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TITRE: **Modelling and automatic control of the iron ore bed combustion at the sintering plant.**

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Modelling and automatic control of the iron ore bed combustion at the sintering plant

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Abstract

Sintering is an important process to produce sinter before the blast furnace, in which iron ore is melt with coke. It results the sinter cake which quality can depends on burn-through point (BTP) arrangement that today is done manually. For decrease costs in the blast furnace and increase sintering production, the industry is convinced that it is needed to improve quality of sintering which can be achieved with an automatic control of the process. Therefore, this present work depicts about a development of tools to deal with the complete chain automation from data acquisition of industrial control devices, OPC communication, control HMI to process modelling and control design. A fast prototype was generated with MATLAB algorithm and implemented in real plant to test PID as first automatic control. The results showed a positive outcome for process stability and with the work developed it will be possible to improve control solutions with advanced control methods.

Keywords: Sintering plant; BTP control; BTP modelling; ArcelorMittal; Industrial control; Automation; Control design; PID control; Fast prototype; MATLAB prototype.

Résume

L’agglomération est un processus important pour produire le avant le haut fourneau, dans lequel le minerai de fer est fondu avec du coke. Il en résulte le gâteau d'agglomération, dont la qualité peut dépendre de la régulation du point de combustion (BTP), aujourd'hui réalisé manuellement. Pour réduire les coûts dans le haut fourneau et augmenter la production de sinter, l'industrie est convaincue qu'il est nécessaire d'améliorer la qualité de l’agglomération, ce qui peut être obtenu avec un contrôle automatique du processus. Par conséquent, le présent travail décrit un développement d’outils pour traiter l’automatisation complète de la chaîne depuis l’acquisition de données de dispositifs de contrôle industriels, la communication OPC, l’IHM de contrôle, la modélisation de processus et la conception de contrôle. Un prototype rapide a été généré avec l'algorithme MATLAB et implémenté dans une usine réelle pour tester le PID en tant que premier contrôle automatique. Les résultats ont montré un résultat positif pour la stabilité du processus et, avec le travail développé, il sera possible d'améliorer les solutions de contrôle avec des méthodes de contrôle plus avancées.

Mots-clés: Procède de l’agglomération; Contrôle du BTP; Modélisation BTP; ArcelorMittal; Contrôle industriel; Automatisation; Conception de contrôle; contrôle PID ; Prototype rapide; Prototype MATLAB.

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Finally, I wish to thank my family for their support, encouragement and inspiration throughout this time.

Summary

ArcelorMittal

Formed in 2006, ArcelorMittal (AM) is the world's number one steel company and leader in all major global markets, including automotive, construction, household appliances and packaging, with leading R&D and technology, as well as sizeable captive supplies of raw materials and outstanding distribution networks. Headquartered in Luxembourg City and with 320,000 employees in more than 60 countries, it has led the consolidation of the world steel industry and today ranks as the only truly global steelmaker with an industrial presence in 27 countries seeking for solutions in the entire steel production chain since mineral extraction to final products such as automotive technology.

Figure 1 - ArcelorMittal overall picture

The company is involved in research and development, mining, and steel. ArcelorMittal values geographical breadth, product diversity and raw materials security. Around 37% of its steel is produced in the Americas, 47% in Europe and 16% in other countries such as Kazakhstan, South Africa and Ukraine. ArcelorMittal in 2016 produced around 90 million tons of steel. As of May 2017, the company made 200 unique steel grades for automotive purposes, half of which were introduced since 2007. Among the steel varieties are Usibor 2000, which the company announced in June 2016 and released later that year. Upon release, the high-strength automotive steel was said to be about one-third stronger than other steels then available for carmaking.

1. Introduction

The present report depicts the development of a complete sintering process automation in the steel industry including a general industrial control tool and studies of different control strategies. This work took place in ArcelorMittal Maizières Research SA during 6 months that concerns the final internship required by ENSE[3] to conclude the automatic control, systems and information technology master program.

1.1. Context

1.1.1 Burn-Through Point Control

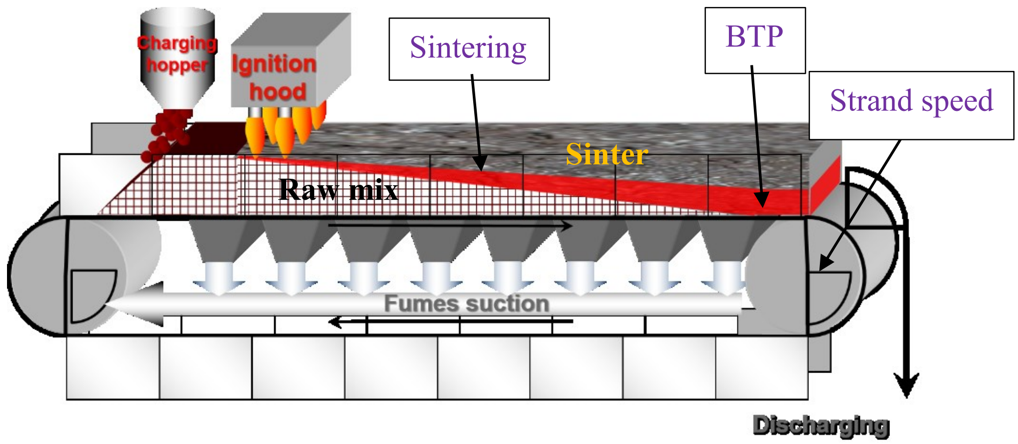


Figure 2- Sinter strand

Illustrated in Figure 3, sintering is an important process to produce sinter before the blast furnace, in which iron ore is melt with coke. The goal of the sintering process is to ensure the required properties of the iron ore mix coming from mining (granularity, morphology, combustion…) in order to optimize the blast furnace operation. The main step of sintering process is the sinter burning step during which the iron ore mix bed is convoyed and combusted until the end of the chain before discharging automatically. An important challenge is to control effectively the combustion end point, called burn-through point (BTP) by optimizing the line speed.

BTP control in sintering process is one of the advanced control projects driven by automation & control team of ArcelorMittal Maizières. The project promotes economic benefits such as reduced costs with some objectives:

- To increase productivity and make the sintering process more stable.
- Automatic control of the strand speed to deal with the deviation of sintering parameters – such as permeability, coke content, and others.
- To continuously optimize BTP position to be as close to the strand end as possible for a constant sinter quality.

With these achievements for an optimal sintering process, the project estimates some benefits for next step production, blast furnace:

- More stable operation on long-term.
- Less use of pellets (purchased material) and, thus, lower costs.

One example of BTP control is the today available AM models implemented at Fos-sur-Mer sinter plant, but not used for long time after implementation due to technical issues and bad tuning of the solution. The control model was restarted and adapted with the help of R&D. Today advanced automatic control approaches are under investigation for implantation seeking for upgrade the existing. In fact, experience of its application showed potential benefit for productivity improvement by 1.5 to 3%.

Also, the project developed last year a fast prototyping to allow tests of different types of control in real time in sinter plants. This technology was chosen because it would allow to easily implement and test different control strategies, since different type of PID to more complex control such as a model predictive control (MPC). With this prototype, it is possible to test control without a presence a R&D engineer in the real plant, which it is not always possible, and to use MATLAB algorithms for easy development of more complex programming levels (machine learning, for example).

Today, this prototype is running in a real plant control station and the control operator is responsible to allow that it takes control over the process. However, since its installation, it is running in background resulting in an insufficient amount of data about the control effects once the production should have the control loop closed for it. It can be explained by a lack of trust of the operator in the control solutions proposed and a lack of studies in control tuning.

1.2 Objectives

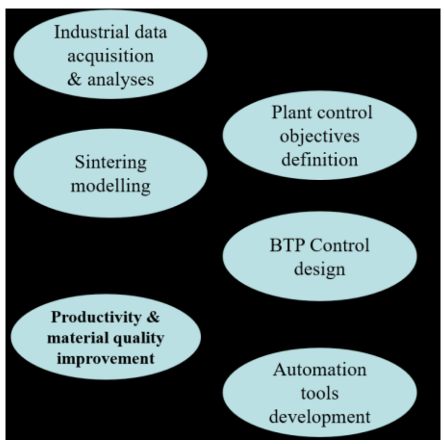


Figure 3- Main activities to achieve the main objective

1.2.1 Internship objective & Main activities

Given the context, the final interests of the BTP control project are productivity and material quality improvement. The main challenge, so, is to actuate in the strand speed to have a stable and fast process but ensuring that all material is cooked at the end of the strand. This would imply a stable process and it would help to achieve the final product in the time requested as well avoid loss of material not well refined in the sintering process.

However, for this automation control conception, it is necessary the development of elements such as models, control strategies, automation hardware and software. Also, the project is today in development phase when the company interests are well defined and part of this conception is already implemented in a real plant, but it needs to be improved. Given this, the objective of the present internship is to work on:

- <u>Models</u> of the sintering process using MATLAB & Simulink.
- <u>Data analysis</u> of sinter plants and evaluate the possible improvements.

- Design and simulation of control strategies to optimize the line speed and improve the current performances.
- Improvement of a general sinter industrial control tool capable of connect with the sinter plant providing the possibility of easily tune and run different control methods.

Figure 4 illustrate the main BTP control objective and how my work will help to achieve it.

1.2.2 Methodology

This present work methodology, illustrated in Figure 5, is to collect industrial data of partner AM sinter plants around the world to analyze and then to study the sintering process producing possible models, isolating different phases of the process as well as the different perturbations and defining control objectives. After, we intend to choose and design the optimal control methods based on our control objectives. Then, to test it in the real plant using automation tools such as OPC communication and a general control prototype developed with MATLAB Appdesigner. With an executable file, the prototype will run in a real plant station where an operator will be responsible to monitor and to allow that our application control tool takes action in the process.

With the results, our job is to reevaluate the data acquired and recorded with software ibaAnalyzer. Then, to improve the control strategy by suggesting and implementing new updates of the prototype that will be delivered to the sinter plant station and tested again.

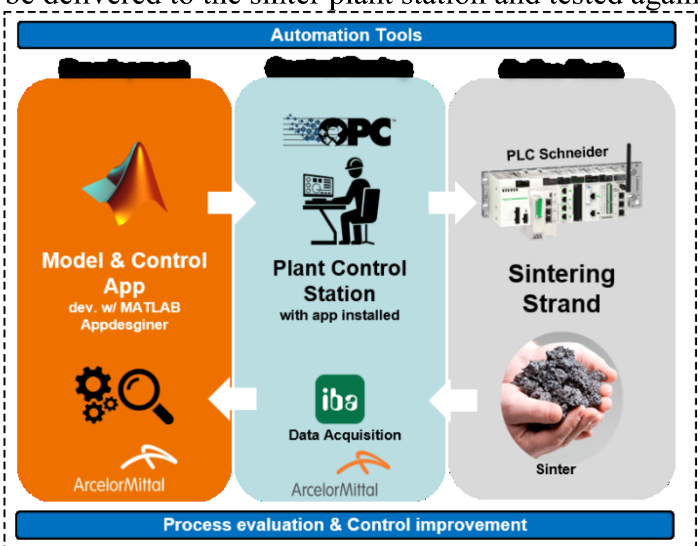


Figure 4 - Project methodology

1.2.3 ArcelorMittal Factories

This project has as partners some AM sinter plant around the world that provides part of their control hardware available in the factory such as gases and temperature sensors, speed actuators, Schneider PLC, HMI panel control, OPC communication and remote desktop connection. These partners and their interest are presented below.

1.2.3.1 Dunkirk's sintering plant

ArcelorMittal France has a steel production located in Dunkirk with a sintering plant. Today, the plant has a particular control solution proposed by a Germany ArcelorMittal factory located in Bremen that is based in previously knowledge of the sintering models and showed good results in

Bremen's production. However, this control does not present the same results in Dunkirk and, so, in the majority time a manual control runs the process. With a partnership with ArcelorMittal Maizières R&D, they seek for improvement in its sintering production chain whether by its automation with Bremen control improvements or new control methods.

1.2.3.2 Tubarão's sintering plant

South America has some contribution in steel production with a few factories of which one is located in Tubarão – Brazil. This factory develops a control solution to automatize the sintering production chain and today the responsible engineers led model & control strategy studies in partnership with ArcelorMittal Maizières R&D.

Our interest with this plant is to act together directly in controller devices to achieve automatic control and evaluate its outcomes.

2. Sintering

To achieve the main objectives, it was necessary to understand the sintering process.

2.1 Process

In the metallurgical industry, sintering, illustrated in Figure 7, is an essential part of the blast furnace charge preparation where the agglomerate material known as sinter must exhibit appropriated physical and chemical properties for optimized steel production. The method consists in mixing iron ore fines and other products such as coke fines and after fired at a temperature high enough to achieve a certain degree of solidification producing an agglomeration of ore on the form of large solidified granular material of a diameter of approximately 30–60 mm [1]. This allows, thus, that the hot air easily flows in next steel production step, blast furnace, which guarantees a more homogeneous and more productive process. On the other hand, the quality of this sinter is a function that depends on the dynamics of the process that is very complex and can be disturbed by several parameters.

