Flexi-Sync

Flexible energy system integration using
concept development, demonstration and replication

DESIGN FLEXIBILITY AND FLEXIBILITY CONSTRAINTS FOR OPTIMIZATION

VERSION 1.0

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EXECUTIVE SUMMARY

The report at hand is the deliverable D1.2. of work package WP1 of the Flexi-Sync project which summarizes how flexibilities on the design and planning level can relate to operational flexibility. The deliverable summarizes the results from task T1.3 which is defined as follows:

> *Task 1.3 is "Design for operational flexibility", in it the principles and aspects that need to be consider on the design stage to enable operational flexibility are considered. There will be an interaction with WP2 and WP3 to safeguard the applicability in these contexts.*

The deliverable describes an approach on how the design flexibility can be considered in the optimization problem for operational flexibility. It is also discussed how a simulation-based approach can be used to assess if design flexibility will violate operational constraints in production and distribution of heat or cold.

The results reported in D1.2 will be used in Task T1.2, and subsequently in WP4. The work has been conducted starting in M12 and concluded in M21.

The main conclusion is that the planning, design, and optimization of operation can be treated in a combined way such that a so-called co-design can be achieved for district heating and cooling (DHC) systems. By that bottle necks and limitations in the operation can be avoided and the overall equipment efficiency can be increased. Hence, a smart design approach is realized achieving a better performing DHC systems right from the start and a better integration of the engineering activities on all system levels supporting investment decisions.

CONTRIBUTION

Main contributors to the deliverable Khalid Atta and Wolfgang Birk from LTU. Further, the work on the optimization problem from T1.2 was performed by Maryam Razi (LTU). The interaction between the work packages and getting feedback on how to integrate the design aspects and climatic effects into the optimization problem was jointly done together with Vahid Nik (Chalmers), Érika Mata (IVL), and Dmytro Romanchenko (IVL).

1 INTRODUCTION

Flexibility in energy system has been studied for quite some time where concepts like demand response (DR) or automated demand response (ADR) are used to exploit the available energy flexibility to mitigate peak load events in the energy system. For a long time, the focus of study has been electrical grids, but more recently heating and cooling grids and the combination of both grid types have been studied.

The aim of T1.3 was to propose an approach on how to integrate the flexibility assessment, quantification, and exploitation on all system levels. The work therefore builds on the results reported in D1.1 and on the progress made on the optimization problem in T1.2.

1.1 Scope - Control and optimization of operation

The Flexi-Sync project has a wide scope when it comes to flexibility in district heating and cooling systems considering levels from planning and design down to low-level operation and consumer thermal comfort aspects. In Figure 1, a typical hiearchy is depicted explaining the interdependencies of the levels, where methodologies on the higher level use aggregated information from the lower levels and imposing boundary conditions on the lower levels. For each of these levels the typical time scales are given and the associated model types to represent the system behaviour are given.

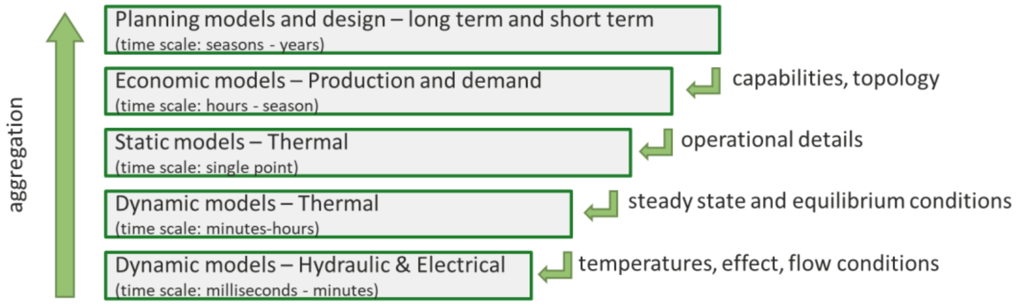

Figure 1: Hierarchical levels according to time scales and associated types of models used for representing the system, and for characterization and assessment of flexibility.

