MOEEBIUS

Modelling Optimization of Energy Efficiency in Buildings for Urban Sustainability

D3.3 Models of DER devices

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Glossary

Acronym	Full name
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEPS	Building Energy Performance Simulation
CIM	Common Information Model
DAE	Dynamic Assessment Engine
ERL	EnergyPlus Run Time Language
DER	Distributed Energy Resources
EMS	Energy Management System
HVAC	Heating, Ventilation, and Air Conditioning
MPC	Model Predictive Control
PV	Photovoltaic
IDF	Input Data File
NTU	Number of Transfer Units
FMU	Functional Mockup Unit
BCVTB	Buildings Control Virtual Test Bed

1 Executive summary

The goal of this task is to develop the enhanced district heating and DER system models, necessary to provide the modelling functions required by the **BEPS** and by the **District DAE** to produce building and district level predictions (Thermal/electric demand, fuel consumption, equipment response), and enable the implementation of energy efficiency-driven or demand response-driven operational strategies.

The developed DER models are divided into load, generation, storage and district heating models, to be combined to form the generic **MOEEBIUS District Heating and DER Model**.

Developed **Load Models** include those with the greater capacity to provide flexibility and support the indoor environment optimization in terms of comfort and health preservation.

On the other hand, the **Generator/Storage models** (renewable and non-renewable) have been defined considering not only the generators, but also, other auxiliary components that can provide flexibility (e.g. storage devices).

Finally, developed **District Heating System Model** provides the required capabilities for District Heating power plants and distributed energy sources modelling, enabling the application of optimal control strategies at the district level through effectively coordinating energy and heating provision capabilities of DH systems.

In order to develop the generic **MOEEBIUS District Heating and DER Model** capable to address district level infrastructure dynamics and energy production, an integrated explicit district model is necessary.

The addition of district level modelling capacities to building simulation programs is technically difficult, as it would require major code or even tool architecture modifications. Object oriented equation based tools present significant advantages for district modelling, but complete migration from legacy building simulation programs to equation based tools in the building domain is not possible, as the required domain specific component model libraries are not available yet.

Co-simulation is considered the most suitable approach to produce integrated district models combining EnergyPlus building models with Modelica district models. Therefore, a sequential co-simulation arrangement has been designed as the starting point for the development of the generic **MOEEBIUS District Heating and DER Model.**

Although the standard capabilities of EnergyPlus include a comprehensive collection of models to address building level DER system modelling, some limitations have been identified to model very specific thermal loads in the

swimming pool domain. These unavailable models are necessary to produce the EnergyPlus model of the educational building of the Portuguese pilot. As a consequence, in order to overcome these limitations, a new **swimming pool thermal balance model** and a **swimming pool heating and makeup water thermal demand model** (Load models) have been developed to be directly integrated into EnergyPlus, using the advanced EnergyPlus Run Time Language functionality.

Regarding district modelling, going beyond the existing physical component oriented approach, the **MOEEBIUS District Heating and DER system Model** has been developed according to a subsystem model based architecture. More specifically, the MOEEBIUS generic district model will be formed by the following subsystem models:

- Load models:
    - District heating thermal loads (Building heating substations).
- Generator/Storage models:
    - District heating plant including the storage subsystem.
    - Solar thermal collector plant, including solar production storage.
    - Electric DER systems (PV systems and wind turbine systems).
- District Heating models:
    - Pumping station.
    - Distribution thermal network.

The models related to the district level electric DER-s will provide electricity production predictions and have been developed based on a statistical modelling approach.

For the thermal subsystems (loads, generation, storage and distribution) specific Modelica models have been developed, encapsulating the physical behaviour of all the equipment deployed on each of the actual subsystems, reproducing the modularity and connectivity rules of each subsystem.

These models provide the required flexibility, scalability and the capability to define the typically existing district typologies from the perspective of the deployed technologies, distribution topologies and operational strategies. Additionally, the modelling detail of the existing dynamics will enable the implementation of demand response-driven strategies and energy efficiency-driven operational optimization.

According to this approach the generic **MOEEBIUS district Heating Model** can be adjusted to the boundary conditions existing on any specific district, combining the required subsystem models as necessary, to configure district heating models of any size, complexity and distribution topology.

The developed models have enabled the definition of a **MOEEBIUS Modelica Library**.

2 Introduction

The goal of this task is to develop the enhanced district heating and DER system models, necessary to provide the modelling functions required by the **BEPS** and by the **District DAE** to produce building and district level predictions, paying special attention to the modelling capabilities necessary to address all specific needs of the MOOEBIUS pilots.

Regarding the DER systems deployed at building level, the available EnergyPlus standard modelling capabilities include a comprehensive collection of models to address DER system modelling, including:

- Most of the conventional and innovative HVAC systems (including the generation, storage, distribution and emission subsystems).
- Distributed electricity production systems such as cogeneration plants, PV systems and wind turbines.
- Solar thermal collector plants.
- Lighting systems.
- Specific electric loads such us office equipment.

All these modelling capabilities will enable to produce the EnergyPlus models of the buildings (including building level DER-s) of the pilots of the project, in the frame of Task 3.6. However, some limitations have been identified in the swimming pool modelling domain. In order to enable the definition of the EnergyPlus model of the educational building of the Portuguese pilot, in this task the following new EnergyPlus models have been developed.

- **Swimming pool room thermal balance model** to be integrated into EnergyPlus.
- **Swimming pool water heating and makeup water system demand model** to be integrated into EnergyPlus.

On the hand, regarding district heating and district level DER system modelling, in this task the following models have been produced:

- **District level electric DER production forecasting models** developed according to a statistical modelling approach.
- **District heating and thermal DER system models** developed in Modelica.

Before addressing the detailed work of specific model development, the process followed to design the approach for the definition of **the Generic MOEEBIUS District Heating and DER system** model will be described in detail. This approach will be based in a sequential co-simulation arrangement that will enable to model each of the domains involved in district definition in the most suitable modelling tool, as summarized below:

- EnergyPlus for building models.
- Modelica for district heating and thermal DER modelling.
- A statistical modelling approach for district level electric DER production forecasting.

Additionally, going beyond the existing physical component oriented approach, the generic **MOEEBIUS District Heating and DER system** model is structured according to a subsystem model based architecture.

According to this approach the generic **MOEEBIUS district Heating Model** can be adjusted to the boundary conditions existing on any specific district, combining the required subsystem models as necessary, to configure district heating models of any size, complexity and distribution topology.

In summary, these generic models will present the needed versatility and flexibility to be adjusted and applied to the three MOEEBIUS pilot sites (Portugal, UK, Serbia). Some of the relevant facilities that will be modelled through the outcomes of this task will be the swimming pool at the Portuguese pilot site and the whole district heating system at Belgrade, which comprises generation/storage models (at district heating plant), load models (at buildings' substation) and district heating models (for distribution and pumping through the grid).

2.1 Relevance with other tasks

The building level DER models developed in this activity will be integrated into the building energy models developed in the frame of Task 3.6, which will be run by the BEPS as programmed in Task 5.1. The Integration of these models will be solved through the advanced ERL functionality, in order to upgrade the modelling capabilities available in EnergyPlus, and provide building level consumption and local production forecasting.

Additionally, the **Generic MOEEEBIUS District Heating and DER system** model, and all the subsystem models developed in chapter 5, will be used in Task 3.6 to produce the specific models of the pilots, and will provide the district level dynamics modelling capabilities required by the district level DAE (Task 5.4).

2.2 Structure of this deliverable

In the following lines a short description of the structure of the document is provided in a compact shape:

- Chapter 2 gives an overview of the objectives of the task, and the scope and structure of this deliverable.
- Chapter 3 provides a description of the building level DER models developed to overcome the modelling limitations existing in EnergyPlus in the sports building domain, as well as a first overview of their implementation through the EnergyPlus run time language advanced functionality.

- In Chapter 4 the limitations existing to include district level modelling capabilities in conventional building simulation programs and the potential of Modelica for district modelling are analysed in detail.
  Additionally, co-simulation is identified as the most suitable approach to produce integrated district models, and an overview of the defined co-simulation arrangement is provided.
- Chapter 5 gives a description of the subsystem model oriented architecture to produce the generic MOEEBIUS District Heating and DER systems, and provides a detailed description of the district heating and thermal DER models developed in Modelica, and the electric DER models developed using a statistical modelling approach.
- In Chapter 6 the conclusions of the activities performed in the frame of this task are summarized.
- Chapter 7 consists on a specific annex focused on the description of the technical details of the implementation of the forecasting models for the electric DER systems.

3 Development of new models for DER systems deployed at building level

3.1 Introduction

As part of the standard modelling capabilities of EnergyPlus several models are already available to address modelling of most of the conventional and innovative thermal/electric loads (HVAC system, lighting system, etc.) and the DER systems (PV systems, solar thermal collector systems, etc.) that can be typically deployed at building level.

The detailed description of the modelling approach followed for each specific pilot, regarding the DER-systems deployed at building level, covered by the modelling capabilities provided by the standard EnergyPlus models, will be included as part of D3.6.

However, in order to enable the definition of the EnergyPlus model of the educational building of the Portuguese pilot, in this section, the models developed to overcome the limitations existing in EnergyPlus in the swimming pool modelling domain will be described.

More specifically, in order to overcome these limitations, a new **swimming pool thermal balance model** and a **swimming pool heating and makeup water thermal demand model** have been developed, to integrate in a more accurate way, the impact of the following effects on the thermal behaviour of the building:

- The evaporation, conduction and radiation energy losses of the swimming pool.
- The Heat demand associated to the water heating system of the swimming pool, including the effect of makeup water heating.
- The heat recovery of the swimming pool makeup water system.

These models will be directly integrated into EnergyPlus, using the advanced EnergyPlus **Run Time Language (ERL)** functionality. The ERL functionality enables the definition within EnergyPlus of programs (EMS programs) specifically designed to include additional modelling or control capabilities. The code of these programs is directly entered into the EnergyPlus input data file (idf).

The ERL is a simplified programming language based on relatively simple rules of syntax and commands, and as a consequence has some limitations (only algebraic statements, no numerical manipulation, etc.). However, as is the case for the developed models, when the complexity level of the models to be added is compatible with the capabilities of the ERL language it is the most efficient approach to upgrade EnergyPlus with additional modelling capabilities. The detailed description of the integration of these models into EnergyPlus will be provided in Task 3.6.

Therefore, specific EMS programs describing the behaviour of the required components will be incorporated to EnergyPlus, along with the additional EMS programs necessary to enable the interaction of these new models with the rest of the EnergyPlus standard components (for input request and output delivery).

3.2 Swimming pool room thermal balance model

The presence of an indoor conditioned water swimming pool has a strong impact on the energy consumption of the educational complex of the Portuguese pilot.

The swimming pool will affect the thermal balance of the swimming pool room, as the pool water layer will exchange energy with room air through evaporation and convection. Additionally, a long wave radiation heat exchange will take place between the water layer and the walls and roof of the swimming pool room. In any case, evaporation will produce the clearly prevalent impact on the thermal balance of the swimming pool room.

In order to ensure a satisfactory comfort level (thermal and internal air quality) of the users of the swimming pool, an accurate control of the temperature, humidity and ventilation of the swimming pool room is a critical issue.

On the other hand, being evaporation so important in relation to the total consumption of the swimming pool room, it is necessary to set the values of the air temperature, relative humidity and ventilation rate setpoints, without compromising user comfort, but at the same time minimizing as much as possible evaporation energy losses. Evaporation is affected by several factors:

- The difference between the temperature of the swimming pool water and the air of the swimming pool room (the higher the difference the higher the evaporation).
- The relative humidity of the swimming pool room (evaporation increases as the humidity level of the room decreases).
- The number of users of the swimming pool (evaporation increases with the number of users, as the free surface of the water layer becomes higher)
- The intensity of the developed activities (evaporation increases with the intensity of the activity, as the free surface of the water layer in contact with room air becomes higher).
- Air velocity and the technical solution of the air distribution system (type and location of the supply diffusion elements and exhaust grills). In order to avoid unnecessary evaporation increase, direct delivery of the supply air over the water layer of the swimming pool should be avoided.

Taking these constraints into account, typically the setpoint value of the swimming pool room air is established 1/2 ºC above the setpoint of the swimming pool water, and the relative humidity setpoint value is set in the range between 60-65%. These values of relative humidity are compatible with user comfort, and

minimize evaporation and condensation risk on the structure of the swimming pool room (eliminating corrosion damage risk).

An indoor swimming pool model is available in EnergyPlus since version 8.4, to evaluate the impact of the presence of the swimming pool on the room thermal balance, and the energy consumption associated to the water heating and renovation of the swimming pool.

However, due to some implementation problems at least in versions 8.4 and 8.5 of EnergyPlus the accuracy of the results provided by this model was considered low. Additionally, this model does not provide the possibility to consider energy recovery from the makeup water system, to preheat the makeup water of the swimming pool.

As displayed below, in the evaporation model included in EnergyPlus, evaporation rate is calculated through a single term that simultaneously evaluates the undisturbed (without the impact of user activity) and disturbed evaporation (with the impact of user activity). In order to do so, an activity factor that has to reflect simultaneously the impact of the evolution over time of the occupancy of the pool and the activity intensity is necessary.

$$\boldsymbol{M_{evap} = S \cdot AF \cdot (P_W - P_{dp})}$$

Where:

- M_{evap} = Evaporation Rate of pool water (kg/h)
- S = Surface area of pool water (m^2)
- AF = Activity factor
- P_w = Saturation vapor pressure at surface of pool water
- P_{dp} = Partial vapor pressure at room air dew point

It is believed that the identification of the AF values that can capture the evolution over time of the occupancy of the swimming pool and the intensity of the activity, is more complicated than considering 2 specific correction factors addressing each of these effects separately (occupancy and intensity of the activity).

In order to overcome these limitations and meet the required modelling capacities, it has been decided to define specific models for the energy balance of the swimming pool room, and for the swimming pool heating and makeup water demand.

Several mathematical models are available to evaluate the evaporation of a conditioned indoor swimming pool. Most of them include a term to consider the undisturbed evaporation (not affected by the number of occupants nor the intensity of the activity), and a second term to account for the evaporation created by pool occupancy.

The results provided through the application of different models can lead to significantly different evaporation rates. In any case, beyond the selected model, the critical issue is the accuracy of the input data used in the model, specially in relation to occupancy and to the considered values for the operational variables of the swimming pool (water temperature, air temperature, air relative humidity).

All these models consider the impact of the swimming pool water temperature, the swimming pool room air temperature/humidity, occupancy and activity intensity. However, the evaluation of the impact of the typology of supply air distribution is more complex and is addressed only in some of the existing models.

As an example, here two of the more frequently used models are mentioned. Many other models could also be mentioned (ASHRAE, etc.) but are omitted here to contribute to the brevity of this document.

As displayed below, in the Bernier model, the impact of HVAC system air delivery velocity in not taken into account.

$$\boldsymbol{M_{evap} = S \cdot [(16 + 133 \cdot n) \cdot (W_e - G_a \cdot W_{as})] + 0.1 \cdot N}$$

Where:

- M_{evap} = Mass flow rate of evaporated water (kg/h)
- S = Area of the swimming pool water layer (m^2)
- W_e = Absolute humidity of the saturated air at the temperature of the swimming pool water (kg water/kg air).
- Was = Absolute humidity of the saturated air at the temperature of the air of the swimming pool room (kg water/kg air)
- Ga = Saturation degree
- n = Density of swimmers inside the swimming pool (persons/m^2)
- N = Total number of viewers in the swimming pool room.

The Carreras model besides the previously described variables takes into account the impact of the discharge velocity of the HVAC system of the swimming pool room.

$$\boldsymbol{M_{evap} = 9 \cdot (W_e - W_{as}) \cdot \left(1 + \frac{V}{1.20}\right) \cdot S + 0.42 \cdot n + 0.08 \cdot N}$$

Where:

- M_{evap} = Mass flow rate of evaporated water (kg/h)
- W_e = Absolute humidity of the saturated air at the temperature of the swimming pool water (kg water/kg air).
- W_{as} = Absolute humidity of the saturated air at the temperature of the air of the swimming pool room (kg water/kg air)
- S = Area of the swimming pool water layer (m^2)
- n = Density of swimmers inside the swimming pool (persons/m^2)
- N = Total number of viewers in the swimming pool room.

After analyzing the existing models to evaluate water evaporation, the Bernier model has been selected. As long as reliable input data are available, it can provide a satisfactory accuracy level without introducing unnecessary complexities from the perspective of the implementation into EnergyPlus.