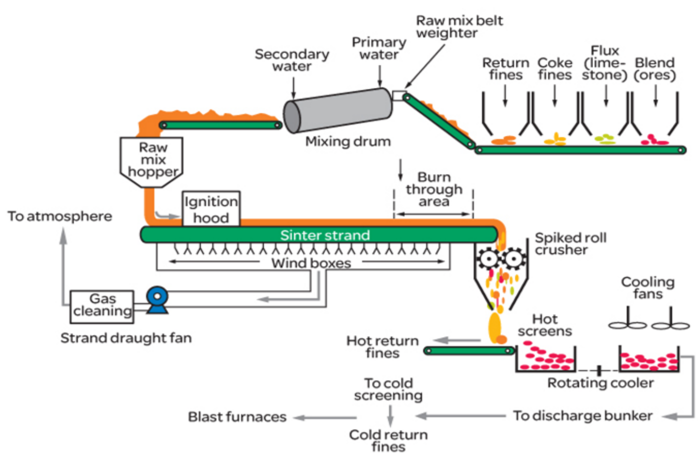


Figure 5 - Simplified diagram of a sinter plant

To pass to blast furnace process with the good properties, the charge mix goes through 3 important steps: the preparation of a charge of minerals and other components, the cooking of this charge knowing as sintering process in a sinter strand and the cooling [2]. In Annex A, it is found more details about the preparation and cooling steps. For now, we will focus on second step, sinter strand process.

2.1.1 Sintering at sinter strand

After first step of preparation, a charge of mineral contained mainly with iron ore and coke, solid fuel, is deposited in a traveling strand to form a bed to go through the sintering proceed which can occurs in a batch process, e.g. in a Dwight–Lloyd type of machine as shown in Figure 3.

On this type of machine, the mixture is moved using sintering pallets on rails. It passes under an ignition hood, where the upper layer of sinter composed by the fine coke is ignited with gas flames producing a coke combustion. After, the moving strand goes through several suction boxes that suck downwardly the blast of air and maintain a constantly down slope of this ignited layer thanks to a heat transfer analogous to a burning cigarette suction concept. So, this burning moves gradually through the charge from top to bottom producing different layers explained in 2.1.1.1. If this process continues properly, at the end of the strand the combustion will be completed in the entire height of material resulting sinter cake that is discharged from the machine. It is known that the more oxidized is the charge at the beginning, the more porous is the resulted cake. Also, it is notorious that the results depends totally on the strand speed over the process.

2.1.1.1 Sintering layers

During the blast air aspiration, the material undergoes a vertical transformation on the layer which can be divided by four zones during the whole grid [2] as shown in Figure 8:

(1) A cold and wet zone of the initial mix.
(2) The other zone of rapid heating of the load where the drying, the hydration and the beginning of decarbonation take place.
(3) A zone of high temperature called flame front (about 1356 ° C in some bibliographies, 1300-1400 on [2] and 1000-1500 on [3]) where there are the chemical reactions: the combustion of carbon, partial reduction of oxides and the melting of the iron ore.
(4) A cooling zone with re-oxidation and crystallization of the agglomerate.

Each zone has a characteristic temperature which propagates either on the material or on the sucked air which is measured by thermocouples placed on wind boxes underneath by the whole grid. These zones move vertically with the suction and the strand moves horizontally giving an appearance as can be seen in the right plot of Figure 8.

Finally, at the end of the grid is hoped that all the carbon is burnt and blown so as to have the flame front (3) at the grid level.

It is important to note that the flame front is the high temperature zone. So, we can conclude that when the wet zone (2) and dry zone (1) is all evaporated, the air temperature of aspirated will be higher [2].

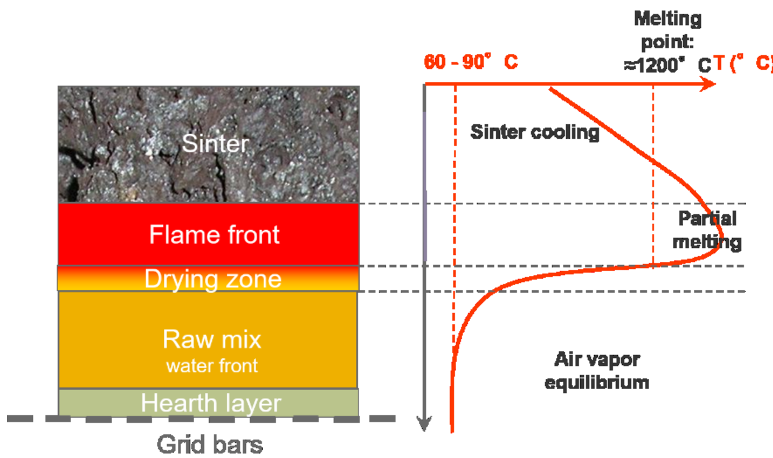


Figure 6 - Sintering Layers and mix temperature evolution

2.1.1.2 Combustion phenomenon and gases exhaustion

A more systematic analysis is considered about the combustion process because it is the key point of the quality of the final product and one is interested in knowing how this zone behaves over time. The first thing to consider is the influence of permeability, the resistance that air can have to shift and that depends on the material encountered in the mix charge. It is well-known that the wet zone is the least impervious zone, but flame front and the sinter agglomerate is where the heat gases flows more easily.

The other aspect to consider is the composition of this combustion where the carbon is burnt and causes a layer of high temperature, flame front, which propagates by convection of gases and materially noticeable on the wet zone. With this high temperature, the water evaporates from the wet zone and then the combustion takes place producing exothermic and endothermic chemical reactions. The most important reactions are shown below. Part of the air produced are CO_2 (1), the others are the pollutants (NO_x, SO_x, etc.) of other reactions.

$$C + O_2 \rightarrow CO_2 \quad (1)$$
$$H_2O_{(l)} \rightarrow H_2O_{(g)} \quad (2)$$
$$CaCO_3 \rightarrow CaO + CO_2 \quad (3)$$
$$2\,Fe_2O_3 \rightarrow 4\,FeO + O_2 \quad (4)$$

The gases production over the grid depends on the quality and the progress of the combustion phenomenon and their evolution over time are illustrated in Figure 9. Once all the combustion is complete, it is hoped a lower CO_2 level. It is also known that partial air produced escapes and disturbs the measurement of the temperature over wind boxes equipped with thermocouples.

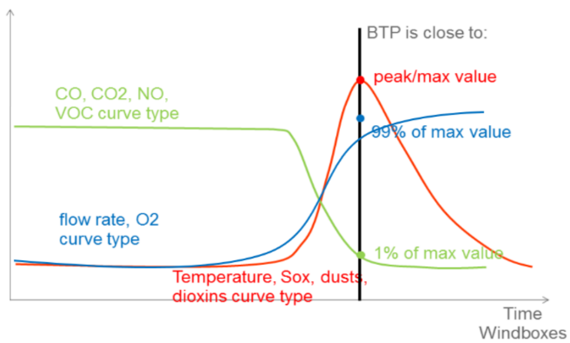


Figure 7 - Wind box gas measures

2.1.1.3 Waste Gas Temperature, BTP, BRP, Alpha and BTT

Among several aspects that can be controlled on sintering, the cooking time, or burn-through time (BTT), is the main interest because it is directly related to productivity. There is also stability of the globally temperature, stability of the amount of CO and the amount of fine return that is used to measure the quality of the process and a minimal consumption of resources.

The BTT is related to time of arrival of front flame in the grid level. The point where it happens is called of BTP. However, there are some disagreement about this location. For [2], BTP is the point where the flame front arrives at the bottom. On the other hand, for [3], BTP is the point where all the flame front just evaporated. In both cases, the BTP is estimated as the maximum point of the waste gas temperature over the strand, as shown in Figure 10, resulted of the sucked blast air plus exhaust gases from combustion layer. Indeed, this estimation is considered accurate enough for industrial developments.

The other way to estimate the BTP is to find the relationship with temperature-rising point (TRP), or alpha point, where the whole wet zone is all evaporated.

Burn-rising point (BRP) is defined as the point where the dry zone is all evaporated and it is can also estimation of the BTP by some models. It should be said that the alpha and BRP is also measured indirectly, but may be easier to find because the highest temperature can be located beyond the strand end and not measured by the thermocouples.

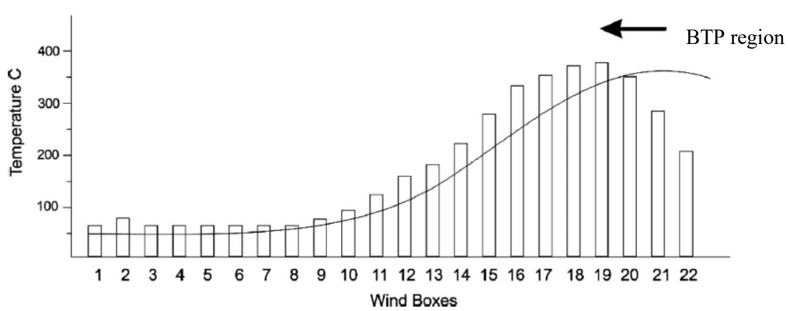


Figure 8 - Effect of BTP position on sucked air temperature of each wind box [5]

2.2 Control methods

If burn-through time (BTT) is targeted and it is estimated by the burn-through point, then the velocity of the strand can arrange the sintering point where the mixture will be fully cooked.

The main difficulty is the estimation of this point, which is not measured directly, but which depends on others parameters to be identified.

In the Bremen approach, for example, it is used the product relation of CO and the BTP. If all the load is well cooked, the percentage of CO at the end is very low, ideally.

In fact, control methods depend on the measures and indicators available in each plant. Therefore, a good control solution would be flexible to different measures and models.

2.3 Models bibliography

To help in a control design is necessary to know some BTP models because there are many important process variables as explained earlier in this section that it is interesting to control, but are not directly measured by sensors.

2.3.1 BRP

One model is based on finding the location of BRP (or *PHT* in French) in the curve waste gas temperature. By the measure of temperature of each wind box is possible to estimate a temperature evolution over the strand. It serves to locate the strand position of the different sintering layers as shown in Figure 11 and detailed in Figure 12.

Based on model of a sigmoid curve equation (shown below) and on the thermocouple measures, and with a linear fitting method, is possible to plot the waste gas temperature evolution.

$$T - T_0 = \frac{G}{1 + e^{\frac{x - x_0}{-L}}}$$

Where T is the Waste gas Temperature and X is the sinter strand position. T_0 and X_0 is the temperature and position of inflection point known as BRP. According to AM Bremen factory algorithm, this point generally has 250ºC, so, it is possible to find X_0 as well. Once, BRP is found, it is estimated that BTP will be X0+3L ahead, while alpha will be X0-2L behind. This method was implemented by the previous project intern and it demonstrated very efficient by placing BRP in the rising point along the temperatures and BTP over the top.

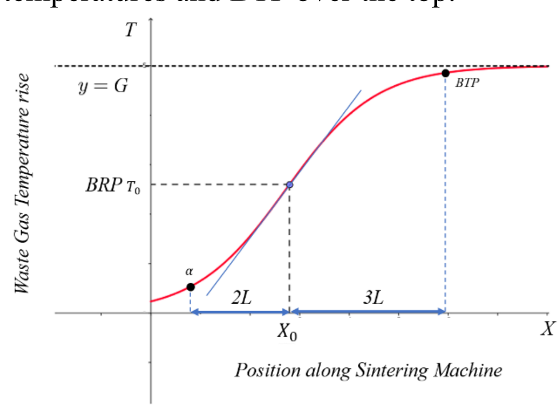


Figure 9 - Waste gas temperature model to fit

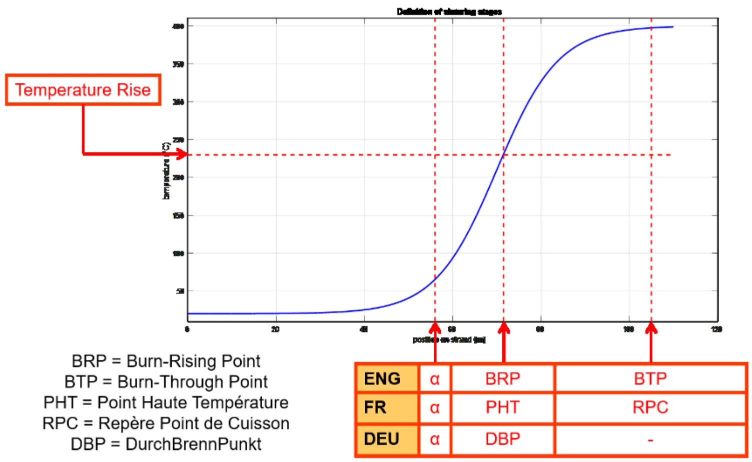


Figure 10 - Sintering stages in a WTG measure

2.3.2 Airflow

The waste gas temperature over time will be also a function of layers location. Other model in study is the relation between this temperature over time and de air flow of each wind box.

$$T_{WGas} = \frac{Q_1}{Q_{Total}} T_{wb_1} + \frac{Q_2}{Q_{Total}} T_{wb_2} + \cdots + \frac{Q_n}{Q_{Total}} T_{wb_n}$$

Where T_{WGas} is the waste gas temperature and it is a sum of the air flow Q rate of each wind box $[1 \ldots n]$ over the total air flow Q_{Total} times the temperature T_{wb} of this respective wind box.