The scope of work package 1 is on control and optimization of operation, which is reflected in time scales up to hours and at most days, and thus only encompassing the lower levels. Moreover, the thermal grid, buildings and thermal storage are considered, alongside with wear and tear on components and economic aspects in terms of boundary conditions.

To characterize the available flexibility in a district heating/cooling system, models representing the system are needed. Depending on the time scale different types of models are used, as shown in Figure 1. Clearly, the time granularity and the primary source of information differ for the design, implementation, and operation of a solution that makes use of flexibility.

1.2 Organization of the report

The report is organized as follows. First, in section 2, an update of the optimisation problem is given as it has been developed further since D1.1 which enables the integration of the results from WP2, WP3 and WP5. Thereafter, it is explained how the results from WP2 and WP5 can be translated into constraints and parameters of the optimization problems in section 3. Finally, in section 4 it is described how the feasibility of the design flexibility from WP2 can be assessed from an operational optimization perspective.

The report will refer to the following deliverables of the Flexi-Sync project using their identifier D1.1 and D5.2:

- D1.1: Flexibility Characterization and Assessment Methodologies
- D5.2: Report on Maintenance Effects on Installed Flexibilities in Demosites

2 OPTIMIZATION PROBLEM FOR OPERATIONAL FLEXIBILITY

This section states the optimization problem and how flexibility can be quantified for operational optimization as it has been further developed from the deliverable D1.1 of work package 1.

Understanding the optimization problem and how it is structured is important for the integration of climate flexibility and design flexibility aspects in the optimization problem. The generic optimization problem as stated in D1.1 is given and its further development thereafter. In addition, the methodology to quantify the flexibility is given more in detail as it will be applied in the pilot site cases.

2.1 Generic setup of the Optimization Problem

For the sake of completeness of this report we will state the generic optimization problem again as a starting point.

In general, optimization of a dynamic system can be described by the following formula, like Arroyo et.al. (2018):

$$\begin{aligned} &\min_{u} Q(x, u, \theta_o, d_e) \\ &s.t. \qquad x^+ = f(x, u, \theta_s, d_e) \\ &\qquad\quad l_L \leq h_i(x, u, \theta_i, d_e) \leq l_U \\ &\qquad\qquad g_i(x, u, \theta_e, d_e) = 0 \end{aligned}$$

There, d_e represent the exogeneous inputs to the plant reflecting an external input to the problem, possibly measured or forecasted (e.g. outdoor temperature or energy prices), u respresent the control (actuation) signals, x denotes the states of the system (e.g. water or room temperature), $\theta_o, \theta_s, \theta_i$ and θ_e represent the parameters describing the system (e.g. the dimensions of the storage tank or the limits of the allowed temperature). The parameters vectors l_L and l_U represent the lower and upper bounds for the constrained vector valued function $h_i(x, u, \theta_h, d_e)$. Note that, the inequality constraints sometimes can be written as $h_i(x, u, \theta_h, d_e) \leq 0$. We write it in the above format to make it clear to the reader how flexibility is interpreted.

The equation $x^{+} = f(x, u, \theta_s, d_e)$ is a representation of the system dynamics in discrete time state space form. Alternatively, it can be represented in continuous time as $\dot{x} = f(x, u, \theta_s, d_e)$.

Note, all variables and parameters are time dependent and thus might change over time but for the sake of readability and simplicity, we dropped the time argument.

The optimizer or controller will find the operational state that minimizes the objective function(s) $Q(x, u, \theta_o, d_e)$, either single or multi objective, while not violating the constraints. These objectives can be, for example, the operational cost, the consumed energy, or the environmental impact.

2.2 Quantification of flexibility for operational optimisation

The quantification of flexibility can be stated as an optimization problem that exploit available flexibility. To integrate exploitation of flexibility in the optimization problem the operational limits for different components must be defined as constraints. Then, these constraints will be added to the optimization problem. Resultingly, the optimization problem solver will find the optimal solution that will utilize the defined limits (as constraints) and in turn exploits the available flexibility. Here, we propose an explorative and simulation-based approach to quantify the flexibility, by simulating the operation of the complete system.

