). The attached video gives an introduction into the problem setting, the approach we are using for addressing it and the status.

Data collected with the sensor, description of metadata

A large dataset for training and evaluation of the soft sensor is crucial for the analysis. In the CAPRI project, SIDENOR has already collected the complete process data and quality assessments for around 400 billets and the resulting bars. More data will be gathered in the coming months, and in the next stage of the project (WP4) the goal is to access the data in the online operation, to retrain the model on a larger dataset and to evaluate the risk and anomalies detector on every new billet that is cast and rolled.

Data model, description of data model

The data model is explained in the section on the steel digital twin in CAPRI deliverable D3.4.

Algorithm, and high-level description to understand how it works

As explained in the attached video, we use an Autoencoder-based anomaly detection to associate a risk to individual products. A preliminary version of this algorithm has been implemented, but the results are not conclusive yet. Figure 3 shows an example of a reconstructed input feature compared to the original data (ground truth). With the larger dataset to be obtained in WP4 we expect to be able to arrive at more unambiguous predictions. Likely, we will also need to adapt the approach for a better detection rate of high-risk products and a reduction of the false positives rate. Currently, the reconstruction error of the autoencoder is used as anomaly indicator. Figure 4 shows the reconstruction error for one of the autoencoders over the test dataset of 82 billets, the model being trained on 238 billets. More sophisticated algorithms remain to be tested. Due to the existence of surface quality assessment data for the steel bars the problem at hand can be phrased as a supervised-learning problem.

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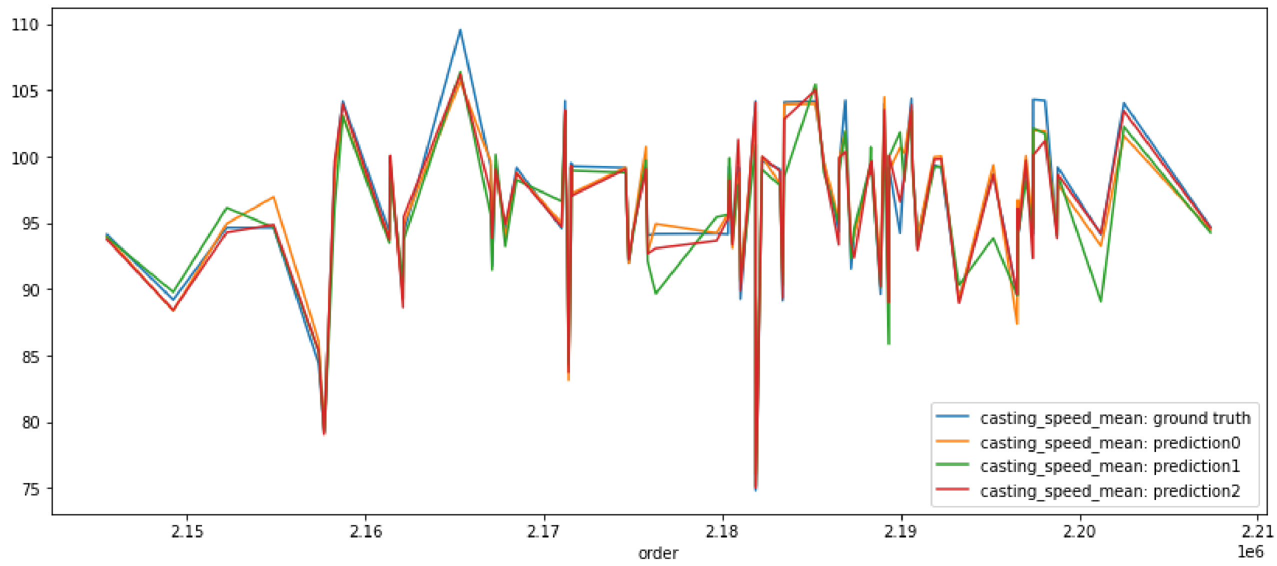

Figure 3: Original (ground truth) and reconstructed input feature for reconstructions by three different autoencoders.