2.3.3 First order model

A simplified model of the waste gas temperature is a function between previous waste gas temperatures and the strand speed. The interest in simplify the process it the possibility to design a PID control explained forward.

$$T_{k+1} = A * T_k + B * V_k$$

This model reflects to a state space of first-order differential equation.

$$\dot{x} = Ax + Bu$$

Dunkirk's plant has enormously contributed with industrial data that contains waste gas temperature and strand speed information during all the time operation. After treat and analyze this data, it was possibly to find a first order transfer function with a remarkable delay:

$$T_{WGas} = \frac{G}{1 + \tau s} e^{-Ds}$$

Where G = -70, τ = 1200, D = 600.

2.4 Sintering pot

Another project involving sintering process and BTP is led by the Iron Making cluster where they prepare a sintering pot to do controlled trials to understand the sintering process, its outcome, dynamics and related process variables such as the mineral composition or the physical environment.

They reproduce the sintering process in a small container using known mineral composition to produce an entire combustion of sintering process - meanwhile they record the resulting data with an infrared camera, thermocouples and gases sensors.

3. Automation solutions

Distributed control system (DCS) is a commonly computerized control system for manufacturing. It presents 4 levels of control processing as shown in Figure 14. Our focus is on the 2rd and 3rd levels, the plant supervisory and control level. In the 2nd level, there are supervisory computers that collect data from process nodes on the system, and provide the operator control interfaces. Also on this level, the operator can monitor the chain production and in cases of manual control, the operator sets the plant actuators (for example, the strand speed in sintering machine). The 3rd level, in turn, is where control process is employed by control devices liked to sensors and actuators. Some of these devices are industrial PLC or microcontrollers with their own communication protocol and control logics.

The present objective is to provide for the control level an automatic control system through a general controller application to handle the sinter machine actuators with strategies proposed by R&D center and, to supervisory level, a control HMI to provide supporting real-time control information to factory operators.

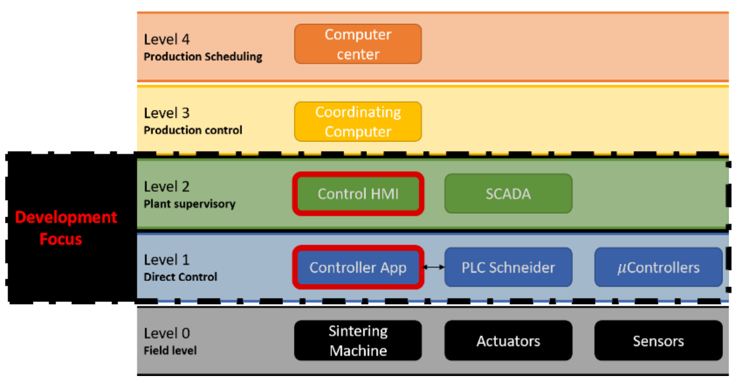


Figure 11 - DCS Diagram

Some automation tools frequently used in industry will help to achieve our objective. In next topics, it is detailed how they are integrated with the industrial plant. A better description of each technology are exposed in Annex B.

3.1 Industrial control application

3.1.1 Prototype functionality

As explained before, to be able to connect and to test different types of control, it was proposed by Arcelormittal R&D a software prototype capable to communicate with the plant via an OPC Server that is connected to sinter plant devices. This application works in different and independent modules (data communication, model estimations, control unit and an interface) explained forward and it is integrated with the plant as shown in Figure 15.

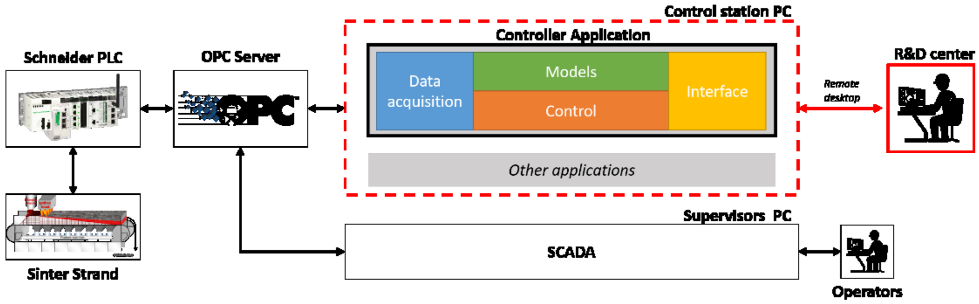


Figure 12 - Project solution connection with remark on R&D role

3.1.1.1 Communication

This module will connect the prototype to the factory network that operates with OPC communication integrated with PLC devices that, in turn, operates with the sinter plant. To do so, the OPC toolbox will establish the communication and a XML file will store configuration info about OPC Server (Host, Server ID) and data features (Groups, Items, permissions, etc.). An outcome of the present work was to generate a global format of xml to be automatic read by the application. This format, shown in Figure 16, allows to add new measures to read or to change server's configurations in 2 steps: Modify XML file + Add the variable name as property in class database on Communication module.

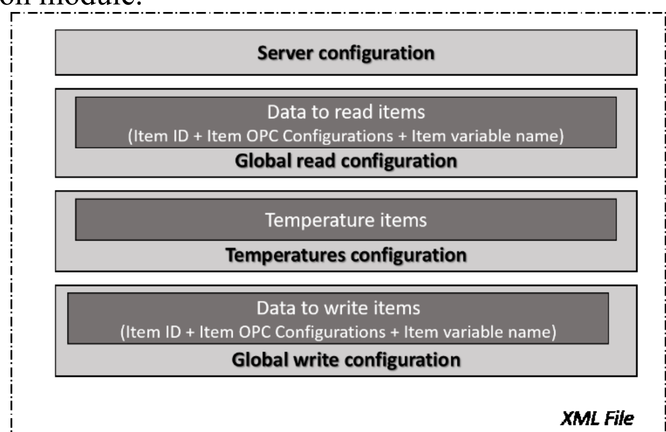


Figure 13 - XML scope to OPC connection

During the application running, this module is responsible to data acquisition, to read and store measures, and to write to OPC server the application outputs, such as the control output. This is illustrated by Figure 17.

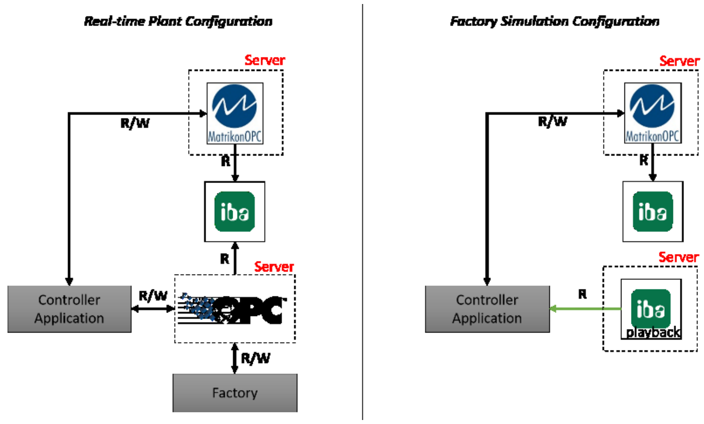


Figure 14 - OPC Communication

More detailed, it will work in two ways: Real process and real-time simulation. In the first mode, the application has to communicate with the plant using the OPC server of the factory. Another server will be provided an OPC communication independent of the factory to receive data generated by the prototype that doesn't go directly to the plant. The interest of this is to record these data in a data acquisition software called IbaPDA allowing later the second mode, real-time simulation. In this last mode, the IbaPDA plays as the factory role by playback mode using all data recorded in a given instant of the process. The disadvantage of this method is that this server in playback does not give writing permissions.

3.1.1.2 Model Estimations

It is known that sintering process has many points of interest, but some of them cannot be measured. Moreover, many control needs model observations that can predict important data. It is essential thus a module responsible for this mathematical calculations which is easy to implement with MATLAB programming.

In operation mode, with the new measures acquired in communication, model estimations or process states will be updated such as the fitting evolution of temperature and BTP, BRP and TRP.

3.1.1.3 Control Unit

For control process, a control unit is implemented to arrange a control programming logic and integrate with the model and the communication interface.

In operation mode, once the models output are calculated, the control unit will be responsible to run a control script for finding the new control output. The prototype can have many control strategies to be chosen by the user. The next Section will explain control design with more details.

3.1.1.4 Interface

Beyond that, there is an interface developed with MATLAB Appdesigner to interact with a controller engineer responsible for set control parameters.

MATLAB Appdesigner provides an entire environment to work with interface objects. The developer can drag to a canvas different components and give them callback behaviors. It is also possible to integrate this interface with the present logical project (communication, model and control units).

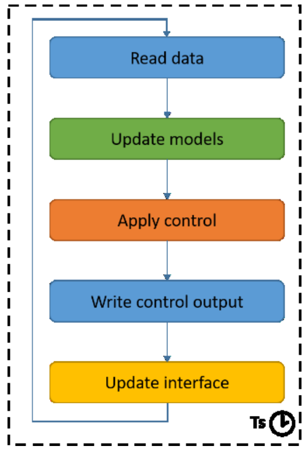


Figure 15 - Control app logic algorithm

Finally, with these 4 modules, it is possible to design a programming logic, as illustrate in Figure 18, to process an automatic control over sintering machine. It will be necessary to use MATLAB timer class for restart the program loop each period *Ts*.

3.1.2 Initial stage

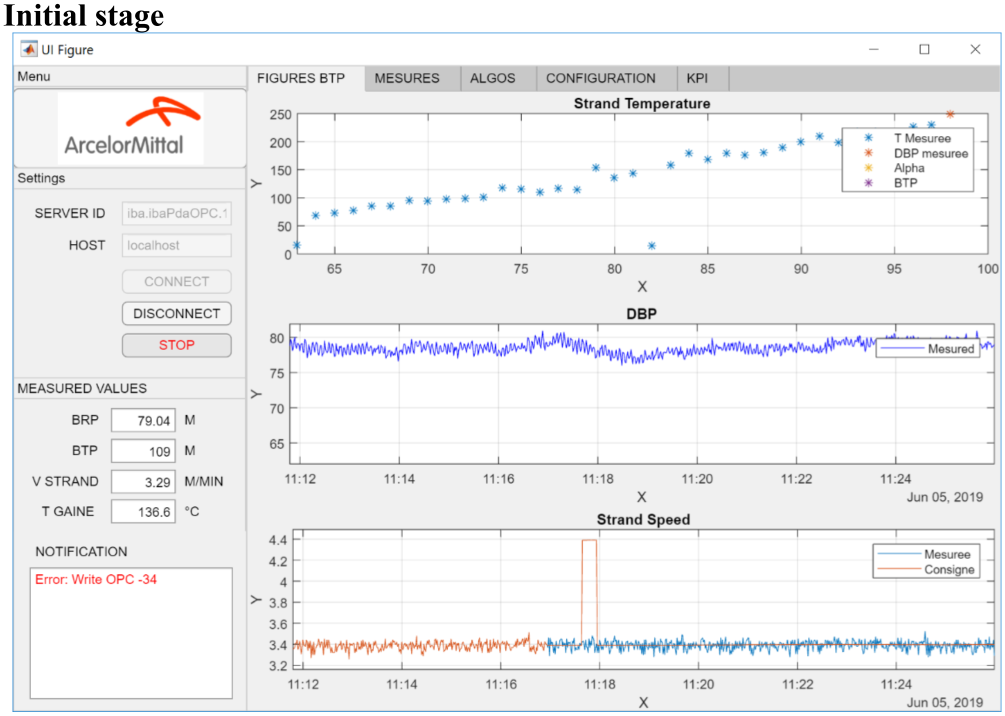


Figure 16 - First version app layout

Figure 19 shows the interface of first version prototype developed last year. In this version, it is already possible to connect to the plant station. The models implemented are the BTP fitting explained in Section 2 using LSE fitting and estimations of BRP, BTP and Alpha point. Controls implemented: PID, PID Cascade, Bremen method and a general Bremen method.

3.1.3 Development

One of our objectives is to improve this solution finding new modifications to boost the control methods and provide a better performance. So, some problems was verified in first version and the following work development was accomplished to correct them.

3.1.3.1 New application

Appdesigner denotes the same arrangement as the oriented object programming (OOP) known as “handle objects” in MATLAB environment. However, in the first prototype, the logic implemented inside appdesigner does not import this structure. This implies that, although it was first proposed to be independent units (control unit, communication, interface and a timer), they were not all independents and, thus, hard to make modifications. Once the project methodology suggest updates, it was certainly a disadvantage.

To deal with this problem, it was proposed a new prototype, a code structure correction based on OOP architecture. That encompassed a development of a totally new application with 3 independent unit arrangements: Communication, Process and Interface. To organize them, a unified modeling language (UML) diagram was generated base on OOP properties showed in Annex C.

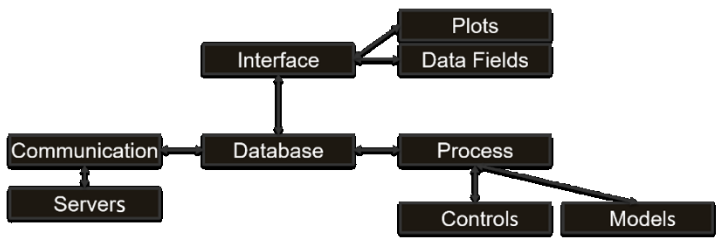


Figure 17 - Classes organization

The result is 3 great modules organized as shown in Figure 20 with their own program logic and period loop as illustrated in Figure 21. With this independency way, they could be used in others process application involving OPC communication and MATLAB Appdesigner, not necessarily only for our control application. Also, it implies to modify a module without affect the others. A new interface was as well generated and it is shown in Figure 22. Now, with this new version, it is easier to add new measures and new control features, as well it is very easy to add and test new control algorithms as requested the project.