To simplify the optimization problem, a unified higher-level flexibility should be used to describe the different system components. As explained earlier in D1.1, the higher-level representation of flexibility will yield a model that 1) is faster to execute, 2) captures the system dynamic at the appropriate time scale. Quantifying a certain flexibility, requires using real-life or simulated process data and elevate to a higher level.

This means if the optimization problem is stated in terms of energy then for example temperatures and water flows do need to be translated into energy.

The simulation-based procedure to quantify the flexibility has the following prerequisites

- A validated simulator that can describe the whole plant at both in terms of thermal and hydraulic behaviour, see Simonsson et. al. (2021) for summary of such a modelling and simulation approach.
- A realistic (validated) model that represents the component under consideration for flexibility quantification.
- A simplified model representing the component under flexibility consideration:
    1. At an appropriate timescale: the model should be simplified such that the time scale matches the optimization problem's timescale
    2. The physical parameters/variables should match the optimization problem variables (i.e. the model should be

described with the new level that match the optimization problem level)

- Historical data at the appropriate time scale.

When the prerequisites are fulfilled the following stepwise procedure can be applied

1. Integrate the component model within the simulator.
2. Simulate the overall plant with the recorded historical data.
3. Perform sufficiently many different simulations runs that cover most of the operating conditions of the plant. It needs to be noted that this can be an exhaustive task to perform and largely depends on the execution speed to feasible from an engineering perspective.
4. Collect the simulated data and transform the component related data into the level at which the optimization problem is realized (i.e. convert the water flow, temperatures, into energy as in the case that the optimization problem level is energy).
5. Filter and resample the data.
6. Use system identification principle based on the acquired data to identify the parameters of the simplified model.
7. From the simplified model, determine the limits of the model and deduce the parameters that quantify the flexibility of the component.

Remark: When deducing the parameters, one need to make sure that the simplified model is valid within the considered operating conditions. For example, the storage tank maximum charged energy and the maximum rates of the charge and discharge during different operating condition can be transformed into equality constraints that will describe the storage tank limits/ flexibility in the optimization problem. While the rate of energy loss due to the isolation of the tank represent the parameters of the model are restricting factors for the exploitation of the flexibility.

2.3 Pilot site adopted optimisation problem

In this section, the energy management optimization problem of a district heating and cooling system (DHCS) is stated. This system consists of energy generation, distribution, and consumption parts. In a DHCS, the thermal energy produced by generation units, including CHP units and boilers on the heating side and chillers on the cooling side, is carried by water medium in pipelines and pumped to primary heat exchangers. Then, it is delivered to consumers by secondary heat exchangers.

To state the problem, time is discretized with zero-order hold. For a chosen sampling interval Δt, discretization will give time instances $\tau = h\Delta t, h = 0, 1, \dots$. The optimization problem is formulated in a model predictive control (MPC) framework with a prediction horizon N. MPC is updated at every instant τ. The time instant along the prediction horizon of each update is represented by $t = \tau + k\Delta t, k = 0, 1, \dots, N-1$.

As mentioned in Section 2.1, system dynamics impose constraints on the optimization problem. Therefore, first, the DHCS model is given and then the objective function is presented.

2.3.1 Pipeline model

The model of distribution part in the DHCS includes energy balance and mass flow continuity equations in pipes and nodes. According to the first law of thermodynamic, the energy flowing into one node is equal to the energy flowing out, Gu et.al. (2017). Then,

$$\sum_{j\in S_{p,l}^{e,n}} Q_{p,j}^{out}(k+h|h) - \sum_{j\in S_{p,l}^{s,n}} Q_{p,j}^{in}(k+h|h) = 0. \tag{1}$$

The delay time of the temperature change at the outlet of every pipe is calculated as, Gu et.al. 2017 and Li et.al. (2020)

$$t_{delay,j}(k+h|h) = K_{delay}\frac{L_j}{v_j(k+h|h)}, \qquad j\in S_{ps}\cup S_{pr}. \tag{2}$$