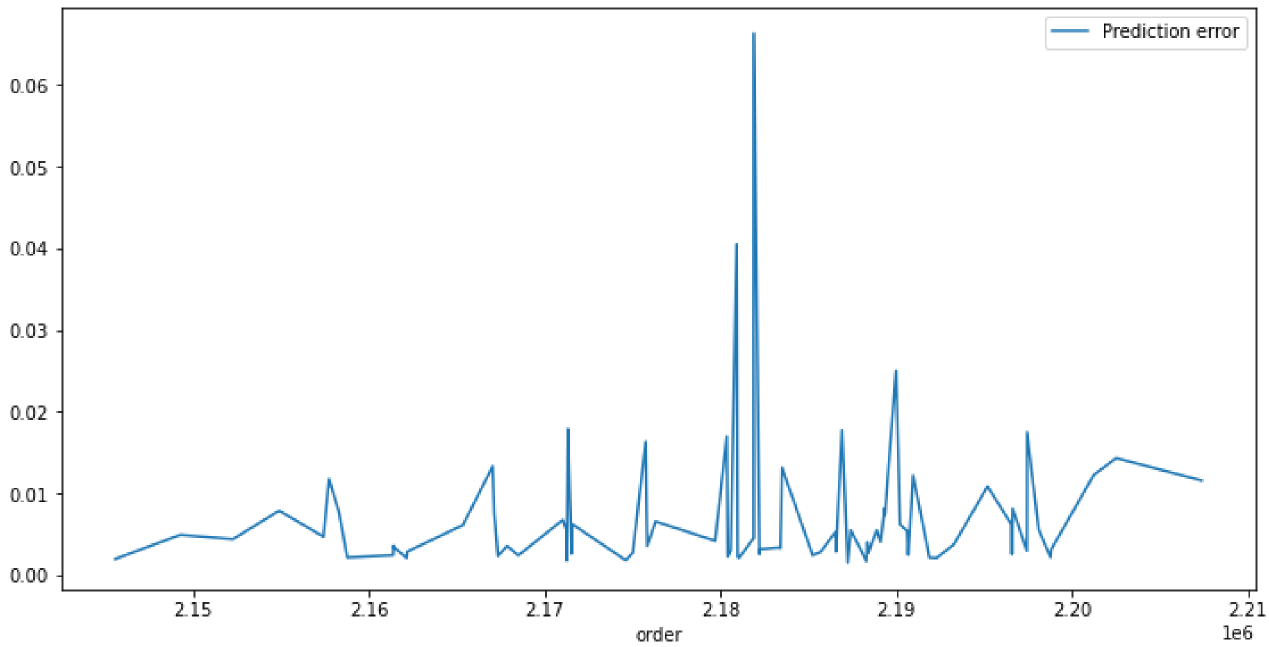

Figure 4: Reconstruction error of an autoencoder over a test dataset of 82 billets.

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4.3 Pharma domain

4.3.1 CPP1 Cognitive Planning Concept

The following assumptions were made:

- The trial runs to be executed are known. The purpose of CPP1 is to schedule for minimal energy and/or time consumption.
- Focus of the models used for estimating the energy and time consumption of the transitions is not high precision, but simplicity.
- Simple criterions are defined to quantify, if a transition period has ended and a new run can be started (e.g., temperature must be within +/- 1°C of the proposed setpoint).
- There is a maximum run-time t_{max} per day that must not be exceeded.
- Each day of operation, the ConsiGma CTL25 starts at a defined initial condition that is given by the ambient air condition in the processing room.
- At the end of each operation day, the ConsiGma CTL25 is switched off.

The core component of the CPP1 solution is a model capable of estimating the energy consumption of the ConsiGma CTL25. This model is based on strongly simplifying assumptions in order to keep the scheduling problem manageable. For each unit operation, a simple model estimating the power consumption during operation is given below.

Twin Screw Granulation (TSG)

The mechanical power P_{mech} needed to run the granulator reads as

$$P_{mech} = \omega T.$$

The torque T depends on screw configuration, solids feed rate, liquid to solid (L/S) ratio, material properties and screw speed ω.

For the investigations in CPP1, material properties are neglected and the torque is approximated by

$$T = f(\omega, \dot{m}, L/S) \approx C + k_1 L/S + k_2 \dot{m} + k_3 \omega + k_4 \omega L/S + k_5 \omega \dot{m} + k_6 L/S \dot{m} + k_7 \omega^2 + k_8 L/S^2 + k_9 \dot{m}^2$$

The time needed to reach the barrel temperature steady state is computed by means of a first order system as shown in Figure 5.