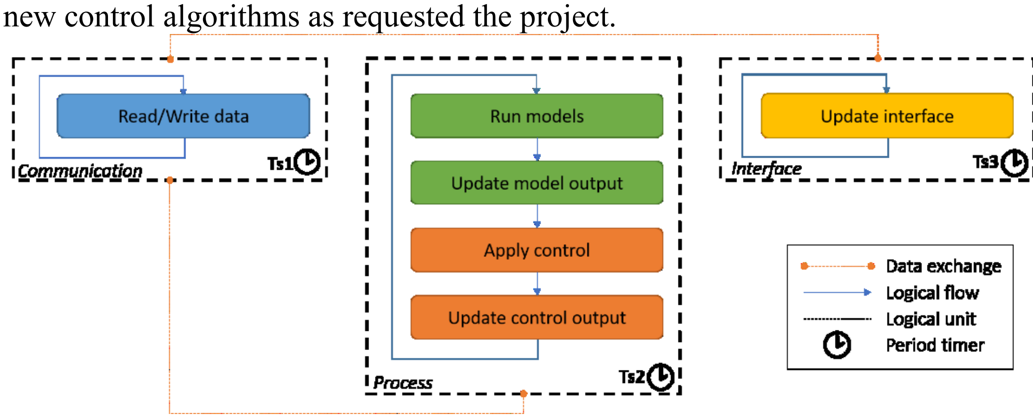


Figure 18 - New independent logic proposed

3.1.3.2 New versions

New measures

It should be remarked that the present objective is to automatic control the strand, but it does not replace the SCADA implemented in factory. And, since the first version, it was noticed a lack of integration between the control application and the SCADA where the supervisor operator monitors the operation and set reference variables. Said that, it was added to this new version the possibility of track an outside reference.

Other modification proposed was to add an automatic switch between manual/automatic controls that the operator can do many times in industry for different reasons. Without it, the operator has a hesitation of letting the control application run continually because in this type of situation as stops or when the switch has to be done quickly which it is not possible with the app, so, it would imply to have someone to constantly be in charge of the control application which is not interesting to the factory.

Other than new measures, it was added a correction of temperature measures once there are a big amount of thermocouple and they can failure damaging the control process.

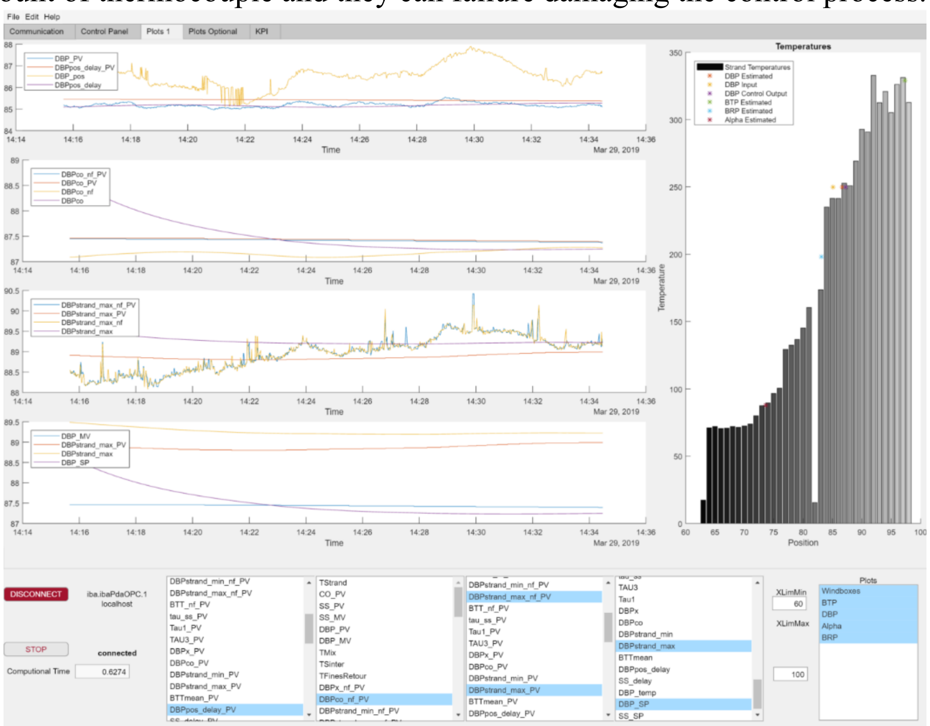


Figure 19 - New control application layout

New control features

Beyond the unit independency, another challenge was the improvement of the control process, specially the PID, with some new features which includes:

- Saturation of critical variables –
  There are some critical states in sintering process and some variables can signalized when they occur. One example is when the BTP is too much beyond the strand end

and the sinter cake is yet uncooked but very hot which can cause a great damage in the factory equipment and also a great loss of material. So, it is used the fines return temperature to signalize if the sinter cake temperature is in a safe range.

It is known that this type of critical measures can be strand upstream or downstream variables. They can work as a global guideline of the process as well because once the upstream and downstream reference variables are in a good range, it indicates a good performance and the control can continue on its automatic loop.

Section 4 will better explain how it affects in the control methods, how it was implemented and some analysis done.

- Track of ramp set points –
  Reference set point as ramp function is commonly used in cases of temperature regulation because it is a very slow dynamic so, it is interesting to avoid big changes in control output.

Figure 23 shows the final interface of the PID with new features.

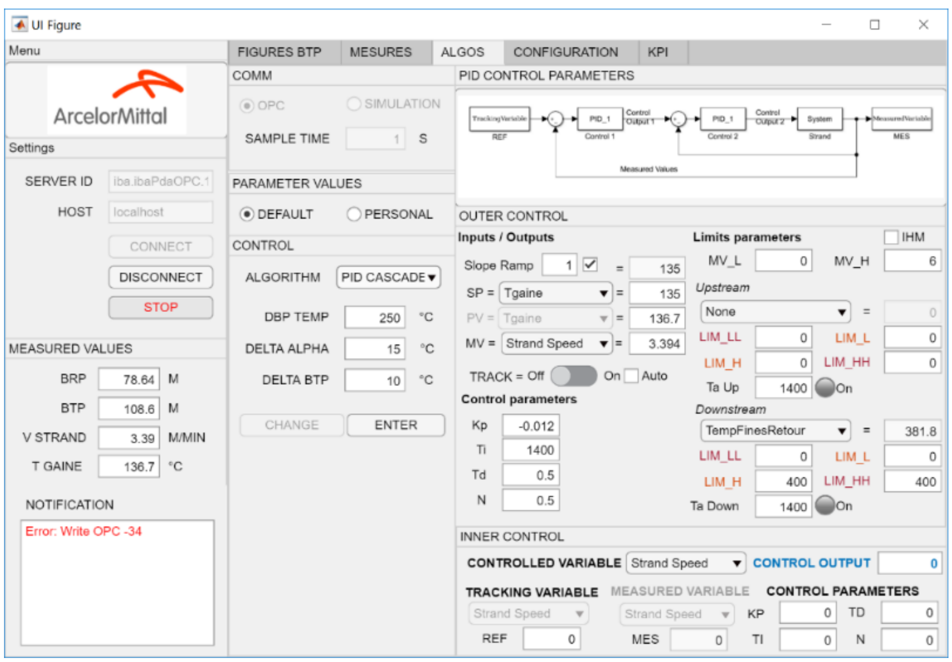


Figure 20 - New version control application layout

3.1.3.3 Controller Supervisor HMI

Because of the lack of confidence noticed and high chances of unavailability in case of failure of many different sensors in which the automatic control are based on. It was proposed another application to support the automatic control process with critical variables as the limit process variables, control saturation and key performance indicators (KPI's).

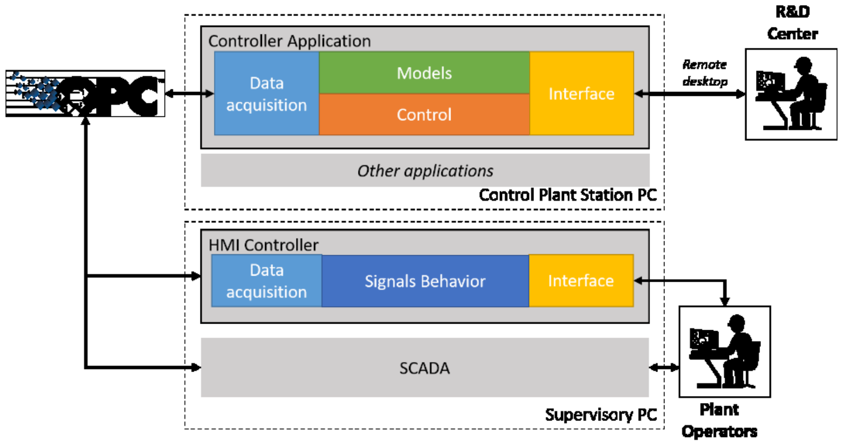


Figure 21 - Project solution with new HMI

As Figure 24 illustrates, this solution allows a control engineer to set the control parameters and test it, while a supervisor has the Controller HMI as support to certify that the controller application is going well and at the same time be responsible for the rest of SCADA system. In this application, the supervisor has the power of set limits of critical process variables as discussed previously, to limit the control output and to quickly slow down or speed up the strand. Figure 25 shows the interface resulted from this present work. More details about the development of interface and logical code can be found in Annex D.

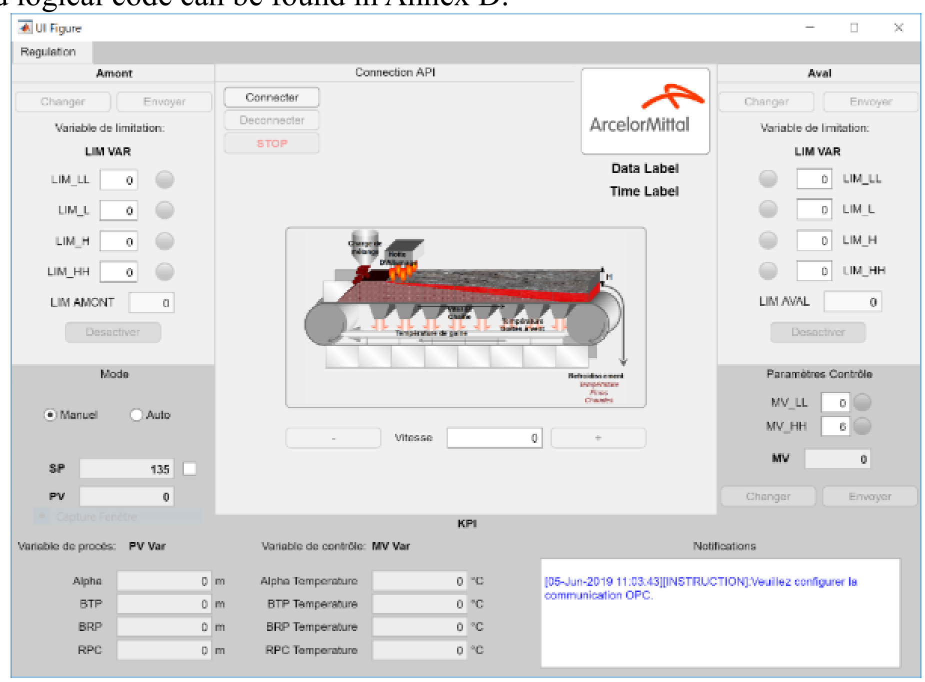


Figure 22 - Control HMI resulted

3.1.4 Final stage

Finally, we arrived in a final version to be tested again in factory with new features and functions correcting problems found in previously version. The problems and solutions implemented are summarized below:

- Algorithm architecture –> New application
- Not general control and critical variable –> New PID features
- Lack of confidence –> HMI operator
- Factory practices and lack of integration –> Ramp reference and new measures
- Slow control mode switching –> Manual outside signal

A detailed algorithm diagram and its implemented code are provided in Annex D. Also, Figure 26 shows how the process actors and project tools are connect to automatic control the sinter strand.