Finally, the expressions to calculate the rest of the components to be added to the thermal balance of the swimming pool room are described below.

$$Q_{conv} = h \cdot (T_p - T_a)$$

$$h = 0.22 \cdot (T_p - T_a)^{1/3}$$

Where:

- Q_{conv}= convective heat transfer rate (W/m^2)
- h = Convection heat transfer coefficient(W/m^{2}ºC)
- Tp = Pool water temperature (ºC)
- Ta = Swimming pool room air temperature(ºC)

And the energy exchange through long wave radiation with each of the walls and the roof of the swimming pool room envelope can be calculated through the following expression.

$$Q_{rad} = \sigma \cdot \varepsilon \cdot ({T_w}^4 - {T_e}^4)$$

- Q_{rad} = energy exchange through radiation (W/m^2)
- σ = Stefan-Boltzmann constant = 5.67 x 10^{-8} (W/m^2·K^4)
- ε= Surface emissivity = 0.95
- T_W = Water temperature (K)
- T_e = Envelope element temperature (K)

All the details related to the implementation of the model in EnergyPlus will be explained in detail in Task 3.6. In any case, in the following lines an overview of the implementation procedure will be provided without addressing the most technical details (the description of the classes necessary in order to enable the implementation of the model).

The implementation of the model will be carried out through the definition of an **Energy Exchange Calculation EMS Program** and of an **Energy Balance Calculation EMS program**.

The Energy Exchange Calculation EMS Program will carry out the calculation of the different components of the energy exchange between the swimming pool and the room, using the model equations described in this section, as well as, the instantaneous values of all the environmental variables of the swimming pool room (temperature and humidity) and the temperature of the swimming pool.

The program will be called and executed at the end of each simulation timestep, in order to calculate all the energy exchange components that will impact the thermal balance of the swimming pool room in the next calculation timestep.

Taking advantage of the calculations performed by the **Energy Exchange Calculation Program, the Energy Balance Calculation program** will populate the value for the ongoing timestep of the internal gain objects used to transfer to the swimming pool room zone thermal balance, the impact of each of the components of the energy exchange between the swimming pool and the swimming pool room.

This program is called and executed at the beginning of each simulation timestep, and will use the results calculated by the **Energy Exchange Calculation Program** for the precedent timestep.

From a numerical point of view this is equivalent to a loose co-simulation approach, and therefore in order to ensure high accuracy and minimize the existing time-lagged data a very short simulation time step will be necessary.

3.3 Swimming pool heating and makeup water demand model

As previously stated the energy demand of the indoor swimming pool to be met by the heating plant of the building will mainly consist on the energy necessary to compensate water evaporation to the ambient of the swimming pool room air, and the energy invested to heat makeup water from mains temperature to the setpoint temperature value of the swimming pool.

Below the mathematical expression of the heat requested by the swimming pool to the heating plant at any specific moment is displayed:

$$Q_{sp_p} = Q_{evap} + Q_{muw} + Q_{conv} + Q_{rad} + Q_{cond}$$

- Q_{spp} **=** Energy requested by the pool to the heating plant
- Q_{evap} = Energy loss to the pool room air through evaporation
- Q_{muw} = Energy demand associated to the makeup water
- Q_{conv} = Energy loss to the pool room through convection
- Q_{rad} = Energy loss to the pool room through radiation
- Q_{cond} = Energy loss of the swimming pool water through conduction on the walls and floor of the swimming pool.

With the exception of the energy demand associated to makeup water and the losses over the walls and floor of the swimming pool, the rest of the components have already been addressed in the swimming pool thermal balance model described in the precedent section.

The equations necessary to calculate these additional terms are displayed below:

$$Q_{muw} = M_{ff} \cdot C_{muw} \cdot (T_{sp} - T_{muw})$$

- Q_{muw} = Energy necessary to heat makeup water from mains temperature to the setpoint temperature of the swimming pool (W)
- M_{ff} = mass flow rate of fresh water (kg/s)

- C_{sw} = specific heat of water (J/kg·K)
- T_{sp} = swimming pool water temperature (K)
- T_{muw} = Mains fresh water temperature (K)

The energy loss component through swimming pool wall and floor will be affected by their constructive characteristics and by the temperature of the basement below the swimming pool (typically swimming pools are deployed above a basement, where all the auxiliary system for swimming pool water heating and disinfection are deployed).

$$\boldsymbol{Q_{cond}} = \boldsymbol{U_{w_{sp}}} \cdot \boldsymbol{S_{w_{sp}}} \cdot (\boldsymbol{T_{sp}} - \boldsymbol{T_e})$$

- Q_{cond} = Conduction of the swimming pool walls (W)
- U_{wsp} = Thermal transmittance of the walls of the swimming pool (W/m^2·K)
- S_{wsp} = Wall surface (m^2)
- T_{sp} = Swimming pool water temperature (K)
- T_e = Basement air temperature (K)

In the next figure, a simplified hydraulic scheme of the swimming pool water heating and makeup system is displayed. The energy necessary to maintain the swimming pool water setpoint is delivered by a dedicated plate heat exchanger with a counter flow configuration, connected to the heating plant of the building.

Usually, in modern facilities a heat recovery system is deployed to recover energy from the renovated water of the swimming pool, to be used to preheat the makeup water. Usually this system is formed by a plate heat exchanger working with a counter flow configuration in order to maximize the efficiency of energy transfer.

As already described, the indoor swimming pool model included in EnergyPlus does not provide the possibility to evaluate the preheating provided by this system to the makeup water.

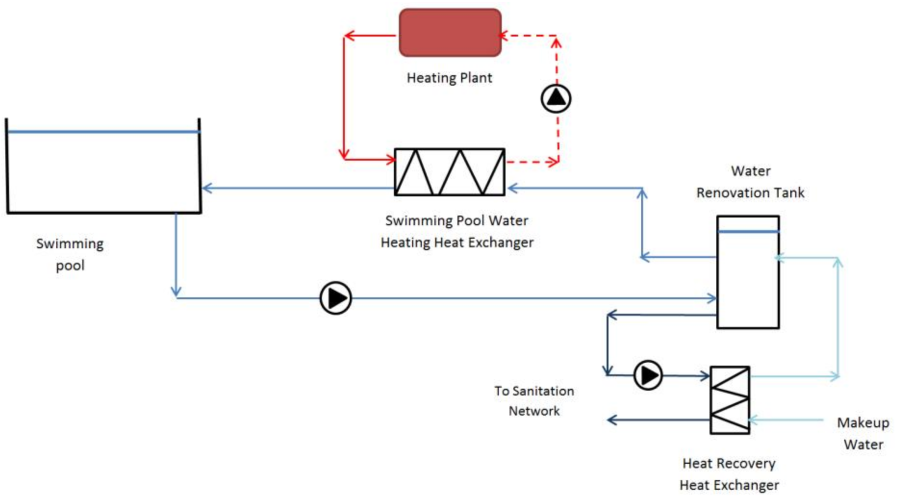

Figure 1 Scheme of the swimming pool water heating and renovation system

The impact of the heat recovery system on the makeup water temperature will be evaluated using the well known NTU-ε model for heat exchanger design and Sizing. The NTU- ε model is usually used to evaluate the operational conditions (outlet temperatures) for a given heat exchanger (UA value) operating under specific primary and secondary side flow rate and inlet temperature values. The model for a counter flow heat exchanger is based on the following expressions:

$$NTU = \frac{U * A}{(\dot{m} * Cp)_{MIN}}$$

$$C = (\dot{m} * Cp)$$

$$\varepsilon = \frac{1 - e^{NTU\,(\frac{Cmin}{Cmax}-1)}}{1 - \frac{C_{min}}{C_{max}} e^{NTU\,(\frac{Cmin}{Cmax}-1)}}$$

$$\varepsilon = \frac{T_{COLD\_O} - T_{COLD\_I}}{T_{HOT\_I} - T_{COLD\_I}}$$

Where:

- NTU: Number of transfer units.
- Cp: Specific heat of the fluids.
- $\dot{m}$: Mass flow on the primary/secondary side.
- C: Heat capacity rate.
- C_{min}: Minimum heat capacity rate (minimum heat capacity of the fluids of the primary and secondary sides of the heat exchanger).
- C_{max}: Maximum heat capacity rate (maximum heat capacity of the fluids of the primary and secondary sides of the heat exchanger).
- ε : Efficiency of the heat exchanger.
- T_{HOT_I}: Inlet temperature of the hot fluid (renovated swimming pool water) in the primary side of the heat exchanger.
- T_{COLD_I}: Inlet temperature of the cold fluid (makeup swimming pool water) in the secondary side of the heat exchanger.
- T_{COLD_O}: Outlet temperature of the cold fluid (makeup swimming pool water) on the primary side of the heat exchanger.

With these model, if the specifications of the deployed heat recovery heat exchanger are known (UA value, etc.) and the temperature of the water leaving the swimming pool (T_{HOT_I}) and the makeup water (T_{COLD_I}) are available, the pre-heating effect of the heat recovery system can be calculated (preheated makeup water temperature/ T_{COLD_O}).

Finally, to evaluate the impact of the energy recovery device on the total thermal load to be met by the swimming pool heating heat exchanger, the pre-heated make water temperature can be used in the expression for the calculation of the

energy necessary to heat makeup water up to the setpoint temperature of the water of the swimming pool.

All the details related to the implementation of this model in EnergyPlus will be explained in detail in Task 3.6. In any case, in the following lines an overview of the implementation procedure will be provided without addressing the most technical details (the description of the classes necessary in order to enable the implementation of the model).

The implementation of the model will be carried out through the definition of the following EMS programs:

- **The pre-heated makeup water temperature Calculation Program**
- **The swimming pool thermal load calculation program**.

The pre-heated makeup water temperature Calculation Program will carry out the calculation of the pre-heated makeup water, using the model equations described in this section, as well as the following values.

- Swimming pool water temperature at the end of the previous simulation timestep.
- Mains water temperature at the beginning of the simulation timestep.
- Makeup water mass flow rate scheduled for the current simulation timestep.

The program will be called and executed at the beginning of each simulation timestep, in order to calculate the value of the pre-heated makeup water temperature to be used in the current simulation timestep.

The swimming pool thermal load calculation program, using the mathematical expressions described in this section will enable the calculation of the makeup water heating energy and the energy loss through the walls and the floor of the swimming pool. In this calculation the following values will be necessary.

- Air temperature of the basement below the swimming pool at the end of the previous timestep.
- Swimming pool water temperature and the end of the previous timestep.
- Mains water temperature at the beginning of the current simulation timestep.
- Makeup water mass flow rate scheduled for the current simulation timestep.

The rest of components (evaporation, convection and radiation losses) will be already available from the **Energy Exchange Calculation Program** of the swimming pool room thermal balance model.

Additionally, the **swimming pool thermal load calculation program** will use the value calculated for the current time step, to populate the object used to transfer the impact of the calculated swimming pool thermal load to the heating plant of the building.

This program will be called and executed at the beginning of each simulation timestep after the execution of **The pre-heated makeup water temperature Calculation Program**.

From a numerical point of view this is equivalent to a loose co-simulation approach, and therefore, in order ensure high accuracy and minimize the existing time-lagged data a very short simulation time step will be necessary.

3.4 Conclusions

The standard modelling capabilities available in EnergyPlus include a comprehensive collection of models to address building level DER system modelling, that will enable to produce the EnergyPlus building models (including all building level DER systems) of the pilots, in the frame of Task 3.6.

However, in order to overcome the modelling limitations existing in EnergyPlus in the swimming pool domain, and enable the definition of the EnergyPlus model of the educational complex of the Portuguese pilot, two specific EnergyPlus models have been developed (the **Swimming pool room thermal balance model** and **the Swimming pool water heating and makeup water system demand model**).

In this section, a detailed description of these models has been provided, as well as, an overview of the procedure to be implemented in task 3.6 to integrate them into EnergyPlus.

The detailed description of the modelling approach followed to define the building models of each specific pilot will be part of D3.6, along with the description of the activities completed to integrate into the calculation engine of the BEPS, the models developed in tasks 3.4 and 3.5.

4 MOEEBIUS District Heating and DER Model

4.1 Introduction

For districts with a district heating system there are infrastructures outside the physical boundaries of the buildings (e.g. distribution thermal network, district heating plant, etc.), that have a big impact in the aggregated energy demand of the district.

On the other hand, to evaluate the aggregated value of the district level distributed production (electric and thermal), it will be necessary to evaluate the production of the DER systems deployed outside the physical boundaries of the buildings of the district.

Therefore, in order to evaluate these aspects it is necessary to produce an explicit model of the district heating system including the infrastructures of the district heating system and the district level DER systems (**MOEEBIUS District Heating and DER Model**).

The modelling scope of the generic **MOEEBIUS District Heating and DER Model** will include:

- The heating plant of the district.
- The distribution thermal network of the district with an accurate topological description of the thermal network and the distribution of the connected buildings.
- The existing pumping stations.
- The thermal substations that connect the buildings to the distribution thermal network.
- Solar thermal collector systems deployed at district level.
- PV systems deployed at district level.
- Wind turbine systems deployed at district level.

Obviously, a simplistic district modelling approach based on a pure aggregation of the demands of the buildings connected to the thermal network would not be able to provide an accurate prediction of the thermal behavior of the district, as needed to implement the MOEEBIUS platform.

With such modelling approach, many of the relevant physical effects present in thermal networks would be ignored (temperature distribution over the thermal network, distribution thermal losses, etc.) leading to poor accuracy of predictions and to sub-optimal thermal network management.

On the other hand, the dynamics present in the interface between buildings and the thermal network (building substation) are so important that a fully integrated

district model is necessary (integration between the district model and the building models), in order to be able to reliably provide performance predictions.

In order to have an accurate calculation of the return temperatures from the buildings to the thermal network, it is necessary to model with an acceptable detail level the dynamics present in the thermal substation.

The Modelica modelling language has been selected to model the district heating system and the thermal DER systems. The limitations existing in legacy building simulation programs for district modelling and the advantages provided by Modelica are described in detail in the next sections of this deliverable (sections 4.2 and 4.3)

Finally, and to complete the **MOEEBIUS District Heating and DER Model**, electric district level DER system modelling will be based on a data oriented forecasting approach. These models will provide the prediction of how much electric energy will be generated from renewable resources (PV and wind turbine).

4.2 Limitations of simulation programs for district modelling

4.2.1 Limitations of legacy simulation programs

Modelling of complete districts is a very complex goal as it involves modelling of systems affected by dynamic effects with very different time scales contained inside space boundaries of very different scales (from components to district scale), and including technical systems and technologies that are part of different domains (lighting, HVAC, Control, etc.).

Most of the existing legacy building simulation programs, such as EnergyPlus, were developed for building and building system design and are suitable for model predictive high level supervisory control implementations (definition of setpoint values, generator operational sequences, etc.).

On the other hand, none of the existing traditional building simulation tools (EnergyPlus, DOE, eQUEST, ESPr, TRNSYS, etc.) is suitable to meet all the requirements necessary to perform an accurate definition of a complete district in a single simulation model, due to the existing modelling limitations. Therefore it can be concluded that none of the currently existing building simulation tools can provide the modelling capabilities required to produce fully integrated district models.

Even though TRNSYS is an equation based tool, it can be classified as a traditional building simulation program, as each physical component is formulated by a block with predefined inputs and outputs (causal relations). The outputs of a model are based on inputs coming from the upstream model and are transferred as inputs to the downstream model, until the changes of all outputs are less than a defined

tolerance. To avoid infinite iterations in case of non-convergence or long computational time, there is a limit on the number of iterations.

Additionally, most of the currently existing legacy building simulation programs were conceived as large monolithic programs written in Fortran encapsulating causal assignments in programming procedures. Procedures call other procedures, to manipulate data, or to transfer the control of the program to other procedures, and then return the control back to the calling procedure. Inside these procedures imperative statements for algebraic equations, differential equations, difference equations, numerical solution algorithms, and data input/output routines are integrated.

The model modularization, the causality to be imposed on the equations to transform them into procedural code and connectivity rules of each object are defined by the program developers to optimize the architecture of the programs, and to accommodate data flows and solution algorithms, in some cases not fully reproducing the connectivity rules and modularity of real equipment.

Therefore, it can be stated that the syntax used in legacy building simulation programs in some cases does not fully resemble how an engineer would define the equations that describe the behaviour of any particular dynamic system. Due to these limitations, the addition of new modelling capabilities and functionalities that were not initially included in legacy building simulation programs is very complicated.