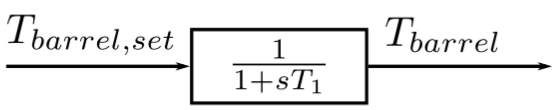

Figure 5: Model to predict barrel temperature

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Fluid bed dryer (FBD)

To estimate the power consumption of the fluid bed dryer, the thermal energy needed to heat the drying air is taken into account as follows:

$$P_{therm} = c_p(T_a - T_{amb})\dot{V}_a\rho.$$

The dryer inlet air temperature T_a is computed from the corresponding set-point $T_{a,set}$ by means of a first order dynamic system as shown in Figure 6. Further, a first order system is used to estimate the time needed to reach steady state of the dryer (outlet temperature T_o). The specific heat capacity of air c_p and the density ρ of air, as well as the ambient air temperature T_{amb} are used in that model.

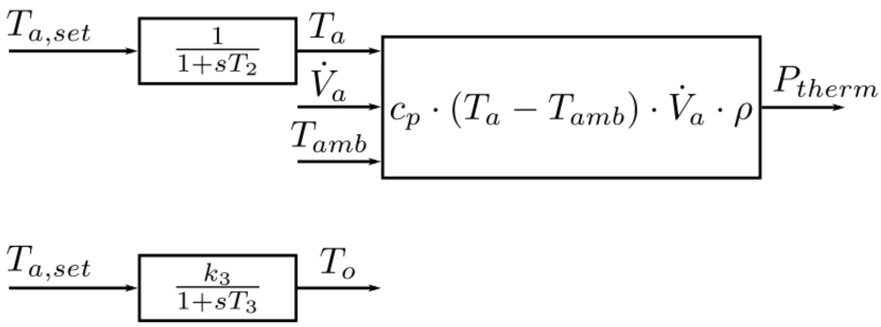

Figure 6: Models used to estimate the FBD power consumption

The models mentioned above are then used to compute two transition matrices: one to quantify the time it takes to go from any process point to any other, and another one to quantify the energy it takes to go from any process point to any other.

In particular, it has to be noted that the transition matrices are not symmetric, in other words, for example the amount of energy required to go from P_1 to P_2 does not need to be the same as going from P_2 to P_1. This suggests that investigating the problem with directed, weighted graphs is possible. The optimal sequence of process points is determined by a combination of:

- The minimal total energy required
- The minimal amount of time required
- All above restrictions are satisfied, in particular, the maximum amount of time per day is not exceeded.

The problem is well determined and a best possible solution must exist. However, listing all possible sequences is computationally very complex in general. For example, if 32 process points need to be examined, this gives rise to $32! = 2.63 \cdot e^{35}$ possible sequences, even without regards for the maximum amount of time per day.

The above transition matrices can be used as adjacency matrices describing a fully connected graph:

- Each process point P_i is modelled by a vertex v_i in the graph
- A vertex v_1 is connected by an edge e to a vertex v_2, if it is possible to run the process in state P_2 right after P_1 without having to pass by a reconfiguration state first.

An exemplary graph is depicted in Figure 7.

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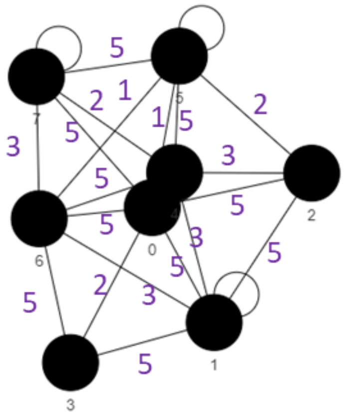

Figure 7: Example of a graph with vertices as process states and edges with transition weights between the states.

In order to address the daily time constraint, a topological filtration on this connected graph is applied. This means, that we start removing all edges and gradually add edges of very low weight. For each step in this low weight, the connected components are analysed and evaluated for their suitability to be executed within the daily time constraint. An example of such a filtration and the resulting connected components are shown in Figure 8.