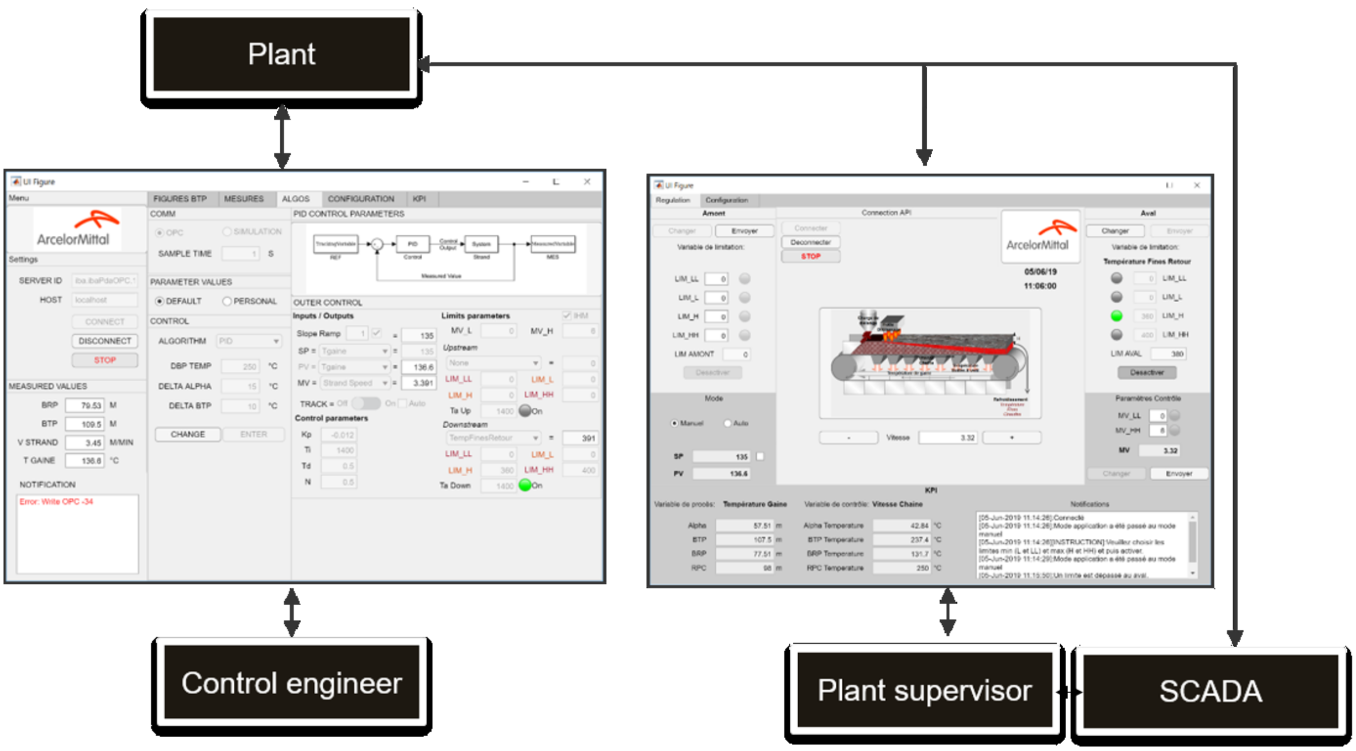


Figure 23 - Control solution resulted

3.2 Sinter pot view

Other than the automatic control the sinter strand, in this internship also it was developed other application to help in BTP control studies, a sinter pot tests view. The interest on this app was to submit an interface to integrate the great amount of data acquired in sinter pot tests for better comprehension of the process over time. A first version was developed and it is shown in Figure 27.

It is possible to reproduce the infrared camera frame together with the others sensors measures in a timeline having an overall process visualization as demonstrated in Figure 28. Before running the app, the user chooses how many frame profiles (a column of pixel values) will be plotted on the left and which sensor measures it will be plotted on the right. After, for each sample, an infrared camera frame is screened in the middle, while the values of each profile filtered are plotted on the left. On the right, there are the temperature waste gas and measures chosen. Also, it is exhibit a plot on the frame screened of an alpha point estimation, where we consider to be the beginning of flame front.

It was also done a work to synchronize the measures acquired for a correct visualization because the acquisition devices had the clock shifted.

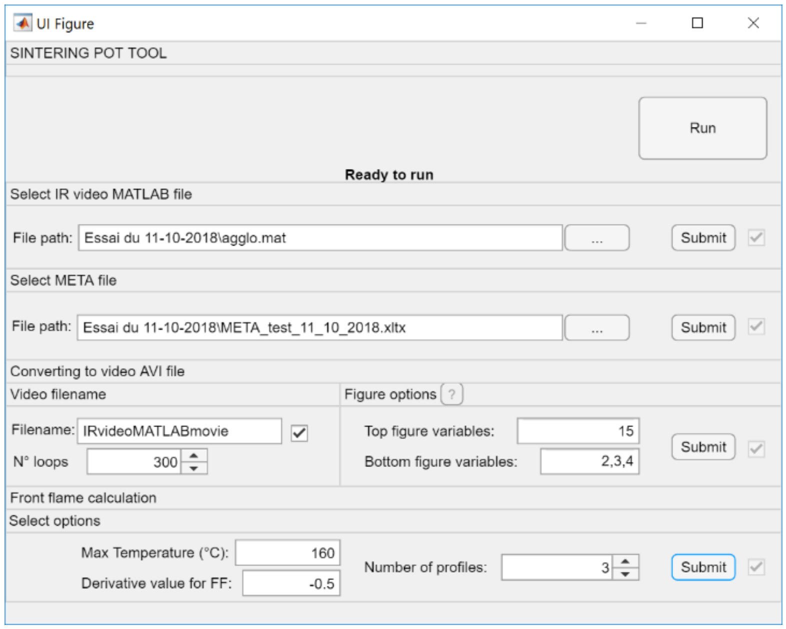


Figure 24 - Sinterpot View layout

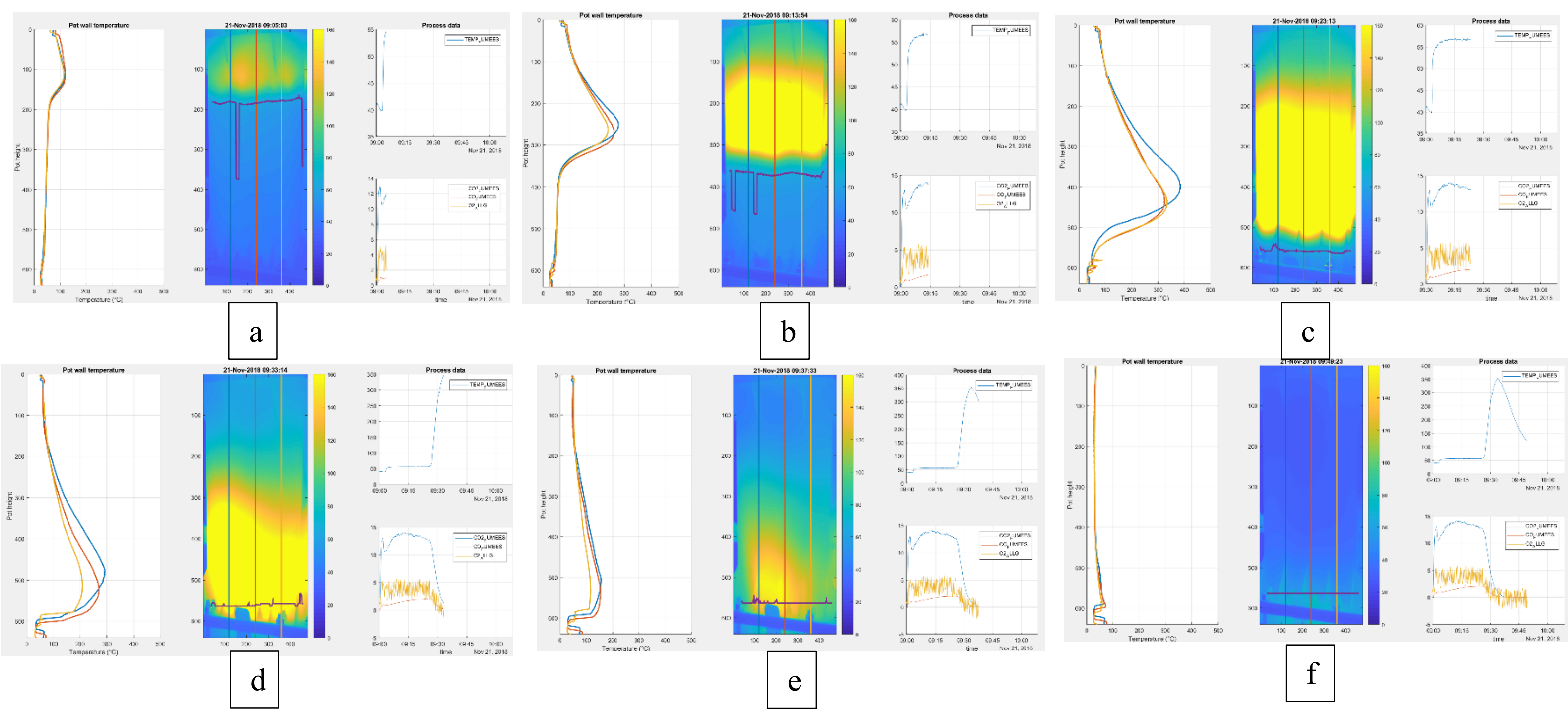


Figure 25 – Sinter pot view simulation frames

4. Control & Modelling

To guarantee a better performance, some studies was done about control design considering different plant scenarios.

4.1 Process review

As detailed in Section 2, the interest of control sinter strand is to ensure that burning-through point will be at the end of the strand for a complete charge cooking. Illustrated in Figure 29, the key player for controlling it is the strand speed, while there are other different variables that indicates a good performance, BTP, for example, or Waste Gas Temperature, and could be chosen to be controlled.

Other than speed strand, some control strategies consider DBP (or BRP) as manipulated variable because it is directly related to strand speed by BTT.

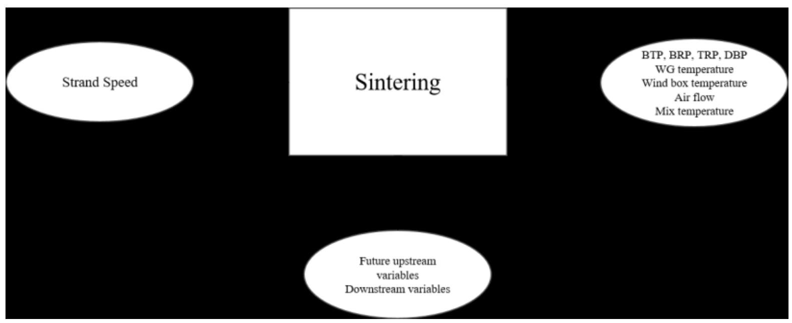


Figure 26 - Sintering Process Scheme

4.2 Control requirements

Some control objective were defined based on general project interests and industrial data analysis.

4.2.1 Reactivity and robustness

There are great amount of BTP control methods in state of the art, however many of them are model based that implies an extensive process study. Therefore, a reactive and robust control is suggested as solution for overcome model exhausting problems because it would rapidly respond to model changes or disturbances.

After industrial data analysis, it was separated 2 kinds of perturbation present in DK data:

Short period

As shown in Figure 30, it was noticed bump disturbance of 30 min of with amplitude between 3 and 20 degrees in the WGT while a process input (strand speed) constant. This can be explained by the impermeability changes over the charge material that can affect BTT (cooking time) allowing the early arrival of flame front to grid level. Given that, the control chosen has to be capable of rejecting this type of disturbance.

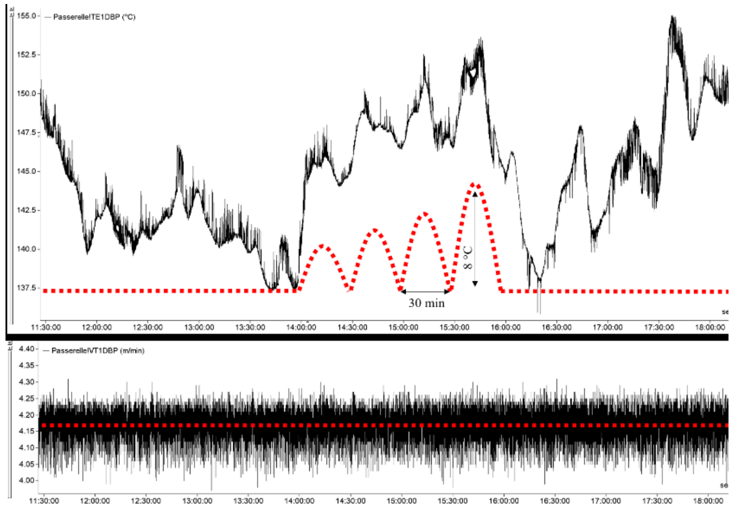


Figure 27 – Output disturbance with 30 min duration

Ramp disturbance

Another disturbance noticed during process is a ramp signal of amplitude between 5 to 15 degrees with a rising time of 1h to 2 h, probably related with model changes, white process input constant. It is shown in Figure 31.

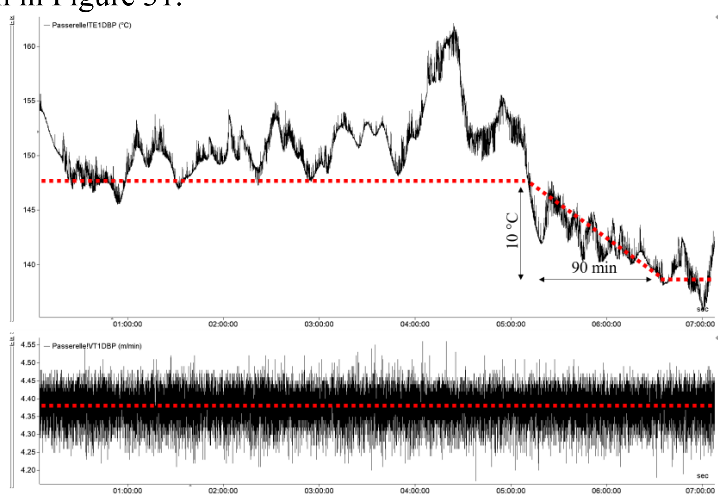


Figure 28 - Output disturbance with slow dynamic

4.2.2 Stability & Material quality

There is a great interest in a stable process because temperature is a very slow dynamic and, also, because it is known that a material quality is related with the burning temperature stability. Said that, one control objective is to ensure that process variables remains stable over time.