To convert the delay time to the length of time interval in hour, $t_{delay,j}(k+h|h)/(3600\,\Delta t)$ is rounded up to $k_{d,j}(k+h|h)$. By considering the delay time and energy loss in pipes, thermal power at the outlet of pipes can be formulated by

$$Q_{p,j}^{out}\big(k+k_{d,j}(k+h|h)+h|h\big) = \big(1-\mu_{loss,j}L_j\big)Q_{p,j}^{in}(k+h|h), \quad j\in S_{ps}\cup S_{pr}. \tag{3}$$

Because of wear protection for the pipes, the thermal power change is limited to

$$\underline{\Delta Q}_p \le \Delta Q_{p,j}^{a}(k+h|h) \le \overline{\Delta Q}_p, \qquad a\in\{in,out\}, \quad j\in S_{ps}\cup S_{pr}. \tag{4}$$

To ensure stable operation of DHCS, the thermal power at the inlet and outlet of supply and return pipes on heating side of DHCS is bounded according to

$$\underline{Q}_{ps,h} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{ps,h}, \qquad a\in\{in,out\}, \qquad j\in S_{ps} \tag{5}$$

$$\underline{Q}_{pr,h} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{pr,h}, \qquad a\in\{in,out\}, \qquad j\in S_{pr}. \tag{6}$$

Similarly, the thermal power at the inlet and outlet of pipes on cooling side is limited as

$$\underline{Q}_{ps,c} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{ps,c}, \qquad a\in\{in,out\}, \qquad j\in S_{ps} \tag{7}$$

$$\underline{Q}_{pr,c} \le Q_{p,j}^{a}(k+h|h) \le \overline{Q}_{pr,c}, \qquad a\in\{in,out\}, \qquad j\in S_{pr}. \tag{8}$$

According to Kirchhoff laws, the balances of flow in nodes is expressed as, Gu et.al. (2017) and Zhou et.al. (2019)

$$\sum_{j\in S_{p,l}^{e,n}} m_{p,j}(k+h|h) - \sum_{j\in S_{p,l}^{s,n}} m_{p,j}(k+h|h) = 0. \tag{9}$$

Pressure loss in pipe j is formulated by

$$\Delta P_{p,j}(k+h|h) = \mu_{p,j} m_{p,j}^{2}(k+h|h), \qquad j\in S_{ps}\cup S_{pr}. \tag{10}$$

The total pressure loss in the pipes is equal to the pressure supplied by all pumps, Gu et.al. (2017),

$$\sum_{j\in S_{ps}\cup S_{pr}} \Delta P_{p,j}(k+h|h) = \sum_{i\in S_{pu}} P_{pu,i}\,(k+h|h). \tag{11}$$

The velocity of the medium in pipe j is proportional to its flow and inversely proportional to the diameter of the pipe and can be calculated by

$$v_j(k+h|h) = \frac{m_{p,j}(k+h|h)}{\rho\pi(d_{p,j}/2)^2}, \qquad j \in S_{ps} \cup S_{pr}. \tag{12}$$

2.3.2 Heat exchanger model

The thermal power in a primary heat exchanger is formulated as

$$\left(Q^{in}_{p,j_1}(k+h|h) - Q^{out}_{p,j_2}(k+h|h)\right) / \,\eta_{he,i} = Q_i(k+h|h),\ j_1 \in S_{ps,i},\ \ j_2 \in S_{pr,i}. \tag{13}$$

The continuity of medium in the heat exchangers imposes, Gu et.al. (2017)

$$m_{p,j_1}(k+h|h) = m_{p,j_2}(k+h|h), \qquad j_1 \in S_{ps,i},\ \ j_2 \in S_{pr,i}. \tag{14}$$

The thermal power in a secondary heat exchanger can be calculated as

$$\left(Q^{out}_{p,j_1}(k+h|h) - Q^{in}_{p,j_2}(k+h|h)\right)\eta_{he,m} = \sum_{i=1}^{N_{zm}} Q_{R,i}(k+h|h)\,, \qquad j_1 \in S_{ps,m},\ \ j_2 \in S_{pr,m} \tag{15}$$

Similarly, there is the continuity constraint on the secondary heat exchangers too.

