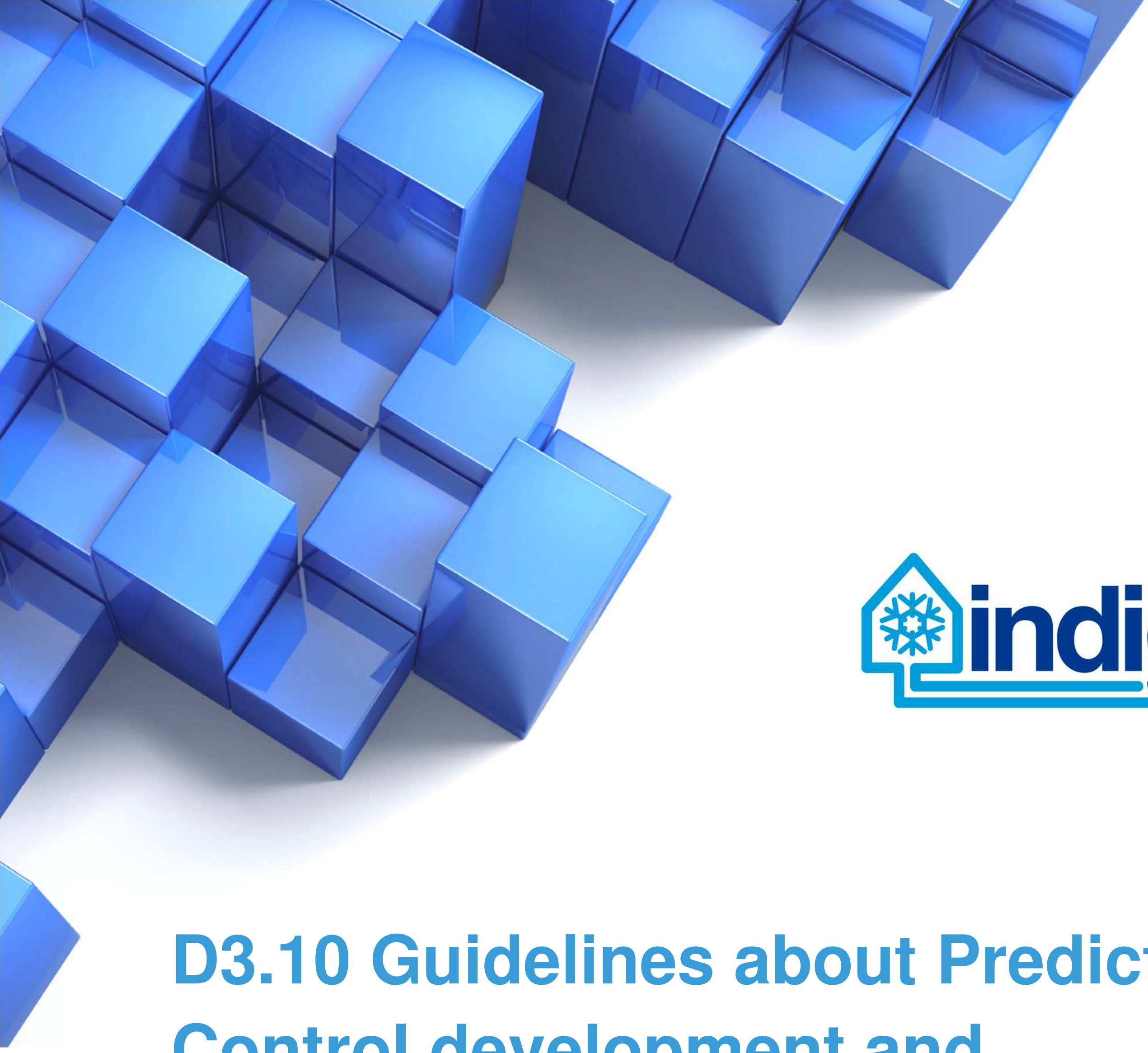

D3.10 Guidelines about Predictive Control development and implementation in DC systems

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Disclaimer

The opinion stated in this report reflects the opinion of the authors and not the opinion of the European Commission.

Executive Summary

The European project INDIGO aims at drastically increasing energy efficiency in District Cooling networks through the development and implementation of a new generation of smart controllers, exploiting demand forecasts and systems knowledge to minimize energy waste.

In this report, the authors summarize the learnings gathered along the project and share them in the form of guidelines for the readers willing to implement a smart control system to improve and boost the performance of an existing DC plant operation.

The information is structured according to the three phases of the implementation plan: planning, commissioning and exploitation.

During planning, the focus is on the information that needs to be gathered on the existing system in order to guarantee that an MPC approach is applicable. For every group of equipment, namely generation, distribution and consumption, the list of variables to be monitored as well as the models that need to be developed for prediction is proposed.

In the commissioning phase, the algorithms are verified and validated and methods for a sanity check are proposed in the document. The validation is preferably performed in a controlled environment, i.e. in simulation or in parallel with the existing system over short periods of time.

Finally, in the exploitation phase, the control algorithms are deployed on a real system and performance measurement options are proposed.

Table of content

Nomenclature

AHU	Air Handling Unit
BFGS	Broyden-Fletcher-Goldfarb-Shanno
DC	District Cooling
DCP	District Cooling Plant
DRM	Demand Response Management
DHC	District Heating and Cooling System
FCL	Fully Connected Layers
FMU	Functional Mockup Unit
HVAC	Heating, Ventilation and Air Conditioning
LSTM	Long Short Term Memory
MAE	Mean Absolute Error
MRAE	Mean Relative Absolute Error
NN	Neural Network
MPC	Model Predictive Control
PRBS	Pseudo Random Binary Sequence
RELU	Rectified Linear Unit
RES	Renewable Energy Sources
RH	Relative Humidity
RNN	Recursive NN
SCADA	Supervisory Control and Data Acquisition
SQP	Sequential Quadratic Programming
VFD	Variable frequency drive

1 Introduction

Global warming, building design, heat island effects and people lifestyle are all contributing to a significant rise in cooling energy demand in Europe, especially in urban regions. Traditionally, this cooling demand is satisfied using small scale distributed electrically-driven appliances (mainly compression chillers) which have a high impact on primary energy consumption, greenhouse emissions and peak electricity demand.

District Cooling Plants (DCP) offer an efficient and cost effective alternative to decentralized cooling technologies in densely populated areas with high cooling demand, as for instance in districts with hospitals, shopping malls and industrial plants. In fact, the centralized production using high-efficiency systems lowers the primary energy demand, making a DC more reliable, efficient and environmentally friendly than standard options at the building level. Moreover, the centralized management of the distribution plant offers a reliable solution to building managers who can thus lower maintenance costs. For this reason, many countries in Europe, such as Spain, France, Sweden and Denmark, have built DC plants in some of their cities.

Nevertheless, DCP are relatively new systems and there is a high potential of improvement in terms of energy efficiency and energy flow management. Demand Response Management (DRM) solutions, for instance, might be applied for sustainable operation and waste reduction while the use of Renewable Energy Sources (RES) coupled with storage are used to reduce primary energy consumption.

The optimization of the entire DC system is far from trivial, due to the difficulty in predicting the building's cooling demand and to the technical limitations posed by the differential temperature in the piping system.

This report provides guidelines on how to plan and deploy smart management systems for DCP based on MPC (Model Predictive Control) techniques, so as to improve the plant's energy efficiency and reduce carbon emissions. These guidelines have been developed considering existing DCP sites for which a refurbishment in terms of control management is planned. In these cases, three main phases need to be followed:

- **Planning phase**: At this stage, a study is performed on the test site to understand its specific needs. For instance, a different strategy is needed for an industrial site demanding constant cooling at a fixed temperature when compared with a residential site having a highly variable demand. These key insights need to be included in the planning phase. Furthermore, information on the technical equipment, the IT infrastructure, the plant design and the available sensors/actuators is needed. At the end of this phase the management strategy and the corresponding materials and actions needed to implement it are established.
- **Commissioning phase**: In this phase the MPC based strategy is consolidated and brought to its optimal working conditions. Functionality and stability tests are run in this phase to ensure the software is stable. Tests are first run in a virtual environment and subsequently on the DC to evaluate performance.
- **Exploitation phase**: this is the final phase, taking place once the new management system has been deployed on the DC. In this phase key parameters for the system's operation are tuned in order to boost the system's performance.

A summary of the guidelines presented in this document is reported in Table 1.

Table 1: MPC for DC summary

		Hardware		INDIGO	
		Sensors	**Actuators (incl. Local controller)**	**Models**	**MPC**
Planning phase	Generation level	Inlet, outlet and mass flow of cooling elements (cooling towers, chillers, ...) must be available	The temperature and flow rate of chilled water in the cooling tower must be controllable.	Detailed models based on physics are needed. The actual data from the plant can be used, if not available the virtual data needs to be produced from the detailed models.	The detailed models are simplified into reduced models, NN techniques can be used. The latter need to be stable. Models are used to provide the prediction through the horizon of MPC. Adaptation to the site is required (for the NN and cost function).
	Distribution level	Pressure difference in the group of pumps and total pumped mass flow rate.	Variable frequency drive for each pump.	Number of pumps, configuration and operation curves (efficiency and H-Q).	
	Consumption level	Check existing sensors and make sure measurements for weather	Get information on current controller and plant layout.	Check that enough information is available to develop a control system and its models	The MPC strategy is set up according to the existing system and available information. New

		conditions, pulsed and return air temperature, humidity and flow rate and zone temperature and humidity are available			optimal setpoints are computed.
Commissioning phase	Generation level	Sensors information are provided real-time to the MPC.	Consider the limitations of the internal PID. Consider the actuation signals between the components.	Predictions should be representatives of the system behaviour.	Check the speed and the performance of the solvers in optimization problem to ensure real-time operation.
	Distribution level	To check that the supply conditions are fulfilled.	VFD correctly working.	Check if theoretical operation curves adjust to the real performance.	
	Consumption level	Check that the sensors are correctly installed and the sampling frequency and units correspond to the expectations	Check that the actuators react correctly to the new setpoints.	Benchmark the models against real data.	Use simulation models to check the MPC performance.

Exploitation phase	Generation level	Check for the outliers in the sensory information	Are the actuation signals applied at the correct timings?	Check the predictions to make sense	Consider an error break in the MPC formulation to ensure correct operation of the solvers
	Distribution level	Check the sensors' correct functioning.	Check the actuators proper actuation.	If pumps are changed/modified needs to be amended.	
	Consumption level	Detect abnormal behavior of sensors and undesired system operation.	Check that the actuators react properly to the new setpoints.	Check that the prediction models do not diverge and the prediction is within specified accuracy.	Add a supervision unit.

1.1 Project overview

INDIGO is a European funded project aiming at drastically increasing energy efficiency in District Cooling Plants, thus reducing primary energy expenditure and Carbon emissions.

In order to achieve this goal, the project focuses on the development of a new DC management strategy based on model predictive control (MPC) techniques (Figure 1).

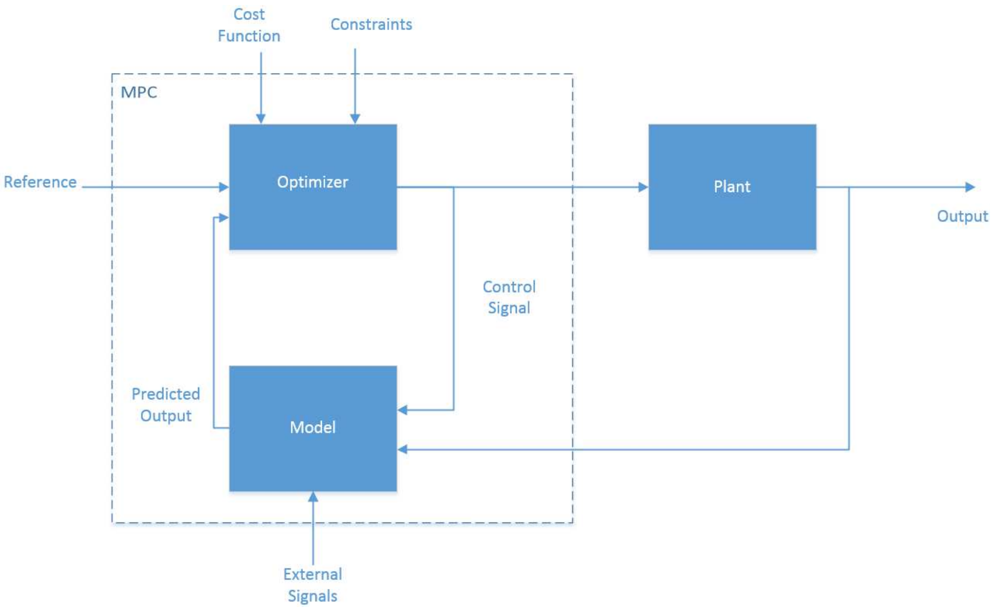

Figure 1: Overview of a classic MPC loop.

INDIGO control strategy is a hierarchical one, with two main levels (Figure 2):

- Level 1: **DC Global management strategy**. The main goal at this level is to schedule the energy supply in order to meet the demand at every moment.
- Level 2: **Predictive controllers at components level**. These controllers act at the equipment level and are able to exploit the dynamics of the systems to schedule its optimal operation.

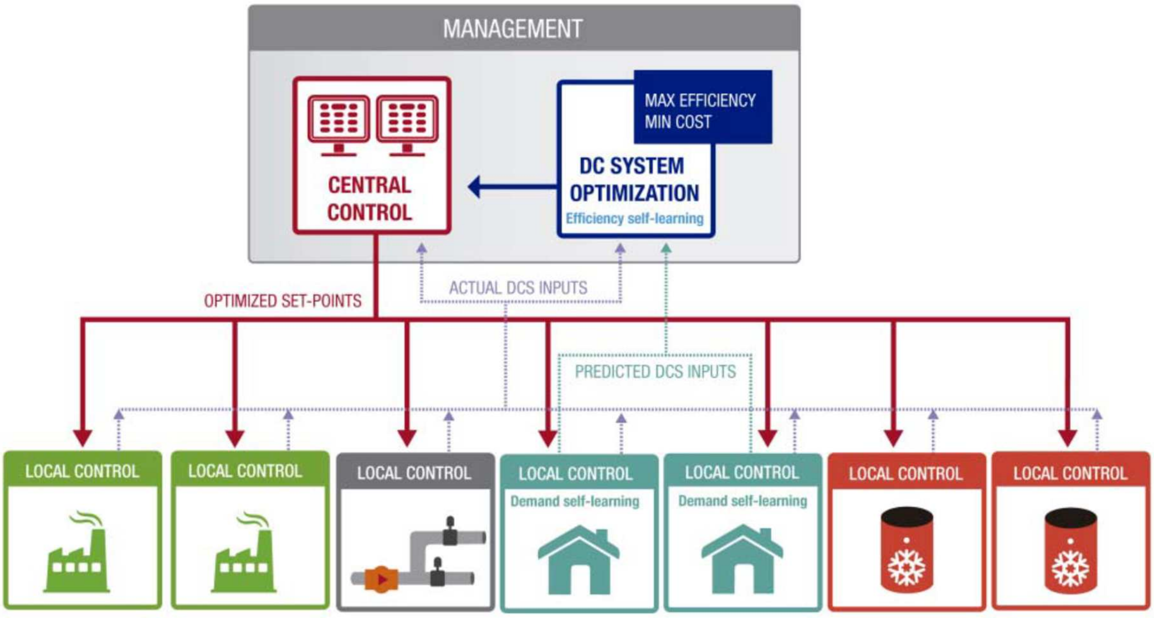

Figure 2: Overview of INDIGO controller hierarchical structure

In this document we will focus on Level 2, grouped according to their functionalities:

- **The production optimizer** is an algorithm with a twofold purpose, i.e. minimizing energy consumption while satisfying the cooling requirements demanded by the manager MPC. The production optimizer is intended to actuate over generation subsystems formed by more than one components, for instance, a combination of a water-cooled chiller and the corresponding cooling tower. The idea is to optimize the group operation by modifying each component's setpoints.
- **The distribution optimizer** is an algorithm that optimizes the instantaneous efficiency of a group of pumps when required to supply a certain total pressure difference and mass flow rate. It obtains the corresponding actuation signals (rotation frequency) for each of the variable speed pumps in the pumping group.
- **The consumption optimizer** is an algorithm that at building level finds the most suitable operating condition in order to minimize energy expenditure while ensuring the occupants comfort. It acts on the HVAC (Heating Ventilation and Air Conditioning) set-points in terms of temperature and humidity.

These algorithms will be tested and validated in three test sites:

- La Marina and Zona Franca, DCP with industrial sites located close to Barcelona (Figure 3);
- Basurto, a DCP for a large hospital with 10 buildings in Bilbao (Figure 4).

Figure 3 Test sites of La Marina (1) and Zona Franca (2)

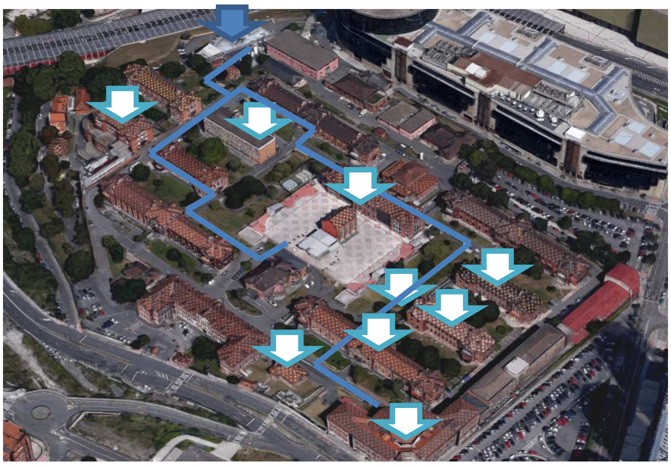

Figure 4 Basurto test site

1.2 Relation to other activities in the project

This document is based on the main findings of WP3, in terms of optimizers and MPCs at generation, distribution and consumption levels.

In addition, it is also connected to WP2 regarding additional sensing needs for modelling, and WP4 as the Management Controller is in charge of generating the local controllers' setpoints.

1.3 Report structure

This report is organized in three main chapters, corresponding to the phases needed for the deployment of the smart DC management system:

- **Chapter 2:** Insights on the key elements to be taken into account when a new management system is to be installed on a specific site will be given. Questions such as: what sensors/actuators exist and/or are mandatory will be answered.
- **Chapter 3:**. In this chapter, the reader will understand how the MPC will be deployed and be brought to an optimal working condition. For instance, how to ensure that the various control models used in MPC are stable, will be explained.
- **Chapter 4:** In this final chapter, insights regarding key operational points will be given. Typically, the user will understand how to further maximise the operation of the system by adjusting objective functions.

Each section is then further divided into three sub-sections grouping the DC main systems to reproduce the hierarchical structure of the controller:

- Generation level
- Distribution level
- Consumption level

2 Planning phase

The following sections highlight what are the key points to take into consideration during the planning phase. In particular, this implies understanding what is available on the site in terms of installed sensors & actuators. This impacts the capabilities of the model predictive control (MPC) that might require the installation of additional equipment.

2.1 Generation level

The following sub-sections present what are the elements to take into consideration when realizing the planning MPC for district cooling (DC) at generation level.

The main part of the generation is the heat rejection circuit between a chiller and a cooling tower. In Figure 5, this circuit is between the chillers on the lower part of the schematic and the cooling on the upper part.

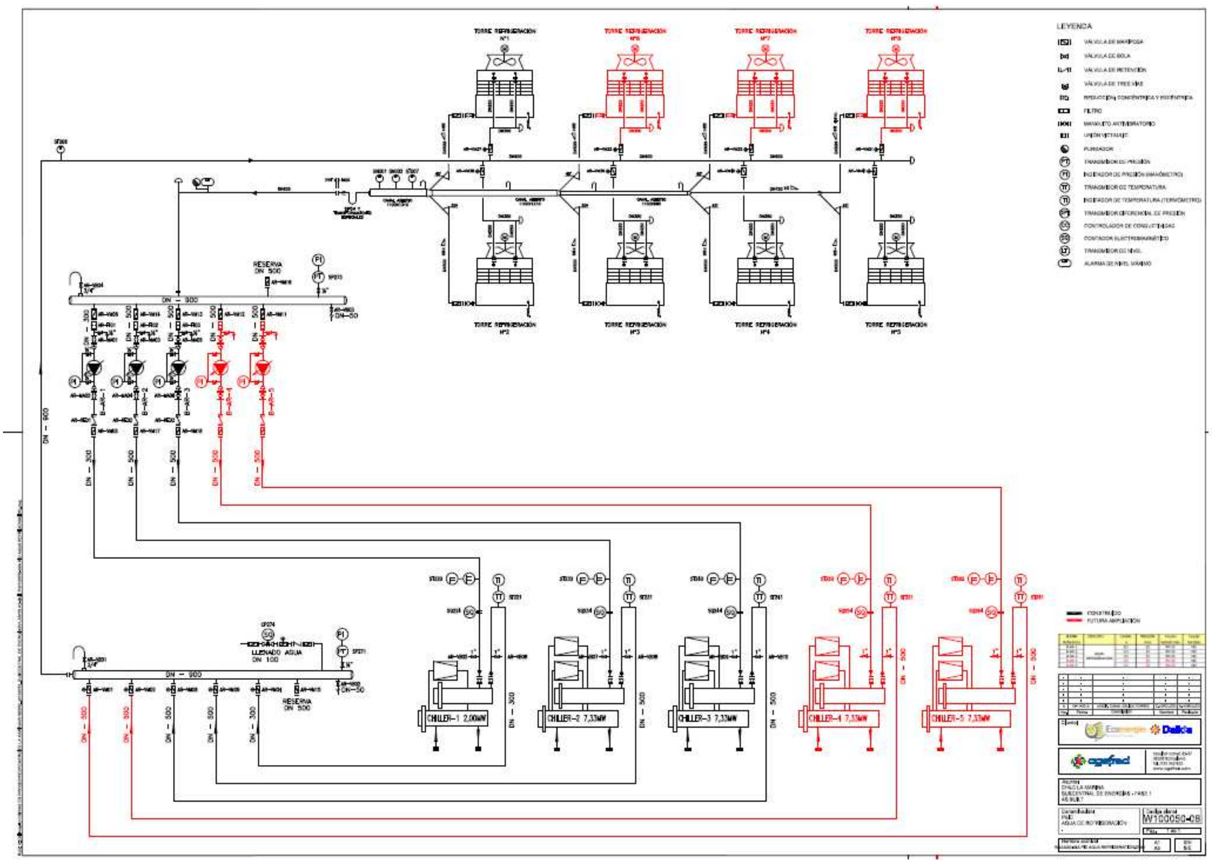

Figure 5. Schematic of the chillers and corresponding cooling towers in La Marina test site.

The chilled water from the cooling tower flows through the condenser in the chiller with a given temperature and flow rate.

For each generation site, a assessment about the plant´s sub-systems must be carried out. The entire plant must be “decoupled” and the main sub-systems identified. This will result in a set of groups of components. The main criteria for defining the component groups is the independency of operation. It means that components that interoperate between each other must be part of the same group. For instance, if a cooling tower is serving two chillers, the components (cooling tower + 2 chillers) would be in the same group. In this way, an MPC is developed for each component group.

2.1.1 Sensors

The main objective of the generation is to track the temperature setpoint given from the manager level while the power consumption is minimized. For this purpose, key signals are shown in the following table:

Component	Location	Sensor/signal
Conventional chillers	Evaporator, inlet water	Temperature
Conventional chillers	Evaporator, inlet water	Mass flow rate
Conventional chillers	Evaporator, outlet water	Temperature
Conventional chillers	Evaporator, outlet water	Setpoint
Conventional chillers	Condenser, inlet air/water	Temperature
Conventional chillers	Condenser, inlet water	Mass flow rate
Conventional chillers	Condenser, outlet water	Temperature
Conventional chillers	Compressor, elec. power	Power
Absorption chillers	Evaporator, inlet water	Temperature
Absorption chillers	Evaporator, inlet water	Mass flow rate
Absorption chillers	Evaporator, outlet water	Temperature
Absorption chillers	Evaporator, outlet water	Setpoint
Absorption chillers	Absorber, inlet water	Temperature
Absorption chillers	Absorber, inlet water	Mass flow rate
Absorption chillers	Condenser, outlet water	Temperature
Absorption chillers	Generator, inlet water/steam	Temperature
Absorption chillers	Generator, inlet water/steam	Mass flow rate
Absorption chillers	Generator, outlet water/steam	Temperature
Cooling towers	Inlet water	Temperature
Cooling towers	Inlet water	Mass flow rate
Cooling towers	Outlet water	Temperature
Cooling towers	Outlet water	Setpoint
Cooling towers	Inlet air	Temperature
Cooling towers	Inlet air	Mass flow rate
Cooling towers	Outlet air	Temperature
Cooling towers	Consumed elec. power	Power
Ambient	Air	Temperature
Ambient	Air	Humidity

If any of the required signals is not measured, it must be calculated indirectly.

They are mandatory for

- Formulating the MPC cost function based on the minimization of the power and temperature setpoint error.
- Realizing the MPC constraints and the physical boundaries on the variables.

2.1.2 Actuators

In a typical cooling generation plant, actuators signals are not usually accessible from the SCADA (Supervisory Control and Data Acquisition) which is generally meant to be used at plant operation/management level. For gathering low level control signals, such as actuators, additional instrumentation most be implemented for each component. This is a very invasive and costly practice. INDIGO approach works around this problem by actuating over the system setpoints. In this way, there is no need of new installation at component level and the entire system can be controlled using the signals available in the actual SCADA. In those cases where the monitoring system does not fulfil the sensor requirements presented in section 2.1.1, only signals at system level are to be implemented (by additional sensors and/or indirect calculation).

2.1.3 Models

As proposed in section 2.1.2, INDIGO controls the system setpoints. Consequently, actuators must be included as part of the models during the modelling stage. Information from manufacturer datasheets is used to define type and parameters of the low-level controllers and actuators.

Two types of models are used:

1. The detailed models. These are component-oriented models, i.e. each component is modelled separately. They are then used to model larger configurations (e.g. the whole production plant). These models are based on thermodynamics principles and include internal and local controllers. Detailed models are used in a first phase to generate the virtual data for the development and test of the algorithms as a substitute for the real data that will be provided from the real plant. In addition, these models are used to validate the results of the MPC and the corresponding reduced models. The components of the models are developed in EnergyPlus and Modelica and compiled as Functional Mockup Units (FMUs)
2. The reduced models. These models are the result of the model reduction of the detailed models. They are used as the prediction model for the MPC formulation.

To evaluate the best option for the implementation in INDIGO, it was decided to approach the MPC problem from two angles, namely MPC based on reduced physical models and classic control theory, and MPC based on real/virtual data using a machine learning approach. While the classical approach was found suitable for single-component control (e.g. a chiller), the combination of components raised several problems and the associated lower stability of the models prevented the further implementation in the aggregation of systems (e.g. chiller + cooling tower).

2.1.4 MPC

The MPCs for generation site are based on machine learning techniques and simulation models. Detailed models of each system to be controlled are developed in Modelica. Using manufacturer and real data the detailed models are calibrated. Once calibrated, the detailed models are simulated to generate enough data to produce the reduced models which are used by the MPC. The reduced models are multi-layer recurrent neural networks (NN) based on long short-term memory units. The number of layers and units is determined manually by means of an iterative process (try and error).

MPC can be setup and used for the individual components of the generation meaning chillers and cooling towers. There were three different dynamics identified in the generation systems of the test-sites: conventional chiller, absorption chiller, cooling tower. Considering these dynamics, MPCs for each configuration must be designed, which means new NN and cost function formulation (cost function, constraints, optimization problem) must be produced based on the corresponding physical system.

2.2 Distribution level

After discarding the suitability of a predictive control for this part, an **optimization algorithm** has been developed for the Distribution level, which determines the optimal operation point of each of the secondary pumps according to their efficiency curves and the supply conditions.

The main objective of the Distribution optimizer is to choose which of the pumps must be working and the working frequency (VFD) of each of them to supply the required total mass flow rate maximizing the efficiency of the pumping group system.

The following sub-sections present the elements to take into consideration when realizing the mentioned optimizer.

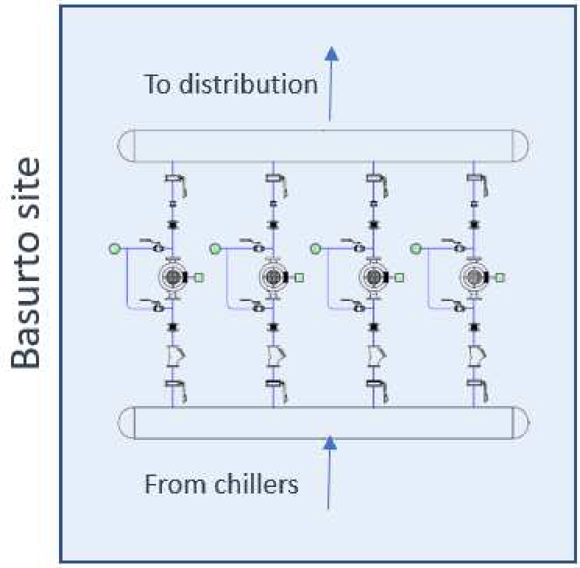

Figure 2. Secondary pumps group at Basurto site

2.2.1 Sensors

The Optimizer needs the following input signals:

- The pressure difference that needs to be provided by the group of pumps. This setpoint is sent by the High Management Level Controller (WP4).
- The required distribution mass flow rate. This value is also sent by the High Management Level Controller (WP4) and is directly related with the pressure difference setpoint.

Additionally, it is not necessary but recommended to install the following two sensors, if not available, for checking purposes:

- A pressure difference sensor to check the real value of the pressure difference in in the group of pumps.
- A mass flow rate sensor in the distribution to check the real value of the pumped mass flow rate.

These will allow to check if the required mass flow rate and corresponding pressure drop are achieved. If not, these signals along with each pump rotation frequency will allow to identify the source of the deviation.

2.2.2 Actuators

In order to apply the Optimizer to the Distribution level, it is required that each secondary pump has a **variable frequency drive** (VFD), so that the mass flow rate through each pump can be controlled by actuating on its speed according to the pressure drop value established.

2.2.3 Models

The optimizer needs to have the following information of the group of pumps of the installation in order to model their behaviour:

- Configuration of the pumping group: number of available pumps and their connection (parallel, series).
- Characteristic curves at nominal conditions (nominal speed) of each of the pumps: efficiency curve and H-Q curve.

In INDIGO project, the control system has been developed to optimize the efficiency of the secondary pumping group (distribution), but it could be easily adapted to optimize the operation of another pumping group location or configuration.

2.3 Consumption level

The following sub-sections present what are the elements to take into consideration when planning an MPC controller for district cooling (DC) at consumption level, i.e. on HVAC systems in buildings.

First, it is critical to analyse the existing system and in particular:

- The HVAC system layout: number of Air Handling Units (AHUs), Fan Coil Units (FCUs), zones served etc. For this, the main source of information are the technical drawing. An example for one of the buildings in INDIGO's test site Basurto is shown in Figure 6;
- The AHU elements (i.e. heat recovery system, number of heating and cooling coils etc);
- The control rules applied for standard regulation (i.e. control applied on supply or return temperature, schedule, comfort boundaries established by norms etc)
- The requirements of the test site, i.e. is the ventilation needed 24 hours a day or just during business hours.

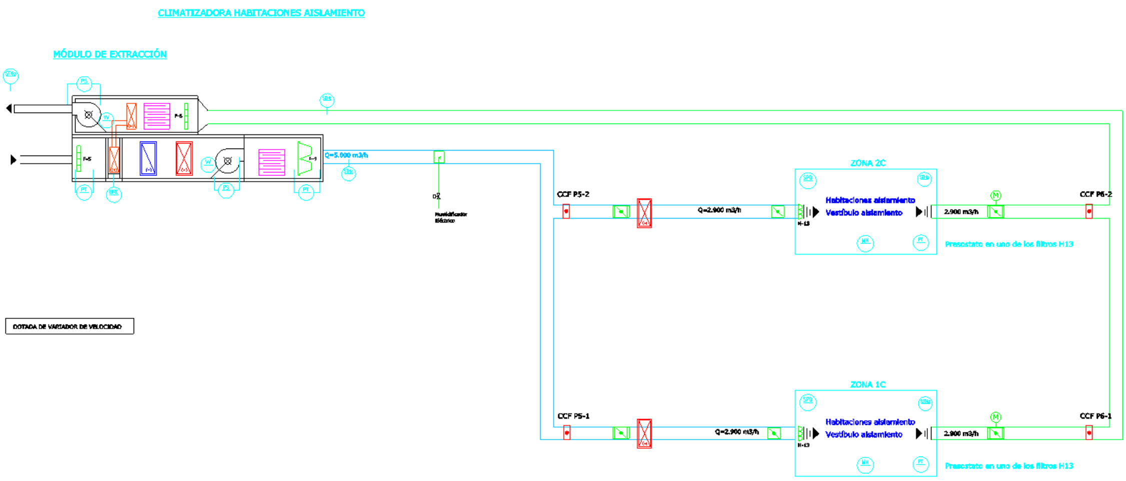

Figure 6: technical schematic of a typical HVAC system (consumption level)

Next, it is important to check that the required input and output signals for the MPC algorithms are available in the form of, respectively, sensors and actuators.

2.3.1 Sensors

The key signals that need to be measured are:

- Outdoor conditions (temperature, humidity, solar irradiance)
- Forward (i.e. pulsed) air values (temperature, humidity, flow-rate)
- Return (i.e. out of the zones) air values (temperature, humidity, flow-rate)
- Zone(s) air values (temperature, humidity)
- Heat recovery status (on/off)

The elements listed above allow the computation of:

1) The energy spent in the various elopements of the AHU (heating coil, cooling coil, humidifier)
2) Understanding how the zone(s) react to the air provided by the AHU (and outdoor conditions)

In addition, sensors measuring air temperature and humidity after each element of the AHU can be used to validate the models and the energy computation mentioned in point 1.

2.3.2 Actuators

It is important to understand what actuators are available and (if possible) how they can be controlled by the MPC algorithm.

The MPC algorithm in INDIGO aims at computing the optimal forward (i.e. pulsed) air temperature. In consequence, the ideal case would be to have access to the: temperature, humidity and flow setpoints of the AHU of the forward air (not the return).

In addition, it is important to know the AHU internal controller limitations and dynamics so that they can be taken into account in the MPC.

These information (controller loop settings) and available inputs can be found in the HVAC controller. However, it is to be pointed out, that having site measurements to verify that the system really behaves as expected is a good practice.

2.3.3 Models

In this early phase, two types of models are of interest:

- Simulation model: this model is to “mimic” how the site behaves (i.e. it will be used to simulate the building, this is the “plant” in Figure 7). This model can be constructed by using data measured on the test site and/or architectural plans coupled to HVAC schematics. In INDIGO case, the simulation model corresponds to the detailed model mentioned above and was developed in Modelica and Energy+.
- Prediction model: this model is connected to the optimizer of the MPC, note that it could be a copy of the simulation model, but for computational (speed) issues this is generally not the case. This is the “model” in Figure 7 and in INDIGO it is generally referred to as “reduced model”.

2.3.4 MPC

In the planning phase, simulation models are integrated in the MPC loop in replacement of the real plant in order to perform a first validation of the MPC algorithm and evaluate the potential gains linked to using a smart controller.

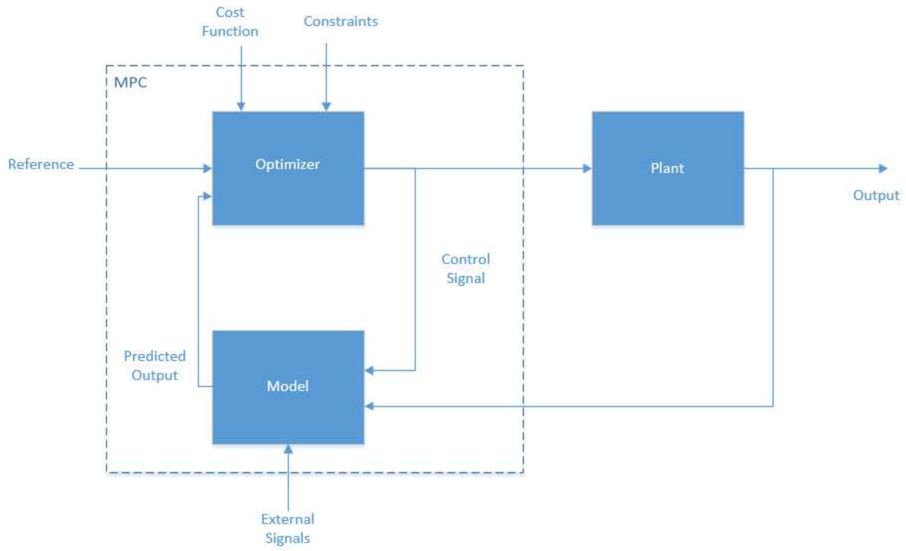

Figure 7: MPC high level schematic

Finally, weather forecast is needed as input to the reduced models which then indirectly compute the amount of cooling energy (in terms of supply air temperature and humidity setpoints) that will be needed over the prediction horizon. For this, an internet connection and a service provider are needed.

3 Commissioning phase

The following sections highlight what are the key points to take into consideration during the commissioning phase. This means:

1) checking that the involved elements:
    a. are installed as expected and that the data is accessible
    b. react as expected to setpoint changes
2) adapt the various models based on the latest information
3) ensure that the models are correct
    a. Simulation models: are there discrepancies with respect to what is measured?
    b. Prediction models: are they providing correct predictions to the optimizer?

3.1 Generation level

The following sub-sections present what are the elements to consider when carrying out the commissioning at generation level.

3.1.1 Sensors

It must be checked that the sensors were correctly installed, and the information like the ambient temperature and supply setpoints are provided in real-time to the MPC. The timing at which the information is provided directly affects the real-time operation of the MPC on the plant.

3.1.2 Actuators

It is important to ensure that the actuators react as expected. For example, in the combination of the chiller and cooling tower, check if there is enough time to actuate the setpoints through the change in the outlet temperature of the heat rejection circuit.

In addition, consider that the internal PID in the physical system may limit the amplitude or frequency of the signals (e.g. the P-controller dictates a certain structure to the power consumption in the cooling tower).

3.1.3 Models

Models can be benchmarked against real data from the plant. It is also important to check the dynamics of the chillers and cooling tower and choose an MPC horizon that includes the main frequencies of the system dynamics in the predictions. Predictions should be representatives of the system behaviour.

3.1.4 MPC

It is important to check the speed and the performance of the solvers that are used to solve the MPC optimization problem. For example, how many iterations are made to solve each optimization? Is the speed enough to perform a real-time MPC on the generation plant?

3.2 Distribution level

The following sub-sections present what are the aspects to take into consideration when carrying out the commissioning at distribution level.

3.2.1 Sensors

In this case, it is necessary to check that the correct signals are received by the optimizer: the required pressure setpoint in the group of pumps and the total mass flow rate to be pumped at the corresponding time instant.

Optionally, to verify the pumps characteristic curves provided by the manufacturer, a mass flow rate meter might be installed at each pump (see section 3.2.3).

3.2.2 Actuators

It is important to guarantee that each pump of the group has a VFD working properly. It must be taken into account that the optimizer output signal towards the pump local controller is the pump working **frequency**. So, if this controller usually works with speed signal instead of frequency, the corresponding transformation should be implemented either in the local controller or in the optimizer algorithm.

3.2.3 Models

The core of the optimizer models are the characteristic curves of the pumps (at nominal speed). These curves can be benchmarked against real data, by checking that the theoretical operation curves for the pumps provided by the manufacturer adjust to the real performance of the pumps. For that purpose, specific mass flow rate sensors should be implemented at each pump, and the similitude theory should be applied.

3.3 Consumption level

The following sub-sections present what are the elements to take into consideration when carrying out the commissioning at consumption level.

3.3.1 Sensors

It is to be made sure that all the sensors are correctly installed. This includes the general location within the building, AHU or piping and also the specific location (i.e. is it placed according to the good practices, for instance avoid placing a temperature sensor close to a radiator or to a south-facing window).

It must be checked that the sensor data arrives at the expected time and frequency and that the overall behaviour is correct. In particular, errors linked to units (°C or K) are to be checked for.

3.3.2 Actuators

It must be checked that the actuators react to the desired setpoints. This can be done by monitoring the data from the sensors.

3.3.3 Models

The two models developed can now be benchmarked against real data:

- Simulation model: even though this model is now replaced by the real plant, it is a good practice to validate that the model is correct, as it served as developing tool to the MPC.
- Prediction model: it is critical to assess that this model provides predictions, to the MPC, that are realistic with respect to real data. This is crucial as this model is needed by the MPC.

3.3.4 MPC

During this phase, it is a good practice to use the simulation models to test the performance of the MPC with respect to the standard controller under the same conditions. It is also advised to run the MPC in parallel to the standard controller without applying the computed setpoint schedule. The output of the MPC, even though is not applied, can be used to check that the computed results are within reasonable (physical) boundaries. Some additional checks should be done at this point, for instance it should be verified how the setpoint changes when comfort boundaries are modified or when configuration parameters in the optimization are changed to favour either low energy consumption or high occupants comfort.

4 Exploitation phase

The following sections highlight the main elements to take into consideration during the exploitation phase. This mostly involves monitoring the installation.

4.1 Generation level

The following sub-sections present what are the aspect to consider during the exploitation phase at generation level.

4.1.1 Sensors

Sensors must be monitored to check if they provide relevant information of the ambient conditions and the changes in the output signals.

Furthermore, final users should be able to spot outlier data measured by the sensors that may come from a faulty instrumentation.

4.1.2 Actuators

The MPC in the generation site generates a new actuation signal with a constant frequency. It needs to be insured that these signals are applied to the system in the desired periods.

4.1.3 Models

Models must be monitored to observe if they generate predictions that make sense. If the models have been validated and recalibrated during the previous phases only a sanity check is needed here to make sure that the prediction falls into reasonable boundaries.

4.1.4 MPC

Supervision should be performed for the MPC of generation. This is done through:

- Analysis and verification of the controlled signals as the MPC is applied to the system with the reduced models.
- Verification of the operational constraints to make sure they are not violated.
- Add an 'error' assert in the optimization loop in case the solver fails at solving the problem.
- The optimization problem can be reformulated by readjusting the corresponding cost function. This can be further exploited during this phase.

4.2 Distribution level

The following sub-sections present what are the elements to take into consideration during the exploitation phase at distribution level.

4.2.1 Sensors

It needs to be checked that the proper communications (input signals) are received during the exploitation.

4.2.2 Actuators

It needs to be checked that the desired frequency is applied to the pumps.

4.2.3 Models

If a modification is introduced in the installation regarding the pumps (a new pump is added or changed), this needs to be modified in the group of pumps description in the optimizer (algorithm modification).

4.3 Consumption level

The following sub-sections present what are the elements to take into consideration during the exploitation phase at consumption level.

4.3.1 Sensors

Sensor values are to be monitored to:

1) Detect abnormal sensor behaviour (i.e. fault detection), this is important as MPC strongly relies on measured data.
2) Detect undesired system operation (i.e. the MPC is doing something). It is a good practice to have a security layer on top of the MPC that checks that over a given horizon, the obtained behaviour is correct. Indeed, as some models are self-learning, it could be that they do not converge and start predicting wrong values.

4.3.2 Actuators

It must be continuously checked that the desired set-point is really applied (with some tolerance linked to internal controllers for instance).

4.3.3 Models

During the exploitation phase, special care is to be given to the prediction model. A routine should be put in place to check that it does not diverge and that the forecasted values do make sense. In the case of self-learning models, make sure that the models are updated at the required rate.

4.3.4 MPC

Adding a supervision layer (i.e. security) over the MPC is a good practice, this can be done at the same time as the checks mentioned above for the models.

5 Conclusion

In the frame of the H2020 project INDIGO, a set of advanced control algorithms based on Model Predictive techniques for the management of a District Cooling Plant was developed, paving the way to a new generation of highly efficient management systems.

In INDIGO, a two-level control strategy is adopted. The higher level corresponds to the DC global management strategy, the goal of which is to determine the schedule of the energy supply in order to meet the demand at every moment. The lower level contains a group of predictive controllers which are deployed at components' level and can exploit the dynamics of the systems for optimal operation.

This report focuses on the lower levels and presents guidelines for the development and deployment of advanced control systems for groups of equipment related to generation, distribution and consumption of cooling energy. The reader is guided throughout the various phases of planning, commissioning and exploitation, with highlights on the key steps to be taken at each stage.

It should be noted that INDIGO system is applied as a new layer on existing DC control systems to refurbish and improve their performance. For this, it is important to first understand how the existing system is working and how it can be interfaced with a new solution. This document should thus be helpful to the reader as a reminder of the information needed to ensure the deployment of the new control system is beneficial.

Finally, the information contained in this report is the results of the learnings acquired during the development and deployment of INDIGO algorithms on a real test-case scenario and do not mean to be comprehensive. Nevertheless, the authors' aim is to share these learnings which shall be applied in different scenarios of DCP control system refurbishment.