Also, it is interesting for the stability a control regulation with small variations in amplitude to not cause great variations in process variables.

4.2.3 Productivity

Productivity is much related with BTT and how long the sinter cake stays at the grid. So, it is interesting to arrange an optimal control searching for small global error in tracking of BTP by having a fast enough control.

4.2.4 Challenges

Beyond the global requirements, others challenges are imposed to automatic sintering. First, it is known that a sintering process is very disturbed and a simple model could not ensure a good arrange. So, it is a challenge to work with robust control that can led with these situations.

It is a challenge to guarantee the availability all over the production, so it is important not depend on a single variable, but also search for control of KPI and limitation variables, predicted or measured process variables that are affects by BTP control and disturbances all over the process.

Aside from technical challenges, there are human factors to influence in control performances. Some operators work in this process for many years and they have some habitual practices to control the plant. Once the automatic control provides a totally different control behavior, it is hard for them to accept it and they tend to inhibit the control to run for long periods.

4.3 Control Methods

The first method chosen to be tested in a real plant is PID because it is commonly used in industry and easy to implement. After, it was proposed some PID modifications. At the end of analysis, it was noticed that some delayed were prejudicing control performance. Thus, some studies with model predictive control (MPC) was realized.

4.3.1 PID

Using previously industry knowledge, operators take waste gas temperature (WGT) as process variable to set performance. Based on this practice, the main control logic chosen to be tested is a first degree transfer function WGT x Speed Strand detailed in Section 2 with a control logic as can be seen in Figure 32.

Figure 29 - PID Control Scheme

PID Specifications

- Track WGT Step in 1 hour with max 5% of overshoot

- Reject bump disturbances of 30 min with less overshoot possible
- Reject ramp disturbances

Challenges

- Avoid big control output variations
- Slow adaptation to sintering slow changes in steady state
- Reject big and sudden sintering changes in steady state

PID Design

1. PID 2DOF

A PID 2DOF architecture was implemented in the application. This architecture was chosen because there are many parameters that can be set on it. For example, it can be set output changes instead of error for the derivative term reaction, a common technique in industry to avoid noises effects. Figure 33 shows the equation provided by this method. It is possible also to choose de integration discrete method.

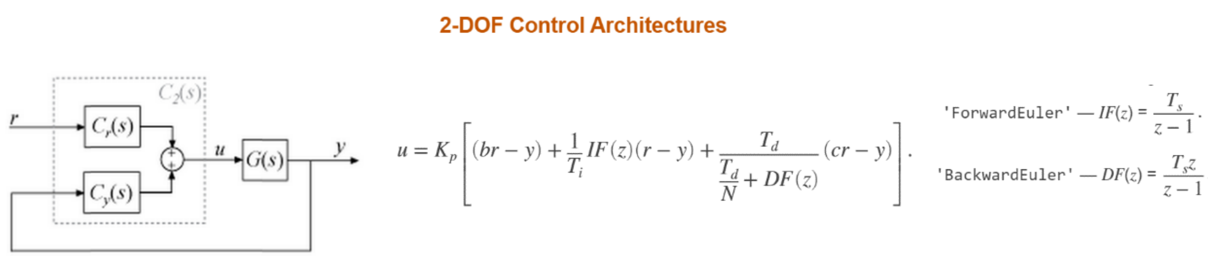


Figure 30 - PID 2DOF Architecture

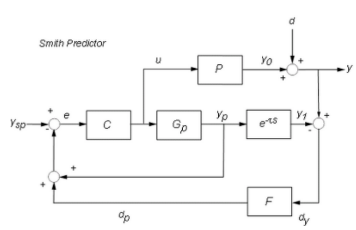


Figure 31 - Smith Predictor PID scheme

To deal with the delay of the model, it was proposed a control logic based on PID Smith Predictor and its architecture is shown in Figure 34. This control uses a model observation without delay to predict next control actions while it corrects the model error leftover with the real process measure when it arrives.

Simulations results

It was developed, thus, a Simulink to test this model and control design. After discussions with the responsible engineers, it was defined PID parameters to be tests. A 900 mininutes response tests was generated with:

1. Step of -11 °C (applied at 0s).
2. Output disturbances of 30 min duration with amplitude of 1.25°C, 2.5°C and 5°C (applied since 250 min).

3. Output disturbance of amplitude 10 °C (applied at around 90 min) with 1h of rising and other with -20°C (applied at around 320 min) with 2h of rising.

The results are shown in Figure 35.

It was also generated some tuning tests to analyze the effects of each PID 2DOF parameters for this reference and outputs disturbance and it is detailed in Annex F.

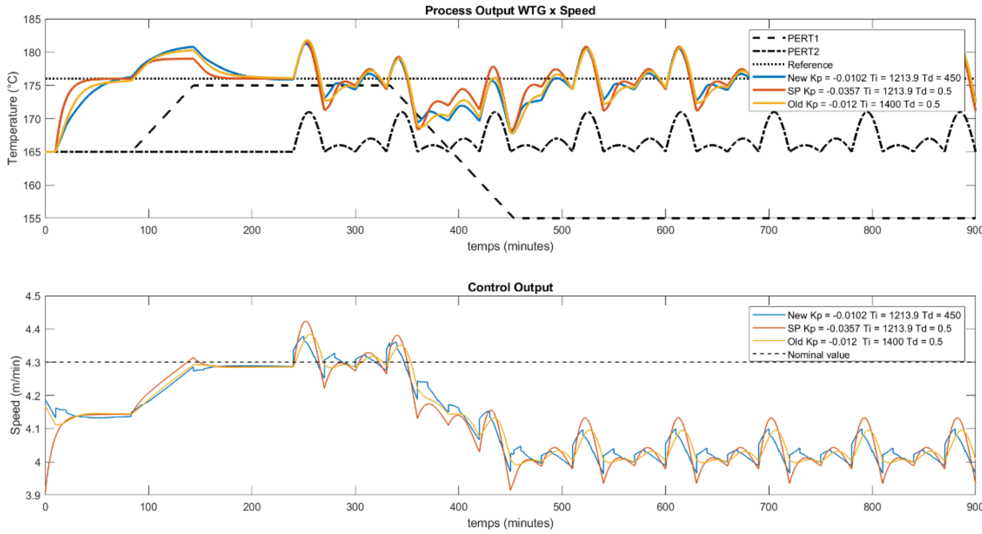


Figure 32 - Step response simulation

It was observed that a low integrator time factor would imply a fast reaction, but it could bring overshoot and amplify small period disturbance instead of rejecting it. Also, a high value of derivative term can help on rejecting sudden changes in sintering temperatures and prevent overshoots during disturbances rejections, however it could give a higher control changes.

Smith Predictor control exhibits that is possible to reduce the step response setting time to half of the time, but in rejecting disturbance it was not so much more effective. But, as Smith Predictor control is a more complex control, there is no advantage of implementing it.

Finally, a good PID parameters was generated to future tests in real plant. It was noticed a difficult to reject bump disturbances in all parameters, so it is concluded that another strategy has to be done. The solution is to model this kind of disturbance or predict it by upstream or downstream measures and models for feed forward actions.

New Control Features

Although it is possible to find a PID to minimal control requirements, this control depends totally from WGT and it is known that this measure can be unstable or disturbed by different external factors. So, it is possible to add some critical variables capable to limit the process allowing properly control reactions during unstable sintering measures and ensuring a normal operation range.

This method require upstream and downstream measures such as upstream variable feed hopper level (*niveau trémie de chargement* in French) for upstream or fines retour temperature (*temperature fines chaudes* in French) for downstream variable.

4.3.2 MPC

As explained before, one solution for the output disturbance is a prediction of the process. DK plant uses nowadays the Bremen solution for predicting some process features, but it is insufficient for improve performance. Given the prediction concept, it was proposed a MPC (Model Predictive Control) for generate the better once this control type has showed great results around the world to different process.

The MPC (Model Predictive Control) controller is an advanced control technique for systems, based on the system's model and capable of handling constraints for the system's dynamics. The MPC can be summarized as formulating the control problem as an optimization problem, considering system constraints and a cost function to be minimized, which is solved over a "prediction horizon", a future window. The degrees of freedom of the controller over this prediction horizon is called control horizon.

Simulation results

Some tests was realized by the other intern Teixeira e Souza that proposed a MPC control to integrate with the controller application. Its parameters is shown in Annex F.

The simulation considered a regular MPC and two Velocity Form MPC controllers, and the current PID implemented in the BTP control project. The scenario is a step of -5ºC at 20s, and two disturbances that are commonly found in the sintering process: a "positive bump" disturbance signal (applied at around 105s) and a ramp disturbance that starts at 0ºC and stops at 20ºC, value that remains in the rest of the simulation. The MPC parameter configuration is detailed in Annex F.

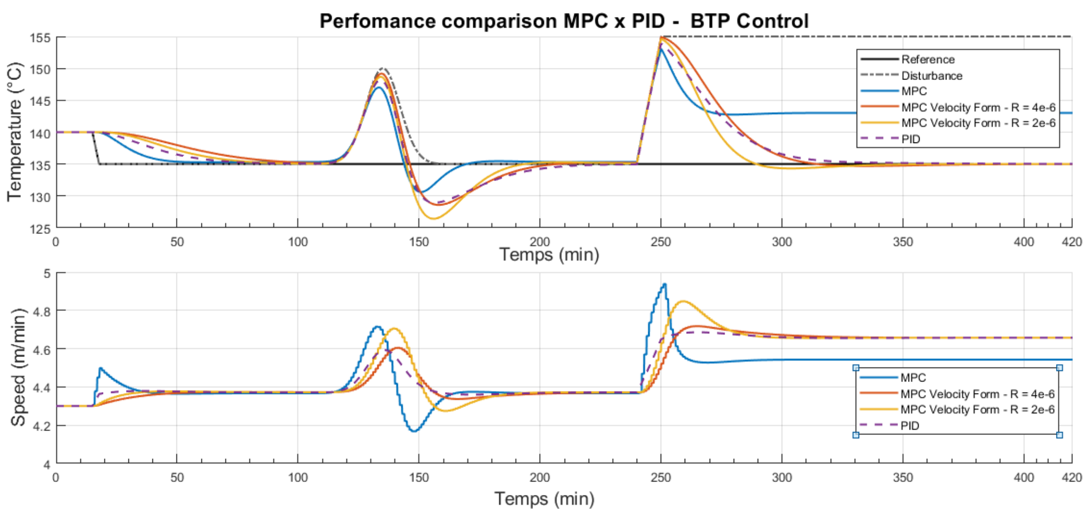


Figure 33 - MPC Simulation of BTP control

The simulation shown in Figure 37 indicates that a regular MPC is not suited for this type of steady disturbance because it is not capable of rejecting its effects. The Velocity Form MPC suits more the objective, and the two possible choices of the R parameter indicates that a compromise must be done: minimizing of settling time and disturbance effects duration, or avoiding abrupt changes in the strand speed.

5. Conclusion

5.1 Development results

DK – France

The first control method chosen to be tested in a real plant is a PID for some reasons:

- Commonly used in industry and 1st step to go from manual to automatic.
- It has a simple logic and easy to implement.
- Sintering behavior is complex and dependent on many variables which implies hard to model, so it is hard to find model-based control solutions.

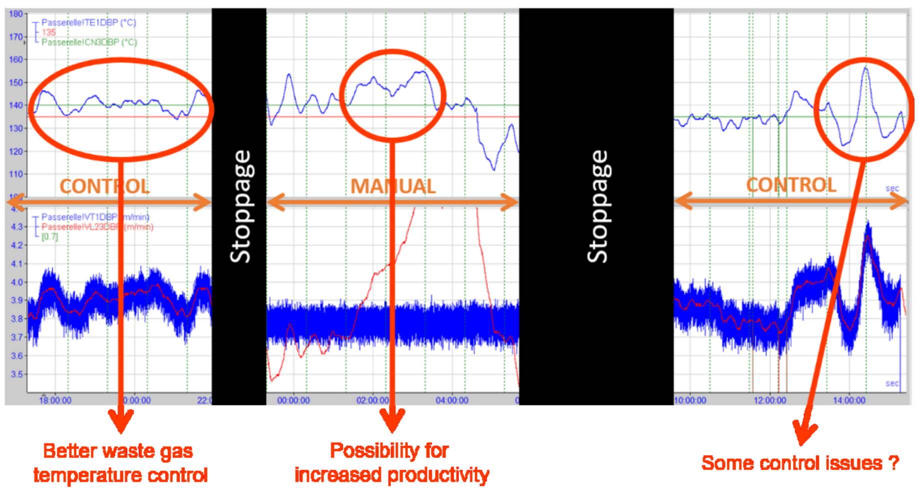


Figure 34 - DK plant Tests results of a PID control

Therefore, with the controller application, a PID control was tested a few hours in DK plant and the results is shown in Figure 38. It shows a more stable process with a more reactive control compared to manual control. However, it was noticed some unexpected behavior with great overshoot in another period of test, this can be explained by measure disturbances or unpredicted control behavior.