More specifically, in the case of EnergyPlus the addition of models out of the building domain, that cannot be integrated through the capabilities provided by the EnergyPlus Run Time Language, would require a big effort to modify the code and even the architecture of the program. This would constitute an inefficient approach to district modelling.

As it will be presented in the next section, the Modelica Modelling language and the Modelica modelling and simulation environments are to a great extent the solution to the open questions described in this section for district heating modelling.

4.2.2 Advantages of Modelica for multidomain Modelling

Modelica is a freely-available, equation-based object-oriented causal modelling language that is designed for multi-domain modelling of dynamic systems that are described by algebraic equations, differential equations, difference equations and discrete equations.

It has been developed by the Modelica consortium since 1997 to define a new language for model representation, combining the benefits of previously existing modelling languages. The Modelica language has been used in various industrial applications and has gained a significant adoption in several industrial sectors

such as the automotive sector. In fact, It is well positioned to become the de-facto standard for modelling complex physical systems.

One of the most innovative aspects of the Modelica language is that it enables decoupling physical modelling from simulation program development. In fact, models developed in Modelica cannot be executed directly and instead, they have to be translated into an executable program in a Modelica modelling and simulation environment.

Typically the traditional process for the development of a simulation program consists in creating a mathematical model from a physical system that is then manually transformed into a simulation program. The manual approach requires that the following sequence is completed by a model developer:

- Writing the code of the simulation program.
- Interfacing it with numerical solution methods.
- Integration into the program kernel.
- Implementation of methods to introduce inputs and to write outputs.

However, in Modelica the translation of mathematical models into a simulation program is fully automated and performed by existing simulation environments such as OpenModelica or Dymola. In comparison to the manual approach this strongly reduces the risk of introducing errors.

Therefore equation-based modelling allows model developers to concentrate their effort on describing the physical behavior of the studied systems, and generating efficient code for numerical simulation is left to the compiler of a modelling and simulation environment.

Modelica language follows the object-oriented modelling paradigm, whose main characteristics are summarized in the table below:

Features	Description
Encapsulation	The complete definition of the behavior of any specific object is encoded in a compact form inside a single model with well-defined interface points.
Topological interconnection	Component models are connected in a topological way, in the same form as real equipment.
Networking Capability	Model interconnection through nodes is supported. In order to guaranty power continuity across the nodes the availability of across and through variables is mandatory.
Hierarchical modelling	Supported declaration of interconnected models as new objects. Model construction in a hierarchical form is therefore supported.
Object instantiation	A mechanism of model invocation allows to instantiate actual objects from the description of generic object classes.
Class inheritance	Encapsulation of knowledge below the level of a physical object allowed through class inheritance. Encapsulated knowledge can be distributed through the model by an inheritance mechanism, avoiding the need to encode it several times in different places of the model.

Table 1 Modelica modelling Language features

Therefore in Modelica physical systems are modeled through objects or component models that encapsulate the mathematical equations that represent their behavior, and standardized interfaces that capture the mathematical relations among its interface variables. Using these standardized interfaces makes models compatible with each other without having to convert one set of interface data into another one.

Each component model represents a physical device with physical interface ports that expose their potential (temperature, pressure) and flow variables (heat flow rate, mass flow) without specifying what input is and what output, as this is not needed to describe physics. A causal relation defines constraints between the port data and between the mathematical models encapsulated inside components.

Thanks to behavior encapsulation inside component models and the standardized interfaces, components can be connected in an intuitive way to form subsystems, systems or complete architectures in a Modelica modelling and simulation environment, using a graphical or textual editor.

Other of the outstanding characteristics of equation based object oriented models in general, and of Modelica in particular, is that component modularization and connectivity rules are the same as in actual equipment. In other words, connectivity between components is only limited by how physical laws allow real equipment to be connected.

In the table below, a list of some of the additional advantages provided by the Modelica modelling language are summarized. Most of these advantages are especially relevant in relation to the incorporation of simulation models to the operational phase of districts for model predictive control purposes.

Functionality	Description
District control implementation	Modelica model use for design and analysis of both supervisory and local level controllers supported thanks to adaptive time step length and event detection
Model predictive control implementation	Direct use of Modelica model outputs in control systems supported due to the consistency of inputs and outputs with actual control systems
Availability of standardized interfaces for co-simulation with other modelling tools	Models expressed in equation-based object-oriented modelling languages can be interfaced with existing building simulation programs to extend the scope of the systems that can be analyzed.
Simple model reuse	Code reusability significantly increased due to the separation of a causal relations between model variables from their solution algorithms
Simple model reuse	Model reuse and testing of sub-models before they are assembled enabled trough hierarchical model composition. Such unit tests allow an early detection of possible programming errors, saving costs.

Fast model development	Component model encapsulation within clearly defined boundaries accelerates model production by allowing parallel development of models belonging to different domains by their respective experts.
Fast model development	Equation-based modelling languages allow a significant reduction of model development time compared to conventional programming languages (C/C++ or Fortran).
Easy adaptation to parallel calculation hardware deployment	Models formulated in equation based, high-level programming languages, can take advantage of parallel calculation hardware deployments. Separation between the algebraic and numerical solvers from model equations can facilitate upgrading them to newer versions that can exploit this new hardware architecture.

Table 2 Advantages provided by the Modelica modelling language

As already mentioned there are several commercial (e.g. Dymola) and free (e.g. Openmodelica) modelling and simulation environments available for Modelica, that support textual and graphical modelling. On the other hand Modelica libraries for multi-domain physics include models for control, thermal, electrical and mechanical systems, as well as for fluid systems.

However, a comprehensive library for building and district modelling is not yet available and this is delaying the generalized use of Modelica in the building and district domain.

Apart from the **Modelica Standard Library**, there are some freely available libraries that enable partial building and district modelling:

- **The Modelica Buildings library** developed by the Laurence Berkeley National Laboratory is a library with dynamic simulation models for building energy and control systems. The library contains models for some air/water based HVAC systems, control systems, heat transfer among rooms and the outside, multizone airflow, and electrical systems.
- **The Modelica Building Systems library** developed by the Berlin University of the Arts, Institute for Architecture and Urban Planning with dynamic models for energy-related building and plant simulation.
- **The AixLib library** developed at RWTH Aachen University, E.ON Energy Research Center, and Institute for Energy Efficient Buildings and Indoor Climate (EBC) in Aachen, Germany, contains simplified models of HVAC systems as well as low and higher order building models for building performance simulations
- **The Ideas library** developed by KU Leuven and 3E, for Integrated District Energy Assessment Simulations, allowing simultaneous transient simulation of thermal and electrical systems at both building and feeder level.
- **The ThermoPower library** for the dynamic modelling of thermal power plants. The library has been developed by Francesco Casella and Alberto Leva (*Politecnico di Milano*) to analyze the dynamic behavior of plants, with the purpose of studying control system strategies and architectures.

- **The ThermoSysPro library** developed by EDF provides component models in various disciplines for modelling and simulation of power plants and energy systems.

Despite the ongoing initiatives to increase the number of the Modelica libraries with dynamic models for building and district modelling, the scope of currently available models does not allow a generalized adoption of Modelica as building simulation language, and additionally several limitations persist for district modelling.

On the other hand, the detailed definition of building and district models involves high number of instances of physical component models, and this creates scalability limitations, as defining complex models strictly from components requires a lot of work to instantiate and connect all the required components.

Building and district modelling should instead be based on a subsystem approach, in order to optimize the effort required for complex model development. However, the models required to implement this approach in the domain of district modelling are not available. To address this issue, in this task subsystem models have been developed for district heating and thermal DER system modelling.

Finally, it is necessary to mention that modelling limitations currently existing in Openmodelica (translation of models based on the Standard Modelica Fluids Library, etc.), limit its potential for District Heating system model development.

Therefore, at this stage of the project Dymola is the only available Modelica modelling and simulation environment that can provide the required functionalities.

4.3 Integrated district model through co-simulation

As already explained the implementation of the MOEEBIUS platform will be based on building and district level behaviour prediction. Therefore the availability of a fully integrated district model will be a mandatory condition.

As explained in the precedent sections, at this moment legacy building simulation programs but also the new equation based object oriented modelling languages, present limitations that make it impossible to provide all the modelling capacities, required for the development of a fully integrated district model.

The addition of district level modelling capacities and functionalities to building simulation programs is technically difficult and costly, as it usually would require major code or even tool architecture modifications. However, immediate and complete migration from legacy building simulation programs to equation based tools in the building domain is not yet possible, as the required domain specific component model libraries are not available yet.

On the other hand, it is necessary to take into account that legacy building simulation programs have been specifically developed for building performance analysis, in some cases, for decades. Therefore, the development of all the component libraries necessary to provide comparable modelling capabilities in the frame of the building domain to equation based modelling languages, will require time.

Therefore, in order to overcome the currently existing limitations in legacy building simulation programs and in equation based object oriented tools, it seems reasonable to find a procedure to combine both types of tools in such a way that it would allow sharing developments and reusing component models, taking advantage of the complementarity of both types of tools. This goal can be achieved through co-simulation.

The co-simulation approach represents a particular case of simulation scenarios where at least two simulators solve coupled systems of differential-algebraic equations and exchange data to couple these equations during time integration.

From a numeral point of view, depending on the interactions and the approach defined for the information exchange between the simulation tools involved in a co-simulation arrangement, two different types of co-simulation coupling schemes can be defined.

In quasy-dynamic or loose co-simulation schemes, the coupled simulation tools exchange data using a fixed synchronization time step. The exchanged data come from the preceding time step without iteration between the coupled simulation tools.

The second co-simulation scheme is called fully dynamic or strong coupling scheme. In this case, within each time step, simulator tools exchange data until a convergence criteria is satisfied by the state variables of the coupled simulators.

Some of the coupled simulators may include iterative solutions of equations. If that is the case, strong coupling will require nested iteration loops, consisting of an inner iteration within the individual simulators, and an outer iteration to achieve convergence of the coupled simulators.

In order to ensure convergence, the inner iterations need to be solved at higher accuracy than the outer iterations. In the case of legacy building simulation tools this would be impractical to implement, as it would require significant code modifications, due to their lack of capacity to explicitly set the precision of the numerical error.

The required calculation time per time step is lower in the case of loose co-simulation schemes, although, due to the existing time-lagged data, it is necessary to use a shorter synchronization time step compared to strong coupling

schemes. Loose co-simulation schemes are computed faster as no iterations are needed at calculation time step level.

A co-simulation arrangement has been designed to generate the Integrated District Model and to couple the Modelica model of the district heating system with the EnergyPlus models of the buildings of the district. It will provide the required modelling capacity and actual building and district level model integration.

Each of the scales involved in the physical system (building and district) will be addressed through specific models developed in the most suitable modelling and simulation tool, providing a flexibility and accuracy level that goes beyond the traditional approach.

A key issue in relation to the implementation of the co-simulation approach is to establish the scope and boundaries of each of the models with very clear interfaces, where interaction dynamics are well known and can be accurately modeled.

The interface between the district heating system model and the building models has been set in the building thermal substation of the buildings connected to the district heating system. With this co-simulation arrangement the value of the operational variables at the primary and secondary side of the thermal substation will be exchanged between the EnergyPlus and the Modelica models, with a calculation time step time resolution.

Different possibilities and procedures to implement the co-simulation arrangement have been studied:

- Creation of a FMU (Fuctional Mock Up unit) of the EnergyPlus model of each of the buildings of the district (slaves) to be imported by the Modelica model that would act as the master of the co-simulation arrangement (simultaneous operation of both simulation tools and variable value exchange during time integration).
- Integration based on the BCVTB (Buildings Control Virtual Test Bed) middleware that would play the role of master of the co-simulation arrangement and enable the variable value exchange of the connected clients (Modelica and EnergyPlus). In this case both simulation tools would operate simultaneously with variable value exchange during time integration.
- A sequential co-simulation approach where EnergyPlus building models would be simulated for the complete prediction period and the obtained results (heat request profiles and inlet/outlet temperatures on the secondary side of building heating substations), used as input of the district heating model for the complete prediction period.
- According to this sequential co-simulation approach, the EnergyPlus building models would be evaluated assuming that the energy delivery from the

district heating system takes place at nominal conditions of temperature and pressure.
- On the other hand, buildings would be integrated in the thermal network model as nodes (building heating substations), with a variable energy request profile distributed according to the topology of the district heating system.

The first 2 procedures would provide the highest accuracy. However, taking into account the service based distributed architecture of the MOEEBIUS platform the first two procedures are less suitable from an implementation point of view. In any case, for any of these approaches the accuracy of the results and the reduction of the gap between simulated and actual consumption values will ultimately be ensured by the periodic calibration of the models.

Therefore, considering the existing constraints a sequential co-simulation approach has been considered as the most suitable one to produce the integrated district model.

4.4 Definition of the MOEEBIUS District Heating and DER Model

As introduced in chapter 3, modelling of the electric and thermal DER-systems (loads and distributed generation systems) deployed inside the physical boundaries of the buildings, will be integrated into the EnergyPlus models of the buildings of the district.

On other hand the evaluation of the impact of the electric production of the DER-systems (PV and wind turbines) existing outside physical boundaries of the buildings of the district, will be evaluated through a statistical modelling approach described in detail is section 5.2.

Regarding district heating and thermal DER modelling, as previously described, with currently available Modelica libraries district modelling is based in a physical component oriented architecture, which is not compatible with the detailed definition of complex district heating and DER systems in an efficient way.

Going beyond the component oriented approaches currently available in Modelica for district heating model generation, the **MOEEBIUS District Heating Model** will be developed according to a subsystem model based architecture.

According to this approach the MOEEBIUS generic district heating model will be formed by the following subsystems (reproducing the physical structure of actual district heating systems):

- District heating plant including the storage subsystem.
- Distribution thermal network.
- Pumping station.
- Solar collector Plant.
- Building heating substations.

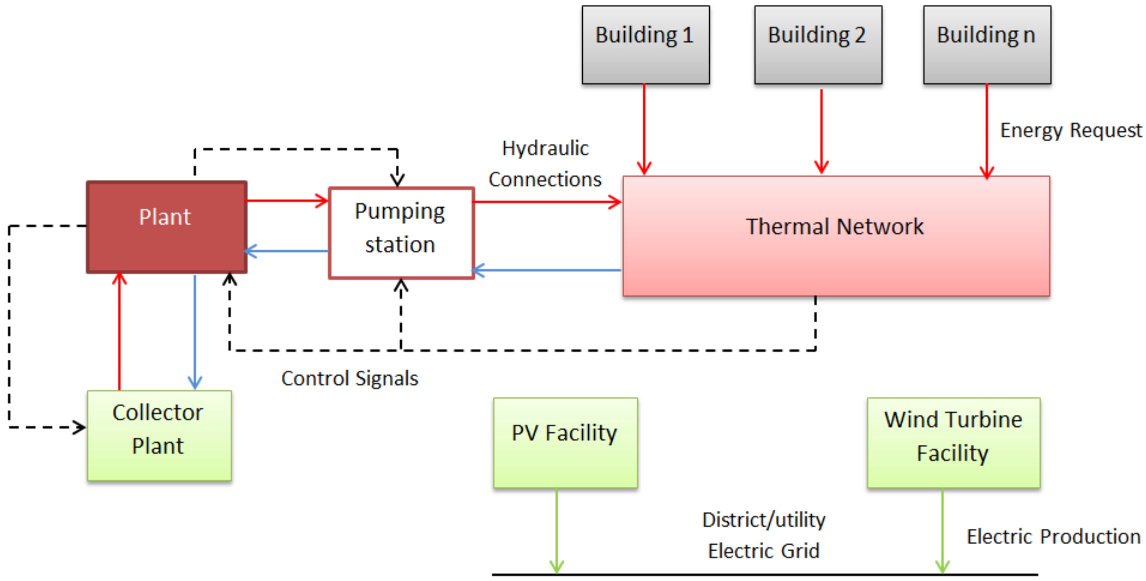

Figure 2 Subsystem model based architecture of the Generic MOEEBIUS District Heating System Modelica Model

As further explained in the next chapter, specific Modelica models have been developed for each of these subsystems, encapsulating the physical behavior of all the equipment deployed on each of the actual subsystems, reproducing their modularity and connectivity rules.

The Modelica **MOEEBIUS district Heating Model** will be formed connecting the required models as necessary, to configure district heating models of any size, complexity and distribution topology.