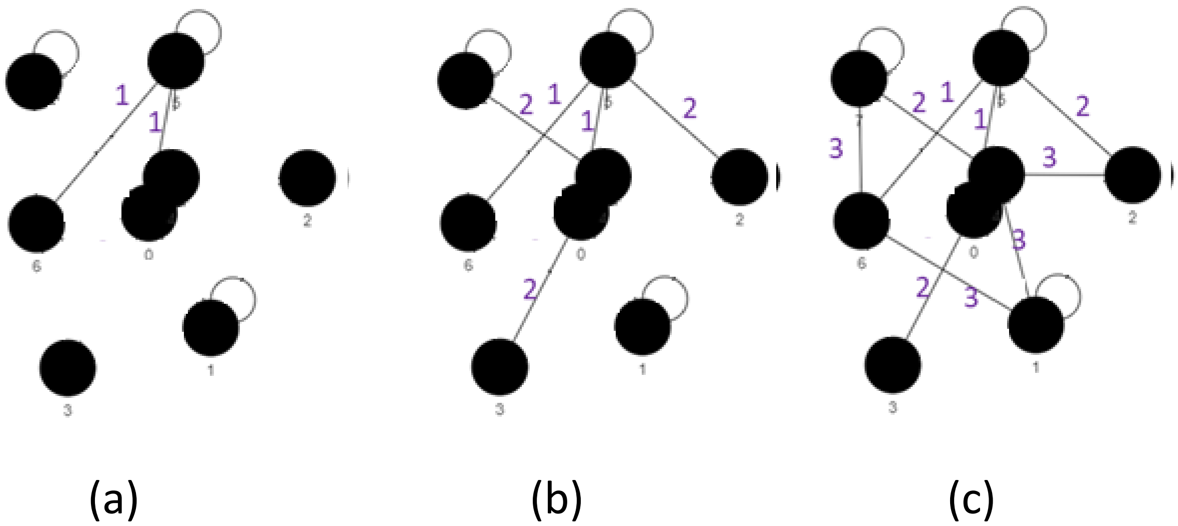

Figure 8: Filtration on graph with weights (a) 1, (b) 2 and (c) 3.

Once suitably sized connected components have been identified, these states will be processed within a day. The first state of the day needs to be run after start-up from the resting state and the last state of the day is again the resting state. Hence, the order in which the states on one day are processed can be determined by applying standard graph theoretical algorithms for finding a shortest loop in the connected component.

In the zip-archive CPP1_Data_1.zip, the two transition matrices computed for the twin screw granulation experiments can be found.

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- TSG_E.xlsx (matrix describing the energy consumption for transitions between operating points)
- TSG_t.xlsx (matrix describing the time needed for transitions between operating points)

In both matrices, the energy/time for a transition from operating point 1 to operating point 2 can be read from matrix element in row 1 and column 2. The very last row is indicating the energy/time needed for going from an initial state of the system to the respective operating point. The two matrices need to be created by the end user before applying the scheduling algorithm (see next paragraph). The DMP associated to this data generated is included as file CPP1_DMP_CPP1_Data1_V1.xlsx.

The zip archive CPP1_App_1.zip contains the python script needed to solve the scheduling problem.

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5 Conclusions and Next Steps

D3.5 – "CAPRI Smart decision support", is a deliverable of type OTHER that, together with D3.3, D3.4 and D3.5, targets the 'MS4' milestone related to technology validation of different cognitive solutions at M24. The document described the concrete achievements in the development of the smart decision support cognitive solutions, leveraging on the CAPRI Reference Implementation described in D3.1. Main practical results have been detailed for each domain and cognitive solution, providing algorithms, sources, data format, data samples, and videos showcasing the implementation done in laboratory activities in WP3.

The output of WP3, starting from the smart decision based cognitive solutions described in this deliverable, will be integrated with 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 algorithms, already analysed in terms of rationale, technology, and intellectual property, will be integrated into the CAP platform for implementing the processing layer. After the integration of the cognitive modules, the platform will be tested and tuned, thus feeding the validation scenarios in the three plants, to be addressed in WP5 through two iterations. WP4 will pave the way to ultimate objectives of quality, flexibility and performance. On the other hand, a toolbox of cognitive solutions for sensing, control, operation and planning will be developed to help the adoption of the CAP for batch, continuous and hybrid process industry plants. The final validation will take place in WP5, addressing manufacturing challenges in industrial operational environments of the three chosen process sectors, and providing useful feedbacks and lessons learnt.

Next steps will be in T4.4 (on Cognitive planning solutions for process industries), where smart decision support tools will be developed in this task in order to provide cognitive functions on a system (and systemic) level in the three industrial sectors characterizing the pilots.

The progression in the maturity of the cognitive solutions will enable an in-depth analysis in WP7, for the shaping of the exploitation opportunities of the different CAP layers and the CAP platform as a whole, as well as opportunities for replicating cognitive solution in other sectors of process industry.

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