Also, it shows that there are clear advantages on remodel the process to automatic control. Also, it reveals that a simple control a PID has its advantages and it is efficient to produce positive outcomes. But, some different situations has to be yet studied and tested with the new features proposed.

5.2 Development next steps

Based on work outcomes, it is defined some following steps:

- Test PID in long term to deal with different and more complex sintering stages.
- Integrate new controls to be tested in real plant.
- Integrate Control HMI in the real plant control station.
- To model strand stops and restarts, which presents different behavior.
- Front flame model estimation for better prediction of BTP.

5.3 Professional and personal development

Many challenges were overcome in this internship. Migrate a process from manual to automatic control requires many techniques and steps. The greatest gain on this type of project is to deal with real problems in industry going through each automation step since data acquisition, data processing, model study, process comprehension to advanced controls, investigating a great amount of solutions. Also, it requires collaboration of every technician related to the process and a lot of patient to adjust classical solutions to real problems and understand their limitations.

In this internship, I had the opportunity to learn about metallurgy industry and to be closer to real factories and industrial technologies that I have learnt in school. While the problems were presented, I could give suggestion based on my experiences and it was very nice to implement or discussing them for the present project.

I've learnt also that simplest solutions can be the best solutions for first conceptions, but even so, they have many challenges during implementation. Because, the data is not always available, models can be very hard to define, human factors can affects development and budget is always in discussion.

During an industrial project, the priorities can change based on results or on company needs and as engineer is our job to advise the best procedure for it being flexible. Given this context, I had to deal with flexible project schedule and to adapt solutions, which allowed me to learn more thorough about the problem and about the engineer techniques.

Other than professional development, I had to deal with an international environment, so I had to express myself in other languages and work with people from different cultures. Also, I had to discuss clearly with senior engineers, on the same technical level of talk, about process and technical problems.

Being in a large company allowed me to understand how works a big company structure, follow their conducts, and to deal with bureaucracy that can be an obstacle to overcome but it is necessary.

At the end, I feel that this internship added a lot for my engineer experience. It gave me a realistic vision about industry and how it works as well gave me confidence to look for solution I have already know or to find new ones. It showed me the great education that I had so far allowed me to explore a world of possibilities to discuss and implement them given a problem.

Annex A – Sintering complementary phases

A.1 Preparation

At first, a charge of mineral mix is prepared. This is a phase to determinate the percentage of the loaded composition of a mixture of iron ore, coke (solid fuel), return fines (recycled sinter) and additives.

Iron ore is taken from different parts of the world and is the main component for producing sinter. On the other hand, it does not arrive in an ideal form to proceed to the blast furnace process. For this reason, a solid fuel (CO) is used to produce a combustion whose heat is responsible for melting and agglomerating iron and recycling the final product from previously cooking, the return fines. The operator can add other components, such as lime, dolomite, olivine, limestone and sand (CaO, ...), to achieve an ideal chemical balance and ensure ideal combustion to achieve the desired properties of the product. Then, this mixture is moistened and kneaded to have sufficient permeability for a good gas flow in the baking step.

In this phase it is important to notice that the combustion is related to the relative amount of carbon. But, a larger amount of carbon does not mean a more ideal combustion, because it can interfere directly in the cooking time. Other factors that may directly interfere with the cooking time are the layer height and the permeability of the mixture which depends on the amount of water and the amount and density of the components used.

The amount of return fines is also an important factor because it is a recycling of a product from an earlier burning and, therefore, there are its physical and chemical properties to consider.

A.2 Cooling and quality inspection

After the sinter cake drops out the sinter strand, it goes through a cooling and then an inspection to separate those parts that have the good physical properties and those that are return fines.

The expected size is around 30–60 mm (1) in diameter. The gases produced are also evaluated and it is expected, ideally, a low rate of CO, but not zero because it is expected to have still a little combustion on cooling.

There is an optimal rate of return fines and a high production of it indicates that the strand speed setting was not optimal and it missed the burning-through time of the mixture or there were perturbations on the chain not predicted.

Annex B – Automation tools description

B.1 PLC, Sensors & actuators

Programmable logic controller (PLC) is an electronic device used to control of manufacturing processes in several different industries. A PLC has chart of inputs and outputs. With a computer program, it is capable of command, receive, send and process digital or analogic signals to several electronic devices as sensors, actuators, drives, etc. PLC exports its collected data to supervisory control and data acquisition (SCADA) system. This communication can be done by several types of protocols, for example, the open platform communications (OPC) protocol.

B.2 OPC Server

OPC Communication is a software used to isolate industrial PLC and others devices for data processing, but it can be used between other types of devices. It works in pairs of Server/Client. After connect, the server transforms the dada in a standard format providing a compatibility with the client. Matrikon OPC is the industrial OPC software used in the present work.

B.3 Remote desktop connection

Remote desktop connection is a software used in this work for connecting remotely with an industrial computer located in the sintering plant. Both computers are connected by an Ethernet protocol.

B.4 IbaPDA

Iba is a company that offers solutions for data acquisition. One of this solutions, IbaPDA works as an OPC client and allows to plot and analyses the data receive from the OPC server. It also registers the data to later be used in playback function to simulate an online data acquisition.

B.5 MATLAB

MATLAB is a development environment used for data analysis and processing design with a programming language that expresses matrix and array mathematics directly.

B.5.1 Appdesigner

MATLAB also provides the Appdesigner, a development tool where is possible to design graphical user interface (GUI) of a professional application and integrate it with a logical programming for its behavior. This program can include classes, scripts and functions developed in MATLAB. With the application finished, an executable file is generated to allow running it without having MATLAB installed in the work machine.

B.5.2 OPC Toolbox

MATLAB offers an OPC toolbox to access real time data of others devices. It works as an OPC Client that connects to an OPC Server for reading, writing and logging data.

B.6 XML Files

Extensible Markup Language (XML) file is a text-based database to store and transfer data in machine-readable and human-readable structure. They will be used in this work to store application configurations.

Annex C – New prototype structure

C.1 New prototype adapted to OOP programming

To arrange this new prototype, a unified modeling language (UML) diagram was generated base on OOP concepts illustrated in Figure 39 to achieve good properties (Figure 40) given in this type of programming.

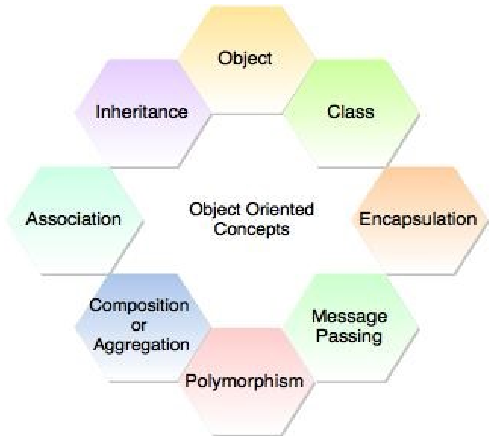


Figure 35 - Object Oriented Concepts

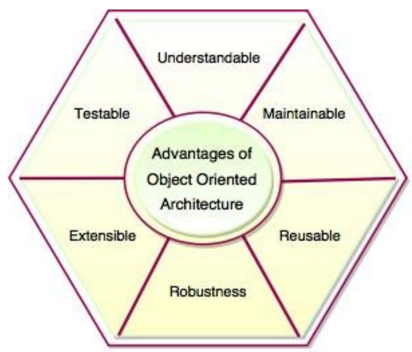


Figure 36 - Advantages of Object Oriented Architecture

Based on OOP concepts, an UML diagram was generated and it is showed in Figure 41.