2.3.3 Buildings model

The thermal network model of the building zones includes thermal resistance (R) and thermal capacity (C), which have the capability to transmit and preserve thermal energy, respectively. Different architectures of RC model can be considered, and the building model is aggregated by several similar structural zone, Li et.al. (2020), Arroyo et.al. (2018), and Jiang et.al (2018). Temperature change in a zone is expressed as

$$C_{z,i}\Delta T_{z,i}(k+h|h) = f\left(T_a(k+h|h), T_w(k+h|h), Q_{R,i}(k+h|h), Q_{rad,i}(k+h|h)\right)\Delta t. \tag{16}$$

The comfort requirement of aggregated buildings should be fulfilled. Then, the indoor temperature of buildings should be kept within the limits set by considering acceptable comfort,

$$\underline{T}_{z,i} \le T_{z,i}(k+h|h) \le \overline{T}_{z,i}. \tag{17}$$

Having a detailed model for the building enables the us to assess the effect extreme climate conditions as scenarios and how operational flexibility is affected. Such extreme climate conditions can be reflected in terms of the ambient temperature, but also wind speeds, air humidity, and solar irradiation.

In the currently suggested building model approach the ambient temperature T_a is available as a factor in (16). Analysing different climatic scenario will result in different levels of thermal energy that can be stored in the building mass and will affect the flexibility offered to the grid operation. Performing simulation-based what-if analysis for the projected climatic scenario will provide the needed insights on how extreme climate will disturb the operation of the current DHC system.

2.3.4 Thermal energy storage (TES) model

In the DHCS, thermal energy storages can be used for some reasons, e.g., peak shaving, and cost optimization, Vandermeulen et.al. (2018). The thermal power of TES is formulated by

$$\Delta Q_{s,i}(k+h|h) = \lambda_{s,i}\big(Q_{s,i}(k+h|h) - Q_{s0,i}\big) + \eta_{in,i} Q_{s,i}^{in}(k+h|h) - \frac{Q_{s,i}^{out}(k+h|h)}{\eta_{out,i}}. \tag{18}$$

Thermal powers in TES model are limited by following constraints

$$\underline{Q}_{s,i} \le Q_{s,i}(k+h|h) \le \overline{Q}_{s,i} \tag{19}$$

$$0 \le Q_{s,i}^{in}(k+h|h) \le \overline{Q}_{s,i}^{in} \tag{20}$$

$$0 \le Q_{s,i}^{out}(k+h|h) \le \overline{Q}_{s,i}^{out} \tag{21}$$

$$Q_{s,i}^{in}(k+h|h) Q_{s,i}^{out}(k+h|h) = 0. \tag{22}$$

The TES initial thermal power at the beginning of the time horizon is

$$Q_{s,i}(h-1|h-1) = Q_{0,i}. \tag{23}$$

2.3.5 Problem statement

The optimization problem objective is to minimize the thermal power production cost while taking account of the income from the electricity market.

$$\begin{aligned}
\min_{Q_i, u_i} \sum_{k=0}^{N-1} \Bigg(& \sum_{i \in S_{hG}} \alpha_i Q_i(k+h|h) + \sum_{i \in S_{ec}} \beta_{c,i}(k+h) Q_i(k+h|h) \\
& - \sum_{i \in S_C} \frac{\beta(k+h)}{\phi_i} Q_i(k+h|h) \\
& + \sum_{i \in S_G} \Big(\gamma_{on,i}\big(u_i(k+h+1|h) - u_i(k+h|h)\big) u_i(k+h \\
& + 1|h) \\
& + \gamma_{off,i}\big(u_i(k+h|h) - u_i(k+h+1|h)\big)\big(1 \\
& - u_i(k+h+1|h)\big)\Big) \Bigg) \Delta t \