The definition of the subsystem models necessary for district heating and thermal DER modelling has been performed according to the following design criteria:

- Capability to define the typically existing district heating typologies from the perspective of the deployed technologies, existing distribution topologies and operational strategies, paying special attention to the modelling requirements imposed by project pilots.
- Optimized modelling capabilities in order to enable addressing all the relevant dynamics present in the different subsystems, with a complexity level consistent with the required accuracy.
  - Heat generator performance.
  - Thermal storage at district heating plant and solar collector plant level.
  - Pressure driven flow control algorithms.
  - Distribution thermal losses over the thermal network.
  - Thermal inertia of the distribution network and detailed thermal network temperature distribution.

- Dynamics present in the interface between the thermal network and the connected buildings (building thermal substation).
- Detailed control algorithms for all the relevant equipment of all the subsystems (heat generators, pumps, valves, etc.).

- Flexibility and scalability.

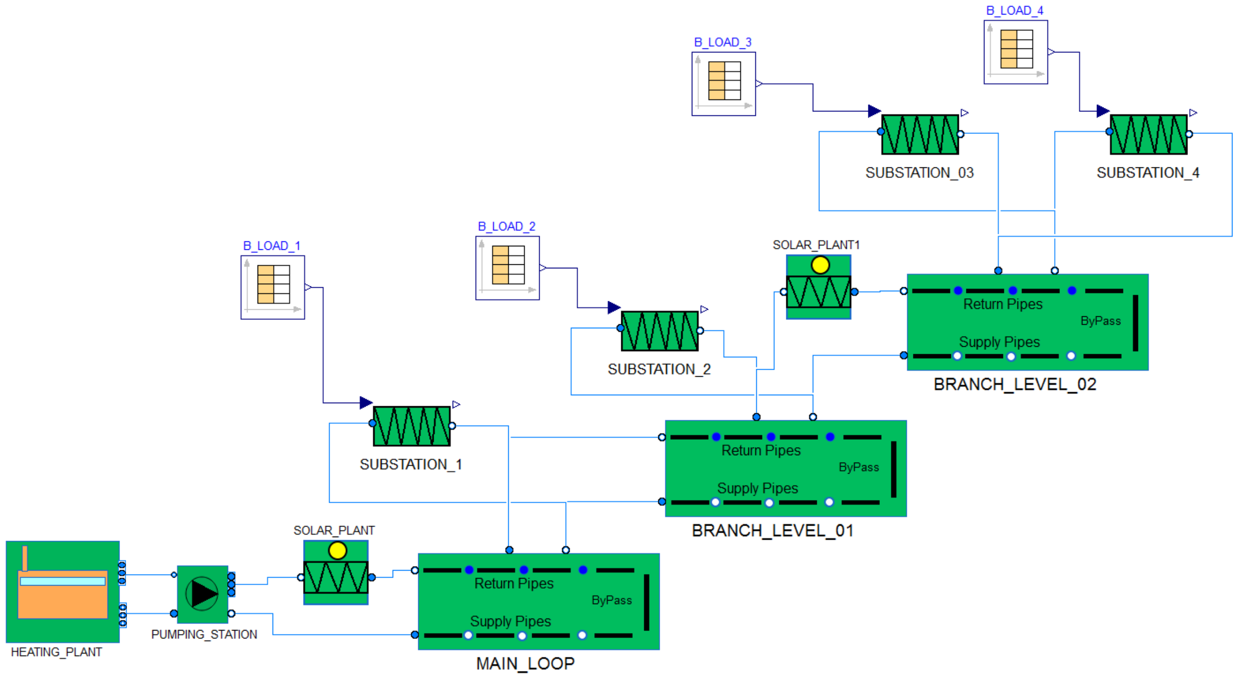

Figure 3 Example of the definition of a district heating and thermal DER model through the generic MOEEBIUS district heating and DER system subsystem architecture approach

The district heating system model displayed in the precedent figure is configured by a district heating plant, connected through the pumping station that produces the water flow all over the thermal network, to the main distribution loop of the network.

From the main distribution loop of the network, an arbitrarily complex hierarchy of branches can be defined just connecting the required number of instances of the MOEEBIUS loop/branch model. In this specific case, besides the main loop, the distribution topology is formed by a hierarchy consisting in two branch levels.

Building substation models allow the integration of the energy requested by the buildings to the thermal network. As displayed by the defined example, building substations, as is the case with actual substations, can be connected to the main distribution loop, or to any of the branches of the branch hierarchy.

The secondary side of the thermal substation models is connected to the Common Information Model (CIM) data base, where the thermal request curves calculated by the EnergyPlus building models for the complete simulation run period are

stored, with a calculation time step time resolution. This allows integrating the impact on the district heating system model of the connected buildings.

Additionally, 2 independent solar collector plants have been included. In general, with the exception of low temperature thermal networks, solar plants will be connected to the return line of the thermal network, in order to maximize the performance of the solar plants, and facilitate the energy delivery of the collected energy to the district heating system.

The definition of the solar collector plant subsystem model supports the connection of the model at any level of the distribution topology of the thermal network.

Finally, and to complete the **MOEEBIUS District Heating and DER Model**, electric district level DER system modelling will be based on a data oriented forecasting approach. These models will provide the prediction of how much electric energy will be generated from renewable resources (PV and wind turbine).

4.5 Conclusions

In order to develop the generic **MOEEBIUS District Heating and DER Model** capable to address building and district level dynamics and distributed energy production, an integrated district model is necessary.

None of the currently existing modelling and simulation tools is completely suitable to provide all the required modelling and simulation capabilities, and therefore, co-simulation is considered the most suitable approach to produce the integrated district model, combining:

- EnergyPlus building models including building level electric and thermal DER system modelling.
- A statistical district level electric DER (PV and wind turbine) production forecasting model.
- A district heating and district level thermal DER model, developed in Modelica according to a subsystem oriented architecture.

With this approach it will be possible to produce predictions for the aggregated electric and thermal demands of the district, to be used by the District **DAE** to implement demand response strategies.

5 Development of new models for DER systems deployed at district level

The Modelica subsystem models necessary for the implementation of the approach described in the precedent section, will be defined using the component models available in the Standard Modelica library and in other freely available Modelica libraries (Buildings Library, etc.) as a starting point.

These models will be modified and upgraded as necessary in order to enable the definition of the following Modelica subsystem models:

- **District heating plant model**, including:
  - All the components of the district heating plant (heat generators, storage tanks, pumps, control components, etc.).
- **Distribution thermal network model**, including.
  - All the components of the thermal network (pipes reproducing the main topology of the network, connection to building substation, etc.)
  - Adjustable number of distribution loops.
  - Adjustable number of buildings connected to each distribution loop.
- **Pumping station model,** including:
  - All the components of the pumping station (pumps, control components, etc.).
  - Adjustable number of pumping groups according to the number of distribution loops.
- **Solar collector plant model**, including:
  - All the components of the solar collector plant (irradiation source, collector field, storage tank, control elements, primary and secondary side pumps, etc.)
  - Adjustable solar field size.

As previously stated this new components have been included in a new Modelica model library. Finally, and to complete the **MOEEBIUS District Heating and DER Model**, electric district level DER systems will be enhanced with data oriented forecasting models (**Photovoltaic unit and Wind Turbine models).**

5.1 District heating and thermal DER models.

In the following sections a description of the developed MOEEBIUS Modelica subsystem models is provided.

5.1.1 MOEEBIUS district heating plant model.

The function of the district heating plant is to provide the energy necessary to ensure the desired supply water temperature at the inlet of the distribution subsystem of the thermal network.

As previously stated, the district heating plant subsystem model will encapsulate all the physical behaviour of the components to be found in any typical district heating plant. The definition of the model has been performed taking into account the usual district heating plant typologies from the perspective of the deployed generation technologies and hydraulic/thermal arrangements.

The objective was to define a generic district heating plant model with the capacity to model typical heating plant typologies of any size and complexity. In any case, in this process special attention has been paid to the technical solutions existing in the district pilots in order to ensure the capacity of the defined model to support pilot specificities.

As a starting point, the defined model has been configured taking advantage of the physical component models available for thermal plant modelling in the Modelica Standard library, the Buildings library and the ThermoPower library. When necessary these models have been upgraded to provide the required modelling capabilities, or adjusted to align them with the implemented subsystem oriented architecture approach.

The model is based on a district heating plant typology where water boiler plants (with or without thermal storage) and steam production plants provide the requested energy to the district heating system.

The Modelica code of the heating plant subsystem model includes specific algorithms to enable the required level of flexibility and scalability. According to the inputs introduced by the user the generic model is automatically adjusted to include:

- The required number of hot water generation groups (the heat generator and all its auxiliary components such as pumps, etc.), without thermal storage.
- The required number of hot water generation groups with thermal storage.
- A single steam production plant, but with the required number of steam generators and water heating lines (condenser+subcooler).

The modelling capabilities of the model will include the following aspects:

- Hot water boiler performance.
- Steam boiler performance.
- Pressure drop calculation in all the hydraulic and steam loops.
- Pump consumption calculation in all the hydraulic loops.
- Distribution thermal losses to the environment of the district heating plant of all the hydraulic loops.
- Performance of the energy delivery heat exchanger of the hot water generation groups.
- Performance of the condensers and condensate sub-cooling heat exchangers.

- Stratification effect and energy loss to the environment of the district heating plant in storage tanks.
- Detailed control algorithms for all the components of the model.

In the following picture, an example of all the physical component models encapsulated within the generic district heating plant model, to define the hot water production part of a specific district heating plant is displayed. In this particular case, the plant includes 2 generation groups, the first one without thermal storage and the second one coupled to a thermal storage system.

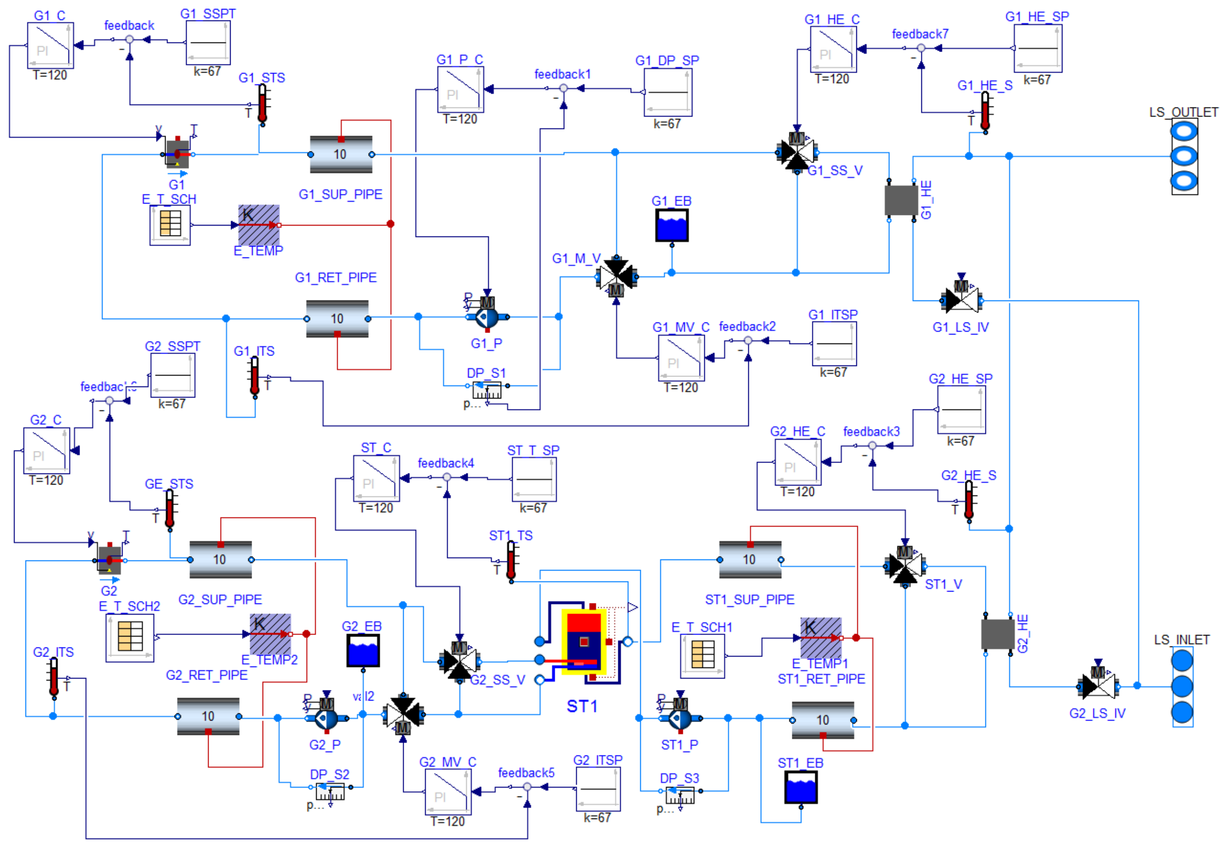

Figure 4 Connection scheme of the component models of the hot water generation groups encapsulated inside the district heating plant subsystem model for the defined example

In order to provide a clearer picture of the structure and scope of the model, in the following lines a description of the hot water production part is given for this specific example.

The hot water generation loop without thermal storage is formed by a hot water boiler (G1) that is coupled to an energy delivery plate heat exchanger (G1_HE_SP), and all the auxiliary components necessary to configure a hydraulic loop, such us a pump (G1_P) and a mixing valve (G1_M_V) necessary to ensure that the return temperature to the generator does not fall below the setpoint value introduced by the user. The pipe component models (ST1_SUP_PIPE and ST1_RET_PIPE) enable to evaluate the pressure loss over the hydraulic loop, as well as the thermal losses of the pipes to the plant environment. Finally, the

energy delivered to the heat exchanger (G1_HE_SP) is controlled through a proportional three way diverting valve (G1_SS_V), deployed on the primary side of the heat exchanger.

The energy consumption associated to the pressure losses over the circulation of each generator loop, is concentrated in the generator supply and return pipe objects, used to represent the impact of the complete generator loop (linear and singular pressure loses. The user is requested to introduce a proportionality factor in relation to linear losses in order to account for the singular losses).

In case of a lack of homogeneity of the diameter of pipes of these hydraulic loops, it would be necessary to pre-calculate the hydraulic equivalent diameter of the pipes of the loop, to reproduce the behaviour of the complete loop through the defined modelling approach.

The thermal loses in these loops are also considered and calculated using a monthly schedule of the plant internal temperatures to be introduced by the user.

The secondary side of the energy delivery heat exchanger (G1_HE_SP) is connected to the load side inlet and outlet ports through a dedicated on/off 2 way valve (G1_LS_IV), that connects or isolates the energy delivery heat exchanger according to the operational status of the heat generator.

Besides the components described for the generator loop without storage, the hot water generator loop with storage includes a storage tank (ST1) and an additional hydraulic loop necessary to couple the tank to the energy delivery heat exchanger (G2_HE_SP). As in the precedent case, this loop will be formed by a variable water flow rate pump (ST1_P) and the pipe components (ST1_SUP_PIPE and ST1_RET_PIPE) necessary to model pressure losses over this hydraulic loop and the thermal losses to the environment of the district heating plant. Finally, the energy delivered to the heat exchanger (G2_HE) is controlled through a three way proportional diverting valve (ST1_V) deployed on the primary side of the heat exchanger.

The operational sequence for the hot water production part of this specific model would be as follows:

- The hot water production setpoint values are adjusted according to weather compensation strategies (G1_SSPT, G2_SSPT, G1_HE_SP, G2_HE_SP).
- Starting from the predefined generator operation priority sequence of the district heating plant (to be introduced by the user), the number of generator groups that must remain active at any moment is adjusted according to the total water flow rate requested by the district heating to the district heating plant.
- More specifically, the number of active generators is fixed comparing the total water flow requested to the plant (this value is an input provided by

the pumping station model), with the secondary side nominal water flow rates of the energy delivery heat exchangers.

- The load side water inlet valves of the active generation groups are kept open to allow water inlet from the thermal network, while the valves of the not activated generation groups remain closed, isolating these generators from the thermal network.
- The position of the 3 way diverting valves (G1_SS_V and ST1_V) is adjusted in order to meet the existing hot water production setpoint values on the energy delivery heat exchangers (G1_HE and G2_HE).
- The 3 way diverting valve (G2_SS_V) is adjusted to control the temperature of the water stored in the storage tank (ST1), according to the existing setpoint value (ST_T_SP).
- The water flow rate circulating through each active generator is adjusted by the pump controllers (G1_P_C and G2_P_C), according to the existing pressure difference setpoint values (G1_DP_SP and G2_DP_SP).
- The water flow rate circulating through each active storage tank loop is adjusted by the storage tank pump controller (ST1_P_C), in order to maintain the desired differential pressure setpoint value (ST1_DP_SP).
- The power delivered by each hot water generator is adjusted by a dedicated control loop, according to the water flow rate fixed by the pump control loop, to maintain the desired hot water production temperature (G1_SSPT and G2_SSPT).

In the following table, all the components of the hot water production plant encapsulated inside the district plant subsystem model for this specific example are summarized.

Hot water plant	
Component name	**Description**
G1	Generator 1
G2	Generator 2
G1_SUP_PIPE	Generator 1 supply pipe
G1_RET_PIPE	Generator 1 return pipe
G2_SUP_PIPE	Generator 2 supply pipe
G2_RET_PIPE	Generator 2 return pipe
G1_M_V	Generator 1 mixing valve
G2_M_V	Generator 2 mixing valve
G1_HE	Generator 1 heat exchanger
G2_HE	Generator 2 heat exchanger
G1_LS_IV	Generator 1 loads side inlet valve
G2_LS_IV	Generator 2 loads side inlet valve
G1_P	Generator 1 pump
G2_P	Generator 2 pump
ST1	Storage tank 1
ST1_P	Storage tank 1 pump
LS_INLET	Load side inlet port
LS_OUTLET	Load side outlet port
ST1_SUP_PIPE	Storage tank 1 supply pipe
ST1_RET_PIPE	Storage tank 1 return pipe

G1_SS_V	Generator 1 source side valve
G2_SS_V	Generator 2 source side valve
ST1_V	Storage tank 1 load side valve
G1_EB	Generator 1 loop expansion vessel
G2_EB	Generator 2 loop expansion vessel
ST1_EB	Storage tank 1 load side loop expansion vessel
G1_SSPT	Generator 1 supply setpoint temperature
G1_C	Generator 1 controller
G1_STS	Generator 1 supply temperature sensor
G2_SSPT	Generator 2 supply setpoint temperature
G2_C	Generator 2 controller
G2_STS	Generator 2 supply temperature sensor
G1_MV_C	Generator 1 mixing valve controller
G1_ITSP	Generator 1 inlet temperature setpoint
G1_ITS	Generator 1 inlet temperature sensor
G2_MV_C	Generator 2 mixing valve controller
G2_ITSP	Generator 2 inlet temperature setpoint
G2_ITS	Generator 2 inlet temperature sensor
G1_HE_C	Generator 1 heat exchanger controller
G1_HE_SP	Generator 1 heat exchanger outlet temperature setpoint
G1_HE_S	Generator 1 heat exchanger outlet temperature sensor
G2_HE_C	Generator 2 heat exchanger controller
G2_HE_SP	Generator 2 heat exchanger outlet temperature setpoint
G2_HE_S	Generator 2 heat exchanger outlet temperature sensor
ST1_P_C	Storage tank 1 pump controller
ST_C	Storage tank controller
ST_T_SP	Storage tank water temperature setpoint
ST1_TS	Storage tank temperature sensor
G1_P_C	Generator 1 pump controller
G1_DP_SP	Generator 1 pump differential pressure setpoint
DP_S1	Generator 1 differential pressure sensor
G2_P_C	Generator 2 pump controller
G2_DP_SP	Generator 2 pump differential pressure setpoint
DP_S2	Generator 2 differential pressure sensor
ST1_P_C	Solar tank 1 pump controller
ST1_DP_SP	Solar tank 1 pump differential pressure setpoint
DP_S3	Storage tank load side differential pressure sensor

Table 3 Component models of the to the hot water production groups encapsulated inside the district heating plant subsystem model for the defined example

Apart from the hot water production groups described in the precedent paragraphs, the district heating plant model gives the choice to include a steam production plant, consisting on an arbitrary number of steam generators coupled to an arbitrary number of heating lines.

The following picture displays an example of all the component models encapsulated within a generic district heating plant model that includes steam production. In this particular case, the plant includes 2 steam boilers and 2 water heating lines.

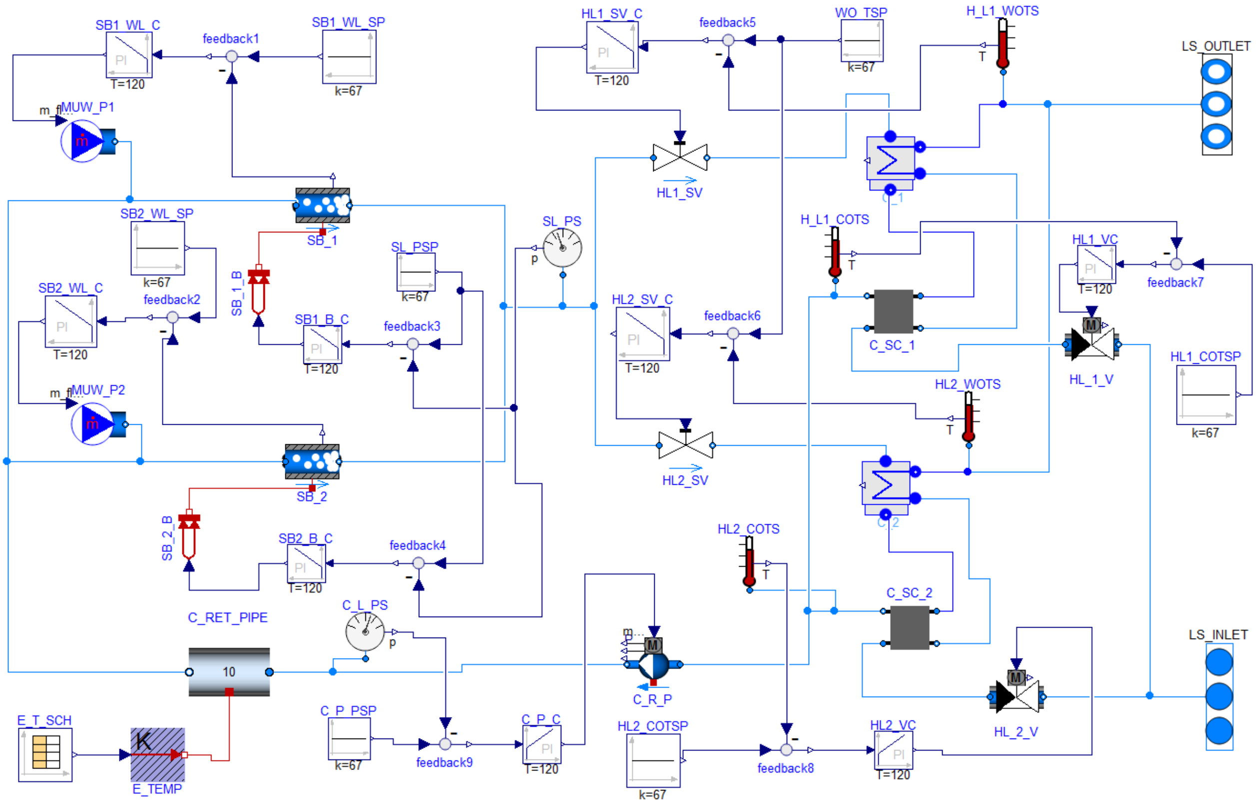

Figure 5 Connection scheme of the component models of the steam production plant encapsulated within the district heating plant model for the defined example

Each heating line is formed by a condenser (C_1 and C_2) and by a condensate sub-cooling heat exchanger (C_SC_1 and C_SC_1) connected in series. The condensers use as energy source the steam produced by the steam boilers (SB_1_B and SB_2_B) and the sub-coolers the condensate leaving the primary side of the condensers.

The secondary side (district side) inlet of the sub-cooler and the secondary side outlet of the condenser of each of the 2 heating lines of the steam production plant are connected, respectively, to the load side inlet port (LS_INLET) and to the load side outlet port (LS_OUTLET) of the district heating plant.

The energy necessary to produce the steam in the boilers is provided by steam boiler burners (SB_1_B and SB_2_B), according to the evolution over time of the energy requested by the district to the steam production plant.

A dedicated boiler make up water system has been included to keep the desired water level inside the steam boilers, to enable their safe and efficient operation. Each of these systems is former by a pump (MUW_P1 and MUW_P1) and a control loop.

The return of the condensate leaving the water heating lines of the plant to the steam boilers is enabled by the variable flow condensate return pump (C_R_P). The impact of the pressure loss on this hydraulic circuit and the thermal losses to

the environment of the district heating plant are accounted for by a return pipe component model.

In the following lines the operational sequence of the steam production plant is described in a compact shape:

- Starting from the predefined steam boiler operation priority sequence of the stream production plant (to be introduced by the user), the number of water heating lines that must remain active at any moment is adjusted, according to the total water flow rate requested by the district heating to the district heating plant.
- More specifically, the number of active lines is fixed comparing the total water flow requested to the district plant with the secondary side nominal water flow rates of the components of each heating line (condensers and condensate sub-coolers).
- The load side water inlet valves (HL_1_V and HL_2_V) of the active heating lines are kept open to allow water inlet from the thermal network, while the valves of the not active heating lines remain closed, isolating them from the thermal network.
- The steam valves of the heating lines (HL1_SV and HL2_SV) adjust the flow of steam supplied to the condensers (C_1 and C_2), in order to ensure that the temperature of the water leaving the secondary side of the condensers meets the existing temperature setpoint value of each heating line (H_L1_WOTS and H_L2_WOTS).
- In order to ensure an efficient use of the steam provided to the condensers, the temperature of the cooled condensate leaving the primary side of the sub-cooling heat exchangers (C_SC_1 and C_SC_2) of the heating lines, is controlled to meet the existing setpoint values (HL1_COTSP and HL2_COTSP). To fulfil this task, two dedicated 2 way proportional valves (HL_1_V and HL_2_V) have been deployed in the connection of the primary side of each of the sub-cooling heat exchangers, to the load side inlet port of the heating plant.
- The energy provided by the burner of each of the steam boilers (SB_1_B and SB_2_B) is adjusted by dedicated controllers, in order to meet the steam pressure setpoint on the main supply line (SL_PSP). In this way, depending on the instantaneous energy request to the steam production plant, the steam production required to meet the existing pressure setpoint will have to be adjusted, and the energy delivered by the burners will have to be modulated accordingly. The required fuel consumption will be calculated using the performance curve of each steam boilers.
- The water flow rate to be provided by the condensate return pump (C_R_P) is adjusted by a dedicated controller, to meet the pressure setpoint (C_L_PSP) existing in the condensate return line of the steam production plant.

In the following table, all the components of the steam production plant encapsulated inside the district plant subsystem model for this specific example are summarized.

Steam production plant	
Component name	**Description**
SB_1	Steam boiler 1
SB_2	Steam boiler 2
SB_1_B	Steam boiler burners 1
SB_2_B	Steam boiler burners 2
MUW_P1	Makeup water pump 1
MUW_P2	Makeup water pump 2
HL1_SV	Heating line 1 steam valve
HL2_SV	Heating line 2 steam valve
C_1	Heating line 1 Condenser
C_2	Heating line 2 Condenser
C_SC_1	Condensate sub-cooler 1
C_SC_2	Condensate sub-cooler 2
HL_1_V	Heating line 1 valve
HL_2_V	Heating line 2 valve
C_R_P	Condensate return pump
C_RET_PIPE	Condensate return pipe
LS_OUTLET	Load Side outlet port
LS_INLET	Load side inlet port
SL_PS	Steam line pressure sensor
C_L_PSP	Condensate line pressure setpoint
C_L_PS	Condensate line pressure sensor
H_L1_WOTS	Heating line 1 water outlet temperature sensor
H_L2_WOTS	Heating line 2 water outlet temperature sensor
H_L1_COTS	Heating line 1 condensate outlet temperature sensor
H_L2_COTS	Heating line 2 condensate outlet temperature sensor
SB1_WL_SP	Steam boiler 1 water level setpoint
SB2_WL_SP	Steam boiler 2 water level setpoint
SB1_WL_C	Steam boiler 1 water level controller
SB2_WL_C	Steam boiler 2 water level controller
SL_PSP	Steam line pressure setpoint
SB1_B_C	Steam boiler 1 burner controller
SB2_B_C	Steam boiler 2 burner controller
WO_TSP	Hot water outlet temperature setpoint
HL1_SV_C	Heating line 1 steam valve controller
HL2_SV_C	Heating line 2 steam valve controller
HL1_COTSP	Heating line 1 condensate outlet temperature setpoint
HL2_COTSP	Heating line 2 condensate outlet temperature setpoint
HL1_VC	Heating line 1 valve controller
HL2_VC	Heating line 2 valve controller

Table 4 Component models of the steam production plant encapsulated inside the district heating plant subsystem model for the defined example

5.1.2 MOEEBIUS pumping station model

This subsystem model encapsulates all the physical behaviour of all the equipment typically deployed in district heating system pumping stations. As a starting point, the defined model has been configured taking advantage of the physical

component models available for thermal plant modelling in the Modelica Standard library and in the Buildings library. When necessary, these component models have been upgraded to provide the required modelling capabilities, or adjusted, to align them with the implemented subsystem oriented architecture approach.

As in the precedent cases the definition of the model allows flexibility and the automatic scalability of the physical component models encapsulated within the subsystem model, through specific algorithms introduced in the Modelica code of the model. More specifically:

- The model is formed by an arbitrary number of pumping groups to be introduced as input by the user of the model. In general, each pumping group will produce water flow, in the hydraulic circuit formed by one hydraulic loop and all the branches connected to it.
- Each pumping group can be formed by an arbitrary number of pumps, according to the input provided by the user of the model.

As in all the defined subsystem models, the connectivity of this model is the same as in the actual subsystem. Therefore, any defined MOEEBIUS district heating and DER model will always include a pumping station model, connected to the district heating plant and to all the existing main distribution loops of the thermal network.

If necessary, additional pumping station models could be deployed at any level of the thermal network branch hierarchy. However, in this case the pumping groups to be included would incorporate a single pumping group formed by an arbitrary number of pumps.

Pumping groups are deployed in the return line the thermal network. This is a typical configuration in district heating systems and is, in fact, present in the case of the Serbian pilot.

In the following picture all the component models encapsulated inside the subsystem model, for an example of a specific pumping station formed by a single pumping group with 2 pumps, is displayed

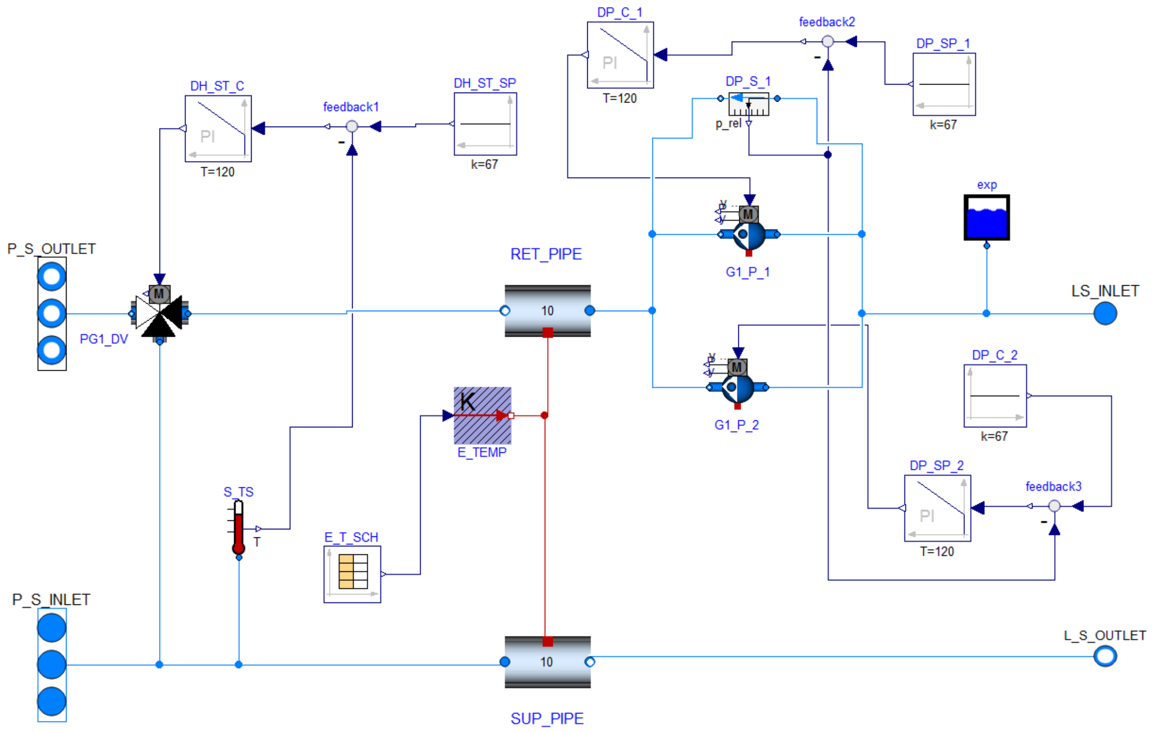

Figure 6 Connection scheme of the component models encapsulated within the pumping station subsystem model for the defined example

For this specific example, the impact of the linear and singular pressure losses, and the thermal losses to the environment of the pumping station room, associated to the pipes and fittings of the hydraulic circuits of the pumping station are accounted for through supply and return pipe component models (SUP_PIPE and RET_PIPE).

Additionally, for each pumping group, the model includes a 3 way proportional diverting valve (PG1_DV) that will allow mixing return water with the supply water coming from the district heating plant. This will give the choice to perform a final adjustment of the distribution hot water supply temperature, according to the setpoint value defined by the user (DH_ST_SP).

This model sets the pressure boundary condition of all the connected main loops, through an expansion vessel component model (Exp) specifically deployed in the pumping station.

All the pumping groups of the model are connected to the plant through the plant side inlet and outlet ports (P_S_INLET and P_S_OUTLET), and to the load side through the load side inlet and outlet connection ports (LS_INLET and L_S_OUTLET).

In the following lines the operational sequence of the pumping station model is described in a compact shape:

- For each of the existing pumping groups (each connected to a different main loop), the number of active pumps (G1_P_1 and G1_P_2) and the water flow rate to be provided by each one, is adjusted through a dedicated control loop. This control loops will maintain the pressure difference setpoint value (DP_SP_1) on the return line, of each of the main loops connected to the pumping station. The selected pump component model uses normalized rotational speed as control signal to adjust the provided water flow rate.
- The total water flow rate to be circulated through the primary side of the energy delivery heat exchangers of the district heating plant model, is provided by this model as an output signal.
  This signal will be used by the district heating plant subsystem model to set the required number of active heat generators at any specific moment.

In the following table, a summary of the component models encapsulated for this example within the pumping station model is displayed.

Pumping station	
Component name	**Description**
P_S_INLET	Plant side inlet port
P_S_OUTLET	Plant side outlet port
LS_INLET	Load side inlet port
L_S_OUTLET	Load side outlet port
SUP_PIPE	Supply pipe
RET_PIPE	Return pipe
Exp	Expansion Vessel
G1_P_1	Group 1 pump 1
G1_P_2	Group 1 pump 2
DP_S_1	Differential pressure sensor 1
DP_S_2	Differential pressure sensor 2
PG1_DV	Diverting valve
DP_SP_1	Differential pressure setpoint 1
DP_C_1	Differential pressure controller 1
DP_SP_2	Differential pressure setpoint 2
DP_C_2	Differential pressure controller 2
DH_ST_SP	District heating supply temperature setpoint
DH_ST_C	District heating supply temperature controller
S_TS	Supply temperature sensor
E_T_SCH	Environment temperature schedule
E_TEMP	Environment temperature

Table 5 Component models encapsulated inside the pumping station subsystem model for the defined example

5.1.3 MOEEBIUS thermal network model

Thermal network system modelling is based, in the combination of the required instances of the defined MOEEBIUS loop/branch model.

With this approach, it is possible to model thermal network topologies with any level of complexity, including an arbitrary number of loops connected to the pumping station of the district heating, and an arbitrarily complex hierarchy of branches, connected to the main loops of the thermal network.

5.1.3.1 MOEEBIUS loop/branch model

This subsystem model encapsulates all the physical behaviour necessary to model the distribution thermal network of a district heating system. As a starting point, the defined model has been configured taking advantage of the physical component models available for district heating modelling, in the Modelica Standard library and in the Buildings library. When necessary, these component models have been upgraded to provide the required modelling capabilities, or adjusted to align them with the implemented subsystem oriented architecture approach.

Initially, two different models were studied to model the main loops of the thermal network, and the branches connected to them. However, taking into account that the pressure boundary conditions of each main loop are set in the pumping station model, the only difference between both models, was the optional character of the bypass in the hydraulic circuits defined as branches of the main loops.

For this reason, ultimately, the definition of a single loop/branch model provided enough flexibility to model the distribution thermal network of district heating systems of any complexity level.

The definition of the model allows flexibility and the automatic scalability of the physical components encapsulated within the subsystem model, through specific algorithms introduced in the Modelica code of the model. More specifically:

- The model supports an arbitrary number of load side connections on the defined hydraulic circuit (main loop or branch), to be introduced as an input by the user of the model. Each of these connections will be formed by a supply line outlet port and a return line inlet port.
- Models declared by the user as main loops will always include a bypass pipe at the end of the hydraulic circuit, whereas in the case of the models declared as branches, the presence of the bypass will be optional.

As in all the defined subsystem models, the connectivity of this model is the same as in the actual subsystem.

- Main distribution loop
  - Loop plant side connection inlet/outlet ports will be connected to the load side inlet/outlet ports of the main pumping station of the district heating system.
  - Each load side connection of the loop models can be connected, to the plant side connections of a branch, or alternatively directly to a thermal substation model. The substation model represents the energy request curve of one of the buildings connected to the thermal network.

- Branches.
  - Branch plant side connection inlet/outlet ports can be connected to one pair of the load side connection inlet/outlet ports of one of the main loops, or of one of the branches of a higher level in the branch hierarchy of the thermal network.
  - Each load side connection of the branch can be connected, to the plant side connections of a branch of a lower level on the branch hierarchy of the network, or alternatively, directly to a thermal substation model.

In the following picture all the physical component models encapsulated inside a loop/branch model are displayed, for a specific example of a loop with 3 pairs of load side connection ports.

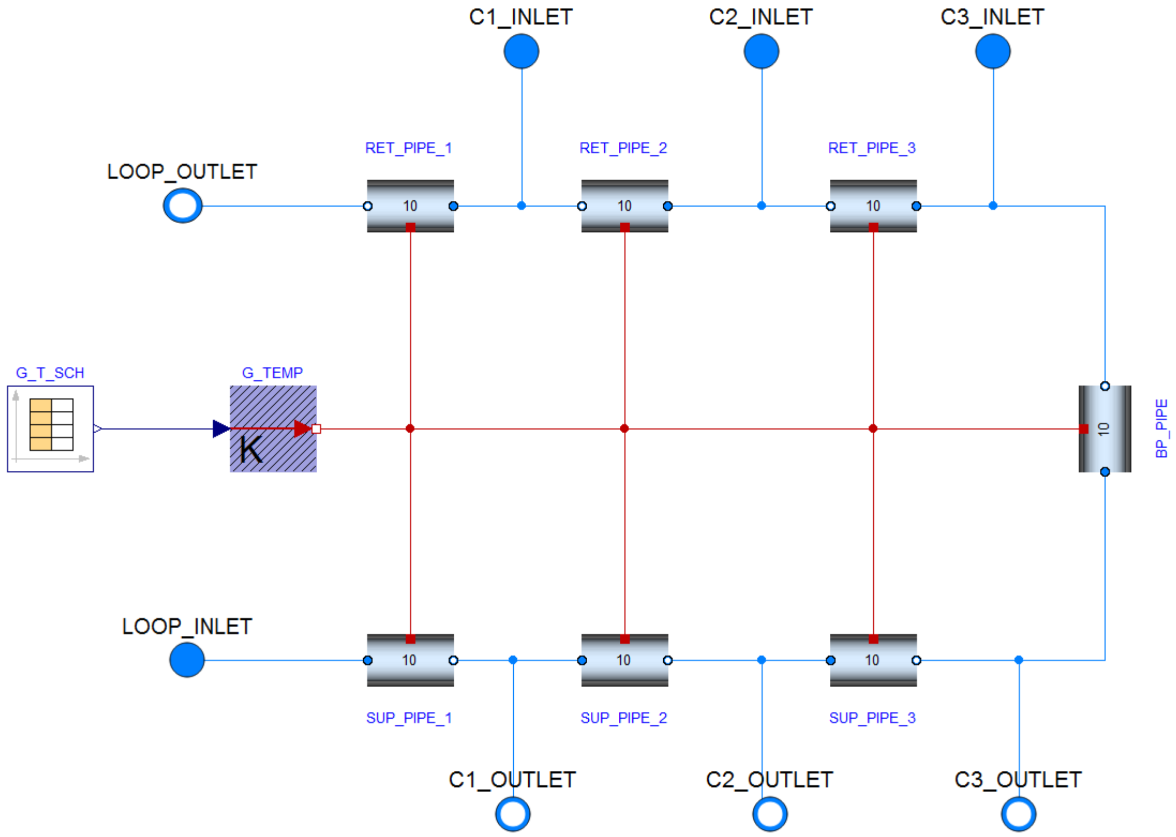

Figure 7 Connection scheme of the component models encapsulated within the Loop/branch subsystem model for the defined example

The loop model is connected to the load side inlet/outlet ports of the main pumping station of the district heating system through the plant side inlet port (LOOP_INLET) and the plant side outlet port (LOOP_OUTLET).

The impact of the pressure losses (linear and singular), and the distribution thermal losses to the ground between consecutive load side connections, is incorporated through a supply pipe and a return pipe component model (the user

is requested to supply a monthly schedule with the yearly evolution of ground temperatures).

In the following table, all the physical component models encapsulated within the loop model for the defined example are displayed.

Loop model	
Component name	**Description**
LOOP_INLET	Loop inlet port
LOOP_OUTLET	Loop outlet port
SUP_PIPE_1	Supply pipe 1
SUP_PIPE_2	Supply pipe 2
SUP_PIPE_3	Supply pipe 3
RET_PIPE_1	Return pipe 1
RET_PIPE_2	Return pipe 2
RET_PIPE_3	Return pipe 3
BP_PIPE	Bypass pipe
C1_INLET	Connection 1 inlet
C2_INLET	Connection 2 inlet
C3_INLET	Connection 3 inlet
G_T_SCH	Ground temperature schedule
G_TEMP	Ground temperature

Table 6 Component models encapsulated inside the Loop/branch subsystem model for the defined example

5.1.3.2 MOEEBIUS thermal substation model

This subsystem model encapsulates all the physical behaviour necessary to model a building thermal substation. This is the model that enables the integration of the impact of buildings in the MOEEBIUS district heating and DER model. As a starting point, the defined model has been configured taking advantage of the physical component models available for district heating modelling in the Modelica Standard library and in the Buildings library. When necessary, these component models have been upgraded to provide the required modelling capabilities.

The model has been designed, so that its connectivity rules reproduce those of actual building thermal substations. In the following scheme, the connections of the physical component models encapsulated inside the thermal substation model are displayed.

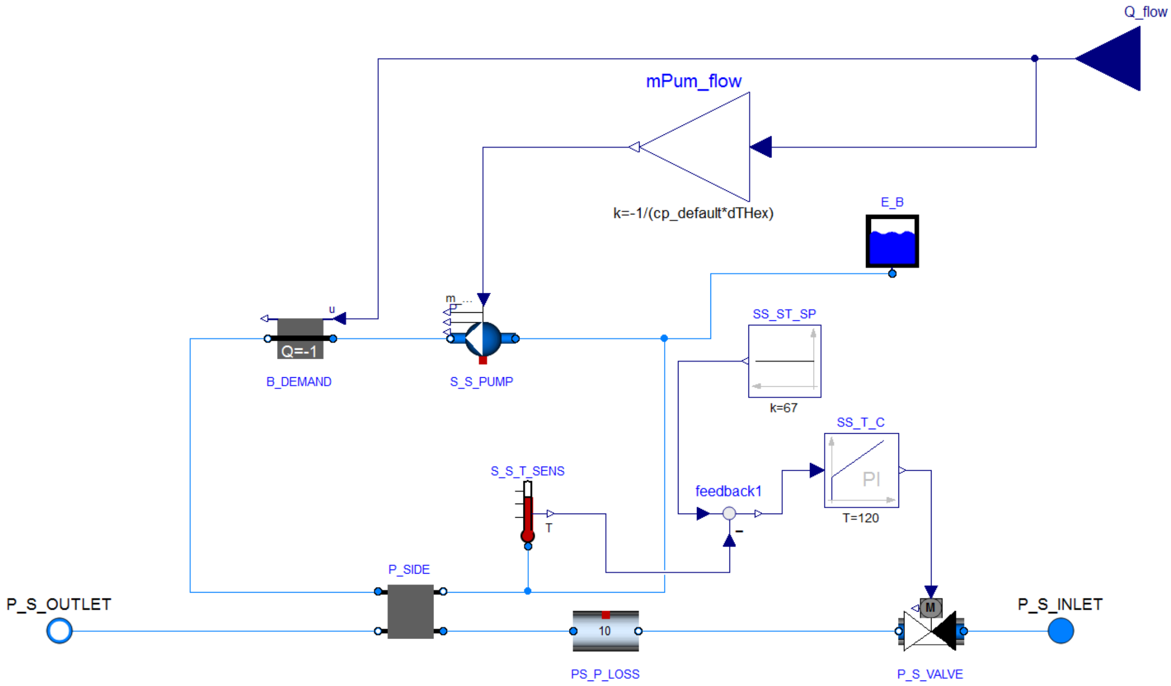

Figure 8 Connection scheme of the component models encapsulated within the thermal substation subsystem.

The primary side of the model of the thermal substation is connected to the thermal network, through the primary side inlet connection port (P_S_INLET) and the primary side outlet connection port (P_S_OUTLET).

The primary water inlet flow rate is controlled by a 2 way proportional valve (P_S_VALVE) deployed in the connection of the primary side inlet of the substation to the thermal network. The opening degree of the valve and the water flow rate on the primary side of the substation is adjusted by a specific controller, according to the evolution of the building thermal load profile, to meet the existing secondary side outlet temperature setpoint (SS_ST_SP). This setpoint value is an input provided by the user of the model.

The impact of the pressure losses produced in the primary side of the thermal substation (linear and singular losses excluding those corresponding to the valve and the primary side of the heat exchanger) are considered through a pipe component model (P_S_VALVE).

The demand on the secondary side of the thermal substation is modelled with an ideal pump (S_S_PUMP) and an ideal heat exchanger (B_DEMAND). This heat exchanger extracts the energy requested by the building from the water flow that circulates over the secondary side of the heat exchanger of the model (P_SIDE), that represents the heat delivery device of the actual building thermal substation.

The water flow rate on the secondary side of the substation is adjusted according to the evolution of the building thermal load profile, and to the temperature increase on the secondary side loop of the thermal substation.

The thermal load profile of the building is read from the Common Information Model Data Base of the MOEEBIUS platform. The temperature increase on the secondary side loop of the thermal substation can also be read from the data base, or alternatively, calculated from a secondary side water outlet temperature setpoint value, provided by the user of the model as an input (SS_ST_SP).

In the following, table all the physical component models encapsulated inside the building thermal substation model, are summarized.

Thermal substation	
Component name	**Description**
Q_flow	Thermal demand profile inlet port
S_S_PUMP	Secondary side pump
B_DEMAND	Building demand
P_SIDE	Primary side
P_S_INLET	Primary side inlet port
P_S_OUTLET	Primary side outlet port
PS_P_LOSS	Primary side pressure loss
P_S_VALVE	Primary side inlet valve
SS_ST_SP	Secondary side supply temperature setpoint
SS_T_C	Secondary side temperature controller
E_B	Secondary side expansion vessel

Table 7 Component models encapsulated inside the thermal substation subsystem model for the defined example

5.1.4 MOEEBIUS solar collector plant model

This subsystem model encapsulates all the physical behaviour of all the equipment typically deployed in a solar thermal collector plant. As a starting point, the defined subsystem model has been configured taking advantage of the physical component models available for solar thermal plant modelling in the Modelica Standard library and in the Buildings library. When necessary, these component models have been upgraded to provide the required modelling capabilities, or adjusted to align them with the implemented subsystem oriented architecture approach.

The definition of the model allows flexibility and automatic scalability of the physical component models associated to the solar field. This is enabled through specific algorithms introduced in the Modelica code of the model. More specifically:

- The solar field can be formed by an arbitrary number of collector batteries connected in parallel (to be provided by the user as an input).
- Each collector battery can consist on an arbitrary number of collectors connected in series (to be provided by the user as an input).

As in all the defined subsystem models, the connectivity of this model is the same as in the actual subsystem. Therefore, in order to optimize the efficiency of the plant and facilitate the delivery of its production, it will be connected to the return line of the thermal network. This connection can take place at main loop level or alternatively at any level of the defined branch hierarchy.

In the case of district heating systems operating with low supply temperature values (<50ºC), alternative connection arrangements could also be supported (connection to the supply line of the district or connection to the return and supply lines of the district).

In the figure below, the component models encapsulated within the thermal collector plant model for a specific plant with 2 parallel collector batteries is displayed.

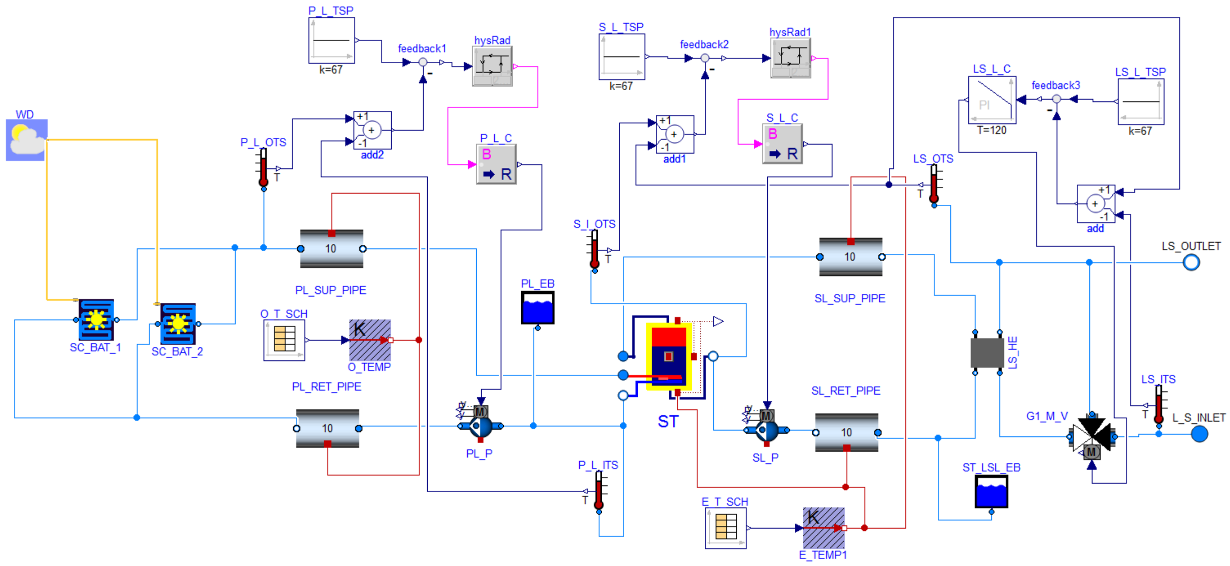

Figure 9 Connection scheme of the component models encapsulated within the solar collector plant subsystem model for the defined example

The plant model is connected to the thermal network through the load side inlet (L_S_INLET) port and the load side outlet port (LS_OUTLET). Additionally, the connection to the thermal network includes a bypass to be used when the value of the temperature of the water stored in the solar plant, is not high enough to ensure a successful energy delivery to the thermal network.

As in the case of actual plants, the model is formed by:

- A collector field formed, in this case, by two collector batteries (SC_BAT_1 and SC_BAT_2).
- A primary side hydraulic loop that connects the solar field with the solar storage system, including a pump to force the flow in this loop (PL_P).
- A storage system, in this case consisting on a single storage tank (ST).
- A secondary side hydraulic loop that connects the thermal storage system to the energy delivery heat exchanger of the plant (LS_HE), including a pump to force the flow in this loop (SL_P).

The impact of pressure losses (linear and singular) and the distribution thermal losses to the environment of the primary side loop is accounted for including 2 pipe component models (PL_SUP_PIPE and SL_RET_PIPE).

Equally, in the case of the secondary side loop, the impact of pressure losses (linear and singular) and distribution thermal losses to the solar plant room environment is considered through 2 pipe component models (SL_SUP_PIPE and SL_RET_PIPE). The used storage tank model also allows computing the thermal losses from the tank to the environment of the solar plant room.

Finally, shading on each of the collector batteries is considered through a shading coefficient, received as a specific input signal.

In the following lines the operational sequence of the solar collector plant model is described in a compact shape:

- The position of the load side connection 3 way proportional diverting valve (L_S_V), deployed in the connection to the thermal network, is adjusted to meet the secondary side loop temperature increase setpoint (S_L_TSP) in the energy delivery heat exchanger. The setpoint value is provided as an input by the model user.
  If the temperature of the hot water stored in the plant is not high enough to ensure an efficient energy delivery from the plant to the thermal network, the connection to the network is closed. In this situation the water flow takes place over the existing bypass.
- The status (on/off) of the constant flow rate secondary side pump is adjusted by a controller, to meet the desired temperature increase in the secondary loop of the energy delivery heat exchanger of the plant. If the temperature of the water stored in the plant is not high enough to ensure an efficient energy delivery from the plant to the thermal network, the pump is deactivated.
- The status (on/off) of the constant flow rate primary side pump is adjusted by a controller, according to the temperature increase provided by the solar field of the plant.

- If the temperature increase decreases below a specific valued provided by the user of the model, the pump is deactivated.
- If the temperature difference rises above a specific value provided by the user, the pump is activated.

In the table below, a summary of all the component models encapsulated inside the solar collector plant model is displayed for this specific example, with a solar field formed by 2 collector batteries.

Solar plant	
Component name	**Description**
SC_BAT_1	Solar collector battery 1
SC_BAT_2	solar collector battery 2
WD	Weather data
PL_SUP_PIPE	Primary loop supply pipe
PL_RET_PIPE	Primary loop return pipe
PL_EB	Primary loop expansion Vessel
PL_P	Primary loop pump
ST	Solar tank
SL_SUP_PIPE	Secondary loop supply pipe
SL_RET_PIPE	Secondary loop return pipe
SL_P	Secondary loop pump
LS_HE	Load side Heat exchanger
L_S_V	Load side valve
L_S_INLET	Load side inlet port
LS_OUTLET	Load side outlet port
O_T_SCH	Outdoors temperature schedule
O_TEMP	Outdoor temperature
SL_EB	Secondary loop expansion Vessel
P_L_TSP	Primary loop temperature increase setpoint
P_L_C	Primary loop controller
S_L_TSP	Secondary loop temperature increase setpoint
S_L_C	Secondary loop controller
LS_L_TSP	Load side loop temperature increase setpoint
LS_L_C	Load side loop valve controller
P_L_OTS	Primary loop outlet temperature sensor
P_L_ITS	Primary loop inlet temperature setpoint
S_l_OTS	Secondary loop outlet temperature sensor
LS_ITS	Load side inlet water temperature sensor
LS_OTS	Load side outlet water temperature sensor
E_T_SCH	Environment temperature schedule
E_TEMP	Environment temperature
ST_LSL_EB	Solar tank load side loop expansion vessel

Table 8 Component models encapsulated inside the solar collector plant subsystem model for the defined example

5.1.5 Auxiliary MOEEBIUS record classes

In this section the auxiliary record classes defined in order to facilitate physical component input data introduction are described in summarized way.

5.1.5.1 MOEEBIUS pipe specification

This class has been defined to allow a systematic introduction of the specifications of the pipe components encapsulated within all the defined subsystem models of the MOEEBIUS Modelica Library. Between others, this specification includes the following input data:

- Pipe insulation thickness.
- Pipe insulation thermal conductivity.
- Pipe inner diameter.
- Pipe Length.
- Pipe roughness.
- Nominal mass flow rate.
- Nominal lineal pressure drop.
- Pressure drop increase coefficient due to singular pressure losses

5.1.5.2 MOEEBIUS pump specification

This class has been defined to allow a systematic introduction of the specifications of the pump components encapsulated within several of the defined subsystem models of the MOEEBIUS Modelica Library. This specification includes the following input data:

- Nominal mass flow rate.

The curves that define the behaviour of the pumps (pressure drop, efficiency, power consumption, etc.) are introduced, through the record classes available in the Modelica Buildings Library.

5.1.5.3 MOEEBIUS heat exchanger specification

This class has been defined to allow a systematic introduction of the specifications of the plate heat exchanger components encapsulated within several of the defined subsystem models of the MOEEBIUS Modelica Library. Between others, this specification includes the following input data:

- Primary side nominal mass flow rate.
- Primary side nominal pressure drop.
- Primary side nominal heat transfer.
- Primary side nominal inlet temperature.
- Secondary side nominal mass flow rate.
- Secondary side nominal pressure drop.
- Secondary side nominal heat transfer.
- Secondary side nominal inlet temperature.

5.1.5.4 MOEEBIUS hot water boiler specification

This class has been defined to allow a systematic introduction of the specifications of the hot water boiler components encapsulated within the defined district

heating plant model of the MOEEBIUS Modelica Library. Between others, this specification includes the following input data:

- Nominal water outlet temperature.
- Nominal power output.
- Nominal mass flow rate.
- Nominal pressure loss.
- Fuel heating value (lower or upper depending on fuel).
- Fuel mass density.
- CO_2 emissions at combustion.

5.1.5.5 MOEEBIUS hot water boiler performance coefficient

This class has been defined to allow a systematic introduction of the performance curves of the hot water boiler components encapsulated within the defined district heating plant model of the MOEEBIUS Modelica Library. This specification includes the following input data:

- Coefficients of the performance curve of the hot water boiler.

5.1.5.6 MOEEBIUS storage tank specification

This class has been defined to allow a systematic introduction of the specifications of the storage tank components encapsulated within some of the defined subsystem models of the MOEEBIUS Modelica Library. Between others, this specification includes the following input data:

- Tank insulation thickness.
- Tank height without insulation.
- Tank volume.
- Heat exchanger nominal heat transfer.
- Nominal mass flow rate through the heat exchanger.
- Nominal pressure drop across the heat exchanger.
- Exterior diameter of the heat exchanger pipe.
- Nominal water tank temperature.
- Nominal water inlet temperature to the heat exchanger.
- Heat exchanger coil inside convective coefficient.
- Heat exchanger coil outside convective coefficient.

5.1.5.7 MOEEBIUS two way valve specification

This class has been defined to allow a systematic introduction of the specifications of the 2 way proportional valve components encapsulated within some of the defined subsystem models of the MOEEBIUS Modelica Library. This specification includes the following input data:

- Valve Kv.
- Nominal mass flow rate.

5.1.5.8 MOEEBIUS three way valve specification

This class has been defined to allow a systematic introduction of the specifications of the 3 way proportional valve components encapsulated within some of the defined subsystem models of the MOEEBIUS Modelica Library. This specification includes the following input data:

- Valve Kv value (from port 1 to port 2).
- Valve frakv value (kv from port 3 to port 2/kv from port 1 to port 2).
- Nominal mass flow rate.

5.1.5.9 MOEEBIUS solar collector specification

This class has been defined to allow a systematic introduction of the specifications of the solar collector components encapsulated within the solar plant model of the MOEEBIUS Modelica Library. Between others, this specification includes the following input data:

- Latitude.
- Surface azimuth.
- Surface tilt.
- Ground reflectance.
- Number of collectors in series.

The parameters that define the behavior of the collectors (gross area, fluid volume, mass flow rate per collector area, etc.) are introduced through record classes available in the Modelica Buildings Library.

5.1.5.10 MOEEBIUS steam boiler specification

This class has been defined to allow a systematic introduction of the specifications of the steam boiler components encapsulated within the district heating plant model of the MOEEBIUS Modelica Library. This specification includes the following input data:

- Total volume inside the drum.
- Mass of surrounding drum metal.
- Specific heat capacity of drum metal.

5.1.5.11 MOEEBIUS condenser specification

This class has been defined to allow a systematic introduction of the specifications of the condenser components encapsulated within the district heating plant model of the MOEEBIUS Modelica Library. Between others, this specification includes the following input data:

- Nominal steam mass flow rate.
- Nominal water mass flow rate.
- Nominal steam pressure.
- Nominal water pressure.
- Energy exchange surface between steam and metal.

- Energy exchange surface between water and metal.
- Steam volume inside the condenser.
- Water volume inside the condenser.
- Coefficient of heat transfer on steam side.
- Coefficient of heat transfer on water side.
- Number of tubes in parallel (shell and tube heat exchanger).

5.1.5.12 MOEEBIUS two way steam valve specification

This class has been defined to allow a systematic introduction of the specifications of the 2 way steam proportional valve components encapsulated within the district heating plant model of the MOEEBIUS Modelica Library. This specification includes the following input data:

- Nominal mass flow rate at full valve opening.
- Nominal pressure drop at full valve opening.

5.2 Electric DER forecasting models

The electricity DER models cover on-site generation for renewable energy sources. The model developed in EPIC-HUB[1] project for forecasting of PV energy generation will be enhanced by automatic tuning functionality. The model will be further extended to the needs of wind turbine (if available).

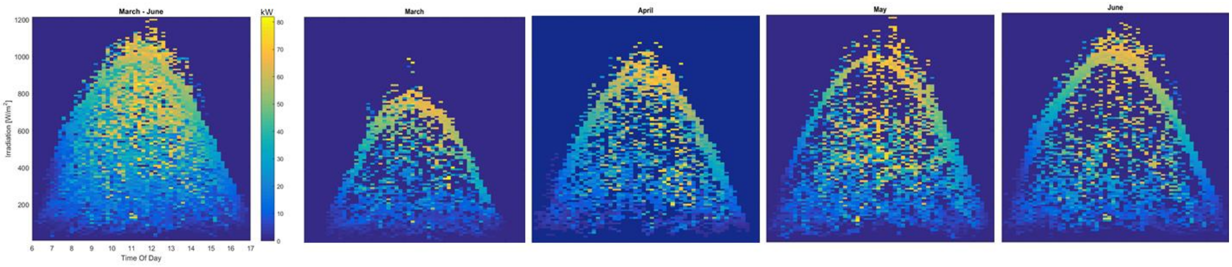

Figure 10 Power generation of PV unit (max value - yellow color is 82kW) for time period of March to June, followed by power generation for each month.

The fundament of all forecasts is modelling of a behaviour of a system. This solution is not focused on modelling of *dynamic* behaviour, but instead the concentration is made on *static* models. The model represents static relations between independent and dependent quantities. The Figure 10 visually illustrates the static relationship between three variables: Time of day, sun irradiation and electric power generation. The x-axis is time of day, the y-axis is irradiation of the sun and color represents actual energy generated by PV unit. The highest energy is generated between 11am to 2pm (in given example maximal energy is 82kW).

The power generation depend on other variables for instance the positions of the sun during the year, orientation of the solar panel. The model does not require to

[1] http://www.epichub.eu/ deliverable D6.2. Validation analysis

specify these extra parameters and learn the behavior from measured variables. The electricity gains are different through the year. Example can be viewed in Figure 10, where amount of energy generated for same irradiation value differs between months. If value of irradiation=800W/m^2, it result in power generation of 60kW in March (the peak value), but only 45kW in June. The forecaster is adopting online to the recent data (more details provided in section 5.2.1). The current model requires an expert to set up several parameters. The automatic calibration module will be developed for easy setup of the model on the current pilots.

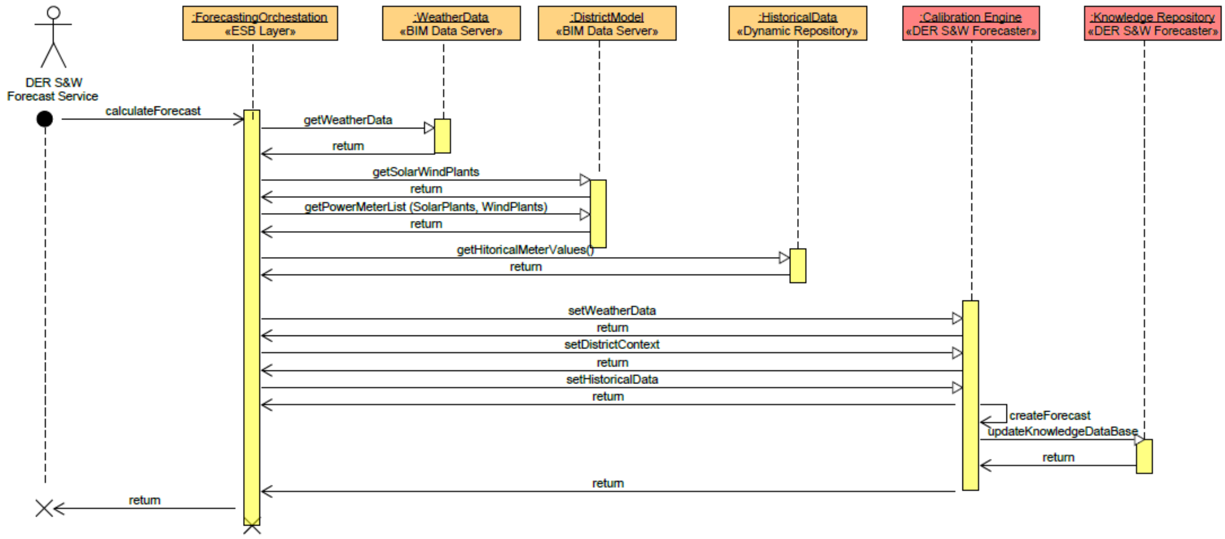

Figure 11 UML diagram of the forecaster

The forecaster module is depicted in Figure 11. The module can be called by other components of the system. It will run as WSO2 micro service and provide up to 24h ahead power generation forecast. The prerequisites for PV unit are

- Historical data points of weather forecast for sky cover, sun irradiation and data collected by meter at PV unit and wind turbine
- Data repository where the historical data will be saved
- Calibration engine that will tune the forecaster model based on history data
- Knowledge repository where the tuned parameters of forecaster will be stored

5.2.1 MOEEBIUS PV system model

The forecaster is a **memory based model** that fit the PV plant behavior for current working point based on relevant history. The Figure 12 illustrates behavior fitting for PV unit. The **model uses queries and historical data**. The queries data specifies the current working point and use following data points: date, time, weather forecast for sky cover and sun irradiation. The historical data contains same data points as queries data plus PV unit power generation. For each query data point a set of parameters must be tuned. All the parameters influence each

other, therefore a proper combination of the parameters is required. In current version of the forecaster model an expert select these parameters based on visual examination of the data. **In MOEEBIUS the expert will be replaced by calibration module that will search for all the parameters at once.**

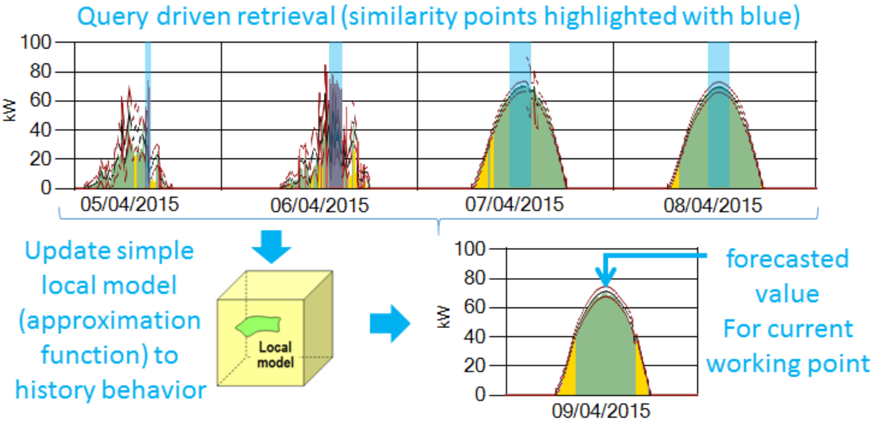

Figure 12 Memory based forecaster

The model is fed with the current query points. Based on the values of query points and defined parameters model selects similarity data points from the historical data. The selected similar data points transform the model to fit behavior of PV unit for current working point. The model provides the forecasted power generation P_F as follows

$$P_F \approx \begin{cases} P_{FU} = \min(\hat{P}_S + \hat{\sigma}_S,\ P_{MAX}) & \textit{upper boundary power} \\ P_{FM} = \hat{P}_S & \textit{forecasted mean power} \\ P_{FL} = \max(\hat{P}_S - \hat{\sigma}_S, 0) & \textit{lower boundary power} \end{cases}$$

where subscript S represents the set of similarity points selected for current working point, $\hat{P}_S$ represent the mean value of approximation function for given set of similarity data points, $\hat{\sigma}_S$ represent the standard deviation among the approximation function and similarity points. The P_{MAX} stands for maximal PV plant power generation (e.g. 100kW). The model for wind turbine will be same as the PV unit model. The main difference will be in data points collected, which will depend on data pilot availability.

5.2.2 MOEEBIUS forecaster model

The Figure 13 depicts the two main parts of the forecaster model: data retrieval and local approximation. Based on the query points and internal parameters of the model the relevant data are retrieved from the historical dataset. The retrieved data are joined into a vector $x(k)$ of independent variables – factors influencing

the prediction $y(k)$ for each discrete time instant *k*. Then the relation is estimated.

$$y(k) = f_N(x(k)) + e(k)$$

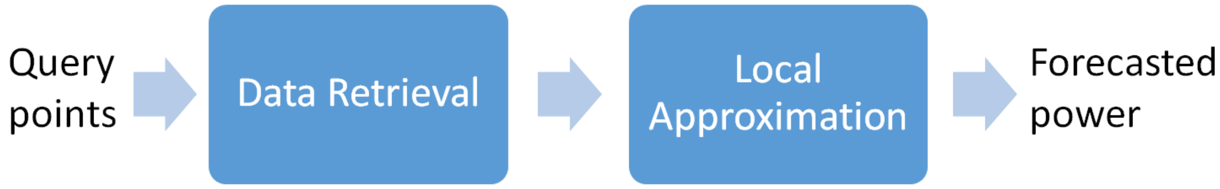

Figure 13 Forecaster model

Using data couples $\{y(k), x(k)\}$ observed in history *k = 1, … , N* The vector $x(k)$ include:

- Time related variables such as serial time, time of day, day of week, time of year, type of day (working/ holiday),
- Weather variables such as outdoor temperature, solar irradiation, wind velocity, wind direction, air humidity.

The vector $x(k)$ consists of

- Continuous components (variables) $x^c = \{x_1^c, x_2^c, \dots, x_{m^c}^c\}$ and
- Discrete (ordinal or symbolic) components (variables) $x^d = \{x_1^d, x_2^d, \dots, x_{m^d}^d\}$.

Discrete component may be e.g. day of week, holiday (Yes/No) or type of activity in the building. While the continuous variables are mapped on real intervals, $x^c \in R^{m^c}$, the discrete variables can be mapped on subsets of integer numbers $x_i^d \in I_i,\ i = 1,2, \dots, m^d$.

The identified model $f_N(.)$ is then used for estimation of future electricity generation for $k = N + 1$.

A natural choice for local approximation $y(k) = f(x(k))$ of a smooth function is a low order polynomial. To simplify the model a fitting function $f(.)$ was chosen as a sum of independent effects of continuous parts of the vector x^c

$$y(k) = f\left(x^c(k)\right) + e(k) = \alpha_0 + \sum_i^{m^c} \sum_j^{n^i} \alpha_{ij} \cdot \left(x_i^c(k)\right)^j + e(k)$$

Here index *k* denotes the time of the data point *x*, n_i is the order of the polynomial in x_i^c and α_0 , α_{ij} , $j = 1,2,\dots,n^i, i = 0,1,\dots,m^c$ are the unknown parameters.

This simplification allows to fit locally even strongly nonlinear mappings *f(.)* with satisfactory accuracy.

The model is linear in its parameters α_0 and α_{ij} , $j = 1,2,...,n^i$, $i = 0,1,...,m^c$. They can be estimated using locally-weighted least squares by minimizing the objective function $\left(\alpha_{0,} \left\{\alpha_{ij}\right\}_{i=0..m^c}^{j=1..n^i}\right)$:

$$F = \min_{\alpha} \sum_{k=1}^{N} \left[W(d(x, x(k)) \cdot \left(y(k) - f(\alpha, x^c(k)) \right)^2 \right]$$

where x is the target point for which the prediction y is to be computed, $\{y(k), x(k)\}$ are the stored pairs of data points, $W(.)$ stands for a kernel function, e.g. for Gaussian $W(d) = e^{-d^2}$ and d denotes a distance function $d(x, x(k))$ for continuous part $x^c$of x that satisfy

$$d(x - x(k))^2 = \sum_{i=1}^{n} d_i (x_i - x_i(k))^2$$

A typical distance for continuous variables is the Euclidean one

$$d(x^c - x^c(k))^2 = \sum_{i=1}^{m^c} \left(\frac{x_i^c - x_i^c(k)}{\gamma_i} \right)^2$$

where γ_i, $i = 1,...,m^c$ are smoothing parameters of the estimator.

For discrete variables the distance usually has no meaning. Yet, it may be sometimes defined if the 'distance' or similarity of situations has some sense. Otherwise categorical variables define separate standalone situations and are treated separately.

In literature, the above scheme has been presented in various contexts (e.g. locally-weighted smoothing, non-parametric regression, local learning, memory-based learning, just-in-time estimation). Implementation details are provided in **¡Error! No se encuentra el origen de la referencia.**.

5.3 Summary

In chapter 5, a detailed description of the models necessary to implement the generic **MOEEBIUS District Heating and DER Model,** as defined in chapter 4, has been provided.

Section 5.1 includes detailed information about the scope, capabilities and control strategies of the flexible and scalable subsystem models defined in Modelica. These subsystems models will enable modelling of the district heating and the

thermal DER systems deployed at district level, according to a subsystem oriented architecture.

Additionally, section 5.2 provides the description of the memory based electric production forecaster model to be used to evaluate the impact of the electric DER systems (PV and wind turbines) deployed at district level.

6 Conclusions

This deliverable documents all the activities carried out to develop the models necessary to provide the building and district level modelling capabilities required to produce building and district level predictions.

As a starting point, it has been described the most suitable procedure to develop the generic **MOEEBIUS District Heating and DER Model,** with the capacity to address district level infrastructure dynamics and energy production, through a co-simulation approach.

With this approach, each of the domains involved in district heating and DER modelling can be addressed with the modelling tool most suitable for each domain (EnergyPlus, Modelica and data based forecasting models).

Regarding building level DER modelling, the limitations existing in EnergyPlus to model the specific thermal loads existing in the swimming pool domain have been identified, and specific models developed to overcome them. Additionally, an overview of the implementation approach of these models, using the advanced EnergyPlus **Run Time Language** functionality, has been provided.

Regarding district modelling, going beyond the existing physical component oriented approach, the **MOEEBIUS District Heating and DER system Model** has been developed according to a subsystem model based architecture.

Additionally, district level electric DER-s production foresting models have been developed based on a data oriented approach. At the same time, for the thermal subsystems (loads, generation, storage and distribution), specific Modelica models have been defined reproducing the modularity and connectivity rules of each actual subsystem.

These models provide the required flexibility, scalability and the capability to define the typically existing district typologies, from the perspective of the deployed technologies, distribution topologies and operational strategies.

According to this approach, the generic **MOEEBIUS district Heating Model** can be adjusted to the boundary conditions existing on any specific district, combining the required subsystem models as necessary, to configure district heating models of any size, complexity and distribution topology.

Finally, with the developed Modelica models the **MOEEBIUS Modelica Library** has been produced.

Appendix A: Implementation of forecasting model

There are several questions that have to be resolved in practice: Amount of data retrieved, dimension of local approximating function and smoothing.

A.1 Data retrieval from local neighbourhood.

The Euclidean distance functions define ellipsoidal neighbourhood

$$d\left(x^c - x^c(k)\right)^2 = \sum_{i=1}^{n^c} \left(\frac{x_i^c - x_i^c(k)}{\gamma_i} \right)^2 <= C$$

Theoretically the constant *C* should be large so that the probability assigned to the searched neighbourhood would be close to 1. But even for moderate databases, such data retrieval would be time exhausting. A practically acceptable alternative is to substitute the local ellipsoid by a cube

$$x_i^c - 3\gamma_i \leq x^c \leq x_i^c + 3\gamma_i \;, \quad i = 1, \ldots, m^c$$

which defines a neighbourhood in the problem space constraining the processed data set. This applies to continuous variables x^c, where γ_i are smoothing parameters of the estimator and m^c defines dimensionality (number of variables). For discrete variables x^d the retrieval is done simply by specifying the class of interest (e.g., all holidays).

Memory based method reliability depends heavily on amount of data retrieved from the neighbourhood of forecasted point *x*. If the neighbourhood of *x* is too small, the query does not retrieve enough data points for a reliable forecast. If the neighbourhood is too large, the query returns unnecessarily many data points, which slows down the computation.

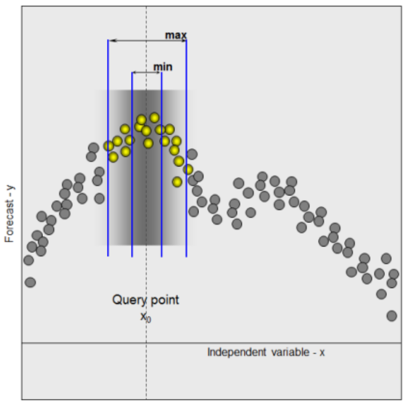

Figure 14 Schema of adaptation of neighbourhood to retrieve enough points.

Therefore some way of relating the number of retrieved points to the neighbourhood size is necessary. In current implementation it is used a neighbourhood size adaptation that is performed in each forecast. The first data

search is performed in a cube shaped neighbourhood using some constant. If not enough data is retrieved by the first query it is iteratively expanded until required number of points is obtained. The number of iterations is constrained - it may occur that not enough data for reliable forecast is available even in large neighbourhood. The Figure 14 illustrates the schema of expanding the neighbourhood in one dimensional case if the number of retrieved points is not sufficient.

A.2 Curse of dimensionality

When the dimensionality m^c of the problem space increases, available data become sparse as the volume of the space fast increases. The stored points are being 'dissolved'. This is problematic phenomenon for any method that requires statistical significance.

To obtain a statistically reliable result, the amount of needed data grows exponentially with the dimensionality. In high dimensional spaces all objects appear to be sparse and dissimilar in many ways which makes data processing strategies inefficient.

The required neighbourhood size depends highly on the dimension m^c of vector x^c. With increasing the dimension it is needed to increase adequately the neighbourhood size to get sufficient number of data. This effect, called 'curse of dimensionality', negatively influences the applicability of local regression method.

The need of higher number of points, that ensure the same level of accuracy in high dimensional problem space, can be addressed in two ways:

- First, the polynomials can be replaced in the local approximating function by other functions, like e.g. ridge basis functions or radial basis functions. The model becomes more global in scope but at the same time also non-linear in parameters. The data smoothing step thus consumes considerably more time compared with plain weighted least squares.
- Alternatively, the curse of dimensionality may be mitigated by selection of quite different smoothing parameters γ_i in different dimensions i. The variables that have a strong, nonlinear effect on the forecasted variable (such as time of the day in energy demand forecast) are fitted locally, i.e., using relatively small γ_i values. The variables that have not relatively small effect (like e.g. wind direction) are fitted using larger γ_i values.

A.3 Data smoothing

The data smoothing is affected by:

- The type of model, namely the orders n_i of approximating polynomials,
- The kernel type, namely by functions defining the distances $d_i\left(x_i, x_i^c(k)\right)$ for $i = 1,2,\dots,m^c$.

The distance functions for the continuous variables are dependent on smoothing parameters γ_i. The choice of γ_i; for each i is closely related to the choice of a local neighbourhood over which the data behaviour is fitted. When the neighbourhood is adapted to include enough data points, the smoothing parameters γ_i become a function of the required number N of data points. Intuitively, proper choice of n^i, γ_i, N should be found as a trade-of between retrieving enough data (to decrease the variance of estimation) and keeping the neighbourhood size small enough. Standard methods for balancing these values can be used in principle at every prediction step.

A.4 Summary

The memory based prediction method depends on parameters n^i, γ_i, N - polynomial orders, smoothing parameters and size of retrieved data set. The choice of their values significantly influences the quality of forecasting. Tuning of these parameters is typically done by an experienced expert. In MOEEBIUS tuning of these parameters will be performed automatically by an optimization module. The tuning procedure minimizes the aggregated deviation of the forecasts from known values of dependent variable. The known values for parameter tuning are obtained from all past known pairs of dependent and independent variable values using so called cross validation. Cross validation consists in dividing known data into two parts: one part is used for local regression, which is then applied on situations contained in the other part of data. The quality of forecast is evaluated using known values from the second set. Usually it is used a 'leave one out' cross validation approach, where the data, which serves for assessment of quality of the forecast, is only a single point.

If historical data, searched for similar situations in the past, are stored in a classical relational database, SQL query is used to retrieve data from the local cube. The data retrieval may be a bottleneck of the forecasting in case of computation of many forecasts is requested in a short time. To decrease the response time, it might be extracted a part of historical data from the main database and store it in a buffer, possibly placed in memory. Then the data retrievals are order of magnitude faster.