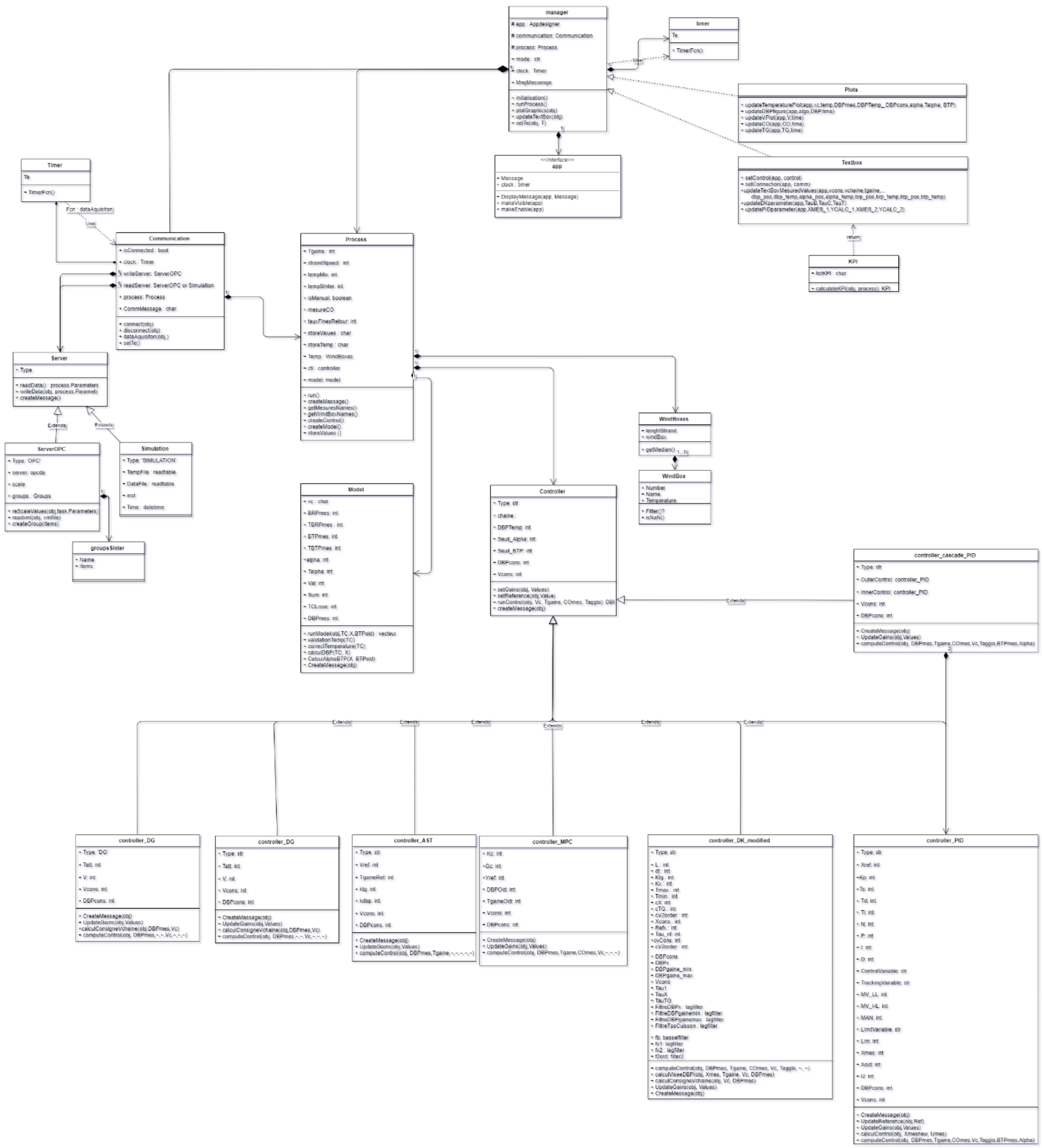


Figure 37 - UML diagram generated of new architecture

Annex D – Control tool final version code details

D.1 Controller Application code details

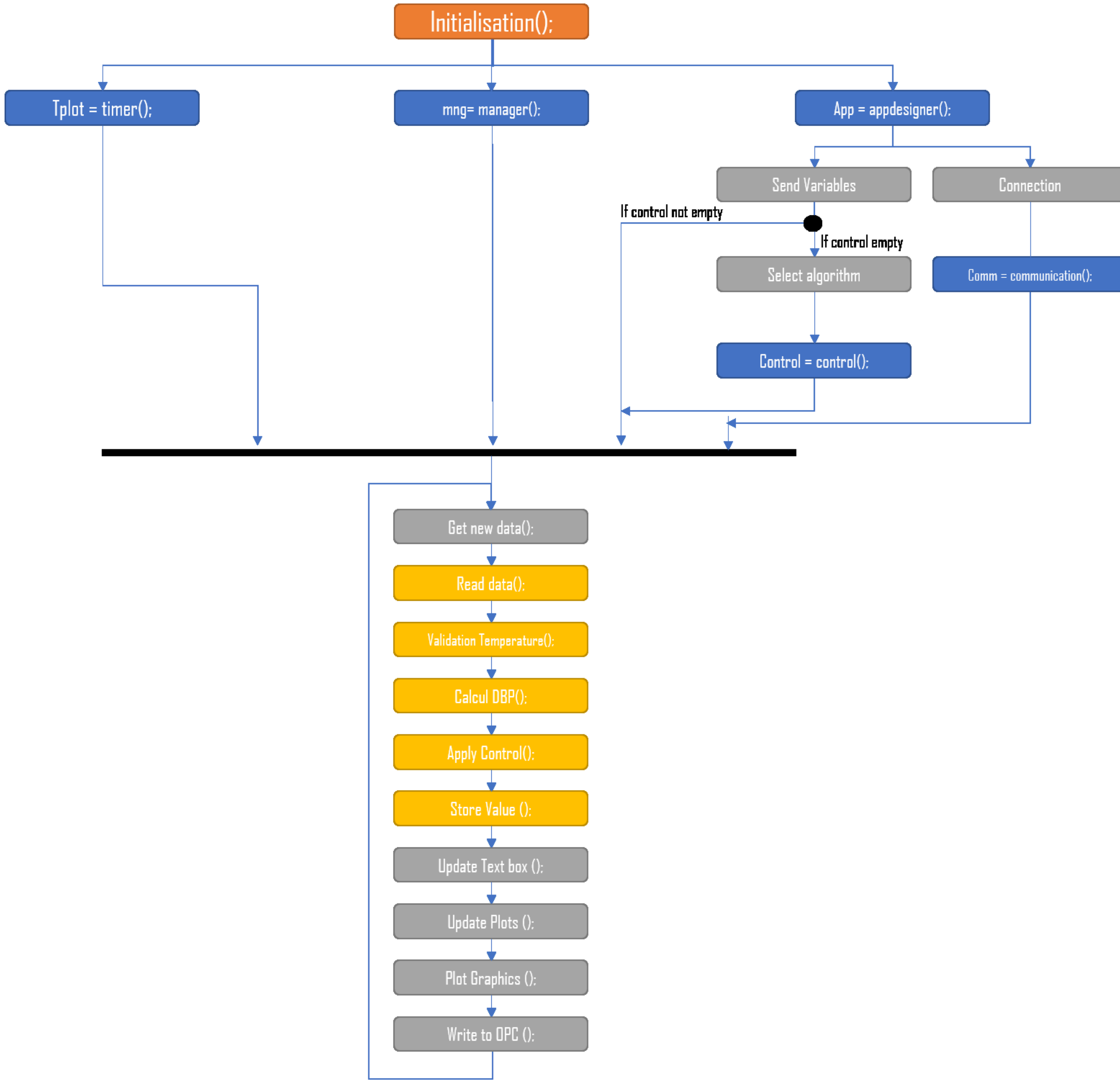


Figure 38 - Logic application flows

Annex E – Data identification

E.1 Identification problems

1. Oversampling
2. High disturbance over process that hide measure
3. Great amount of stops over production time
4. Process variable (PV) sensitive to related external factors
5. It is expected model changes related to different type of mineral and retour fines affects.
6. High relation to impermeability which is not measure yet, but could be a model parameter.

Annex F – Control PID and MPC parameters

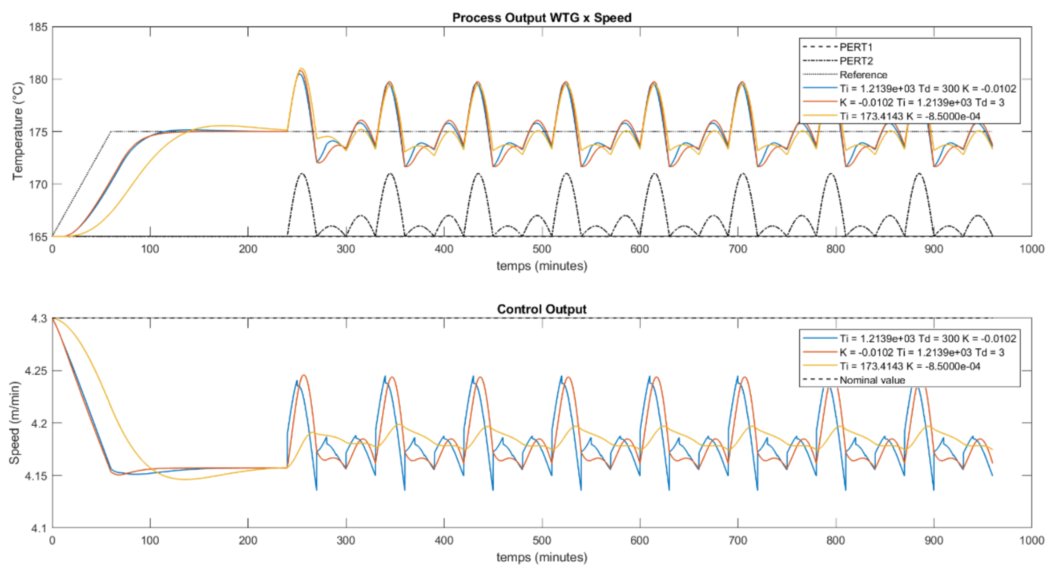
F.1 PID Tuning

Some tests were generated to analyze proportional, integrative and derivative parameters that could match with industrial requirements and operator behaviors.

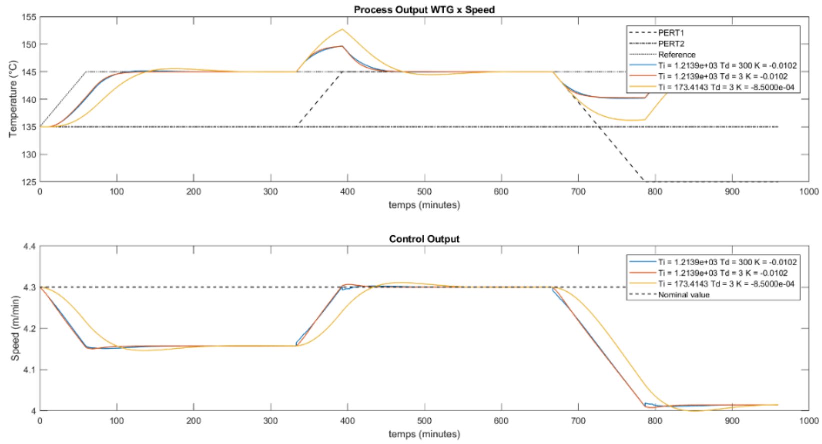
It was conclude that the only way of not reacting bump signals is a very slow control. Factor knowledge suggest a very slow changes in process. Based on that and on the first transfer function found, we estimate 1 hour a good step response.

There is another disadvantage on having a fast control, it could cause an instability on charging phase producing uneven charge at the strand's beginning which could imply in more disturbances or instability.

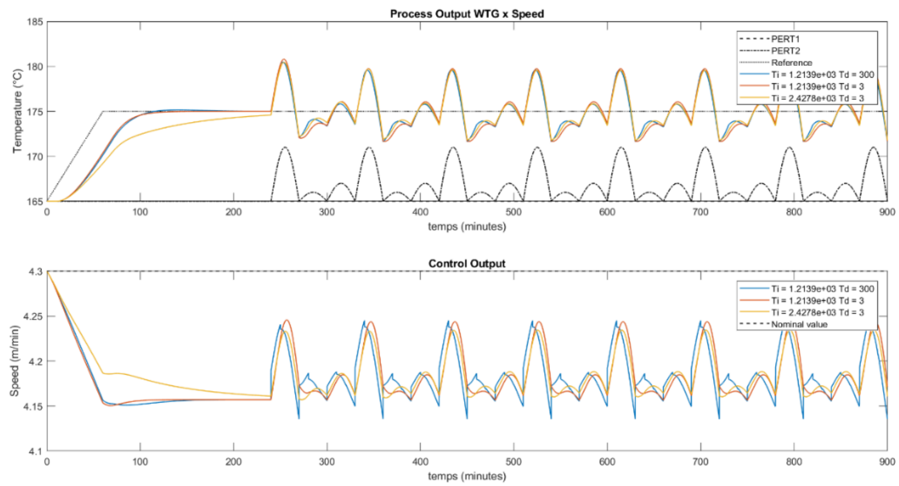
The lower proportional K is suggested in case of less control changes as can be seen in Figure F.1. While a high K try to react fast to correct error, a lower K slow it down with less control changes, which slow down corrections of output disturbances as can be seen in Figure F.2. To deal with this slow reaction, it is possible to decrease the integrator time (Ti) to integrate error faster and speed up the correction. Therefore, some test with different Ti was generated and is showed in Figure F.3.



F.1 – Tests with different K for a ramp reference and bump disturbance

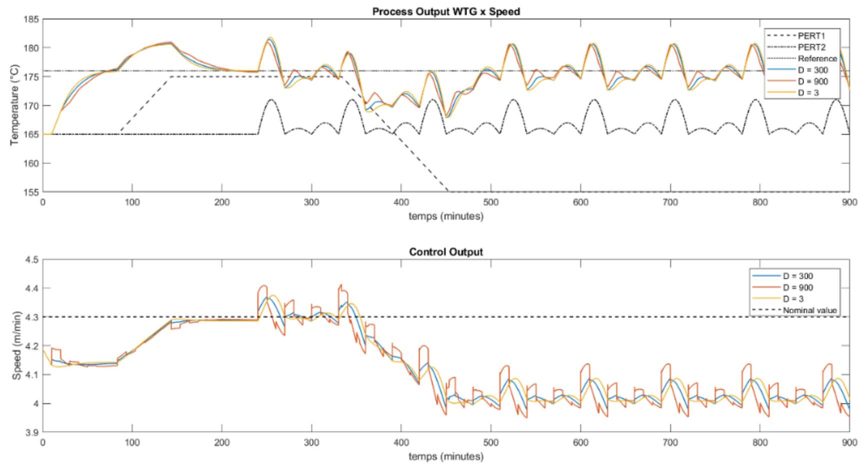


F.2 - Tests with different K for a ramp reference and ramp disturbance



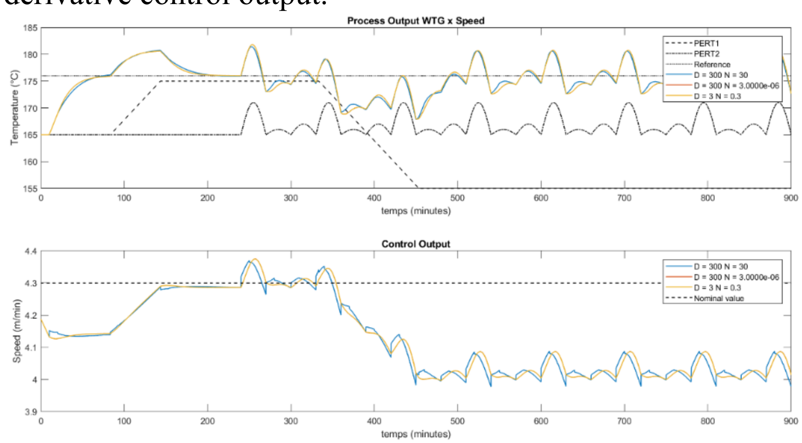
F.3 - Tests with different Ti

The derivative term was also studied to analyze its behavior for the process signals proposed. For control improvements, it has to be considered that a higher Derivative term will cause abrupt changes in control outputs, but it can help in stabilizing the process by decreasing disturbance effects or abrupt process changes as can be seen in Figure F.5.



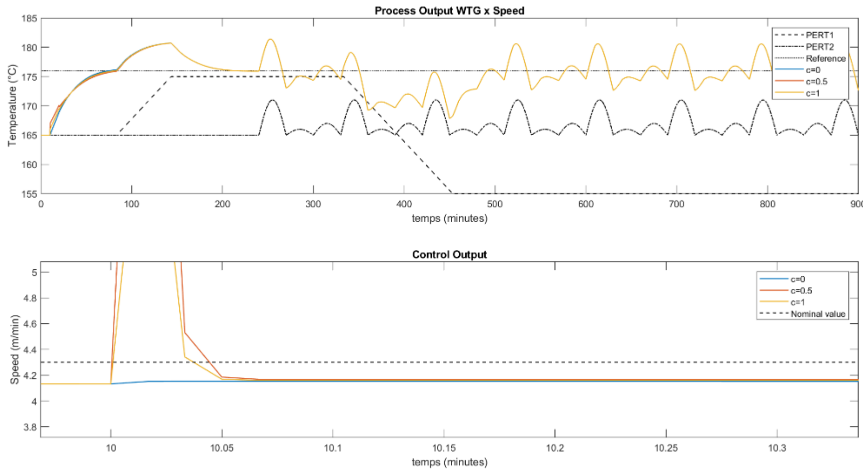
F.4 - Tests with different D

To slow derivative term, it is used a filter with factor N. Figure F.5 shows that a N very small will cancel the derivative control output.



F.5 - Tests with different N

The reference weight (parameter c) was also studied to find its effect over the process. It was noticed that c will soften control output in reference tracking as can be seen in Figure F.6. This effect is better exhibit in step reference. In industry, it is used ramp reference to produce the same result. Another advantage of using reference weight is to be insensitive to output noise effects.



F.6 - Tests with different reference weight c (Zoom in control output)

F.2 MPC

Parameters chosen to BTP control test:

BTP MPC Parameters

T_s	N_1	N_2	N_u	y_{nom}	y_{max}	y_{min}	u_{nom}	u_{max}	u_{min}	$\|\Delta u\| \leq$
60s	1	80	1	140°C	150°C	115°C	4.3m/min	5m/min	3m/min	$0.15 m/min^2$

Table 6.4: Model parameters of the BTP system.

The performance parameter R set for each one of the MPC controllers are found in table 6.5, and simulation results are shown in figure 6.8.

MPC	MPC VF 1	MPC VF 2
$5e2$	$4e6$	$2e6$

Table 6.5: Parameters R for each MPC controller - BTP control.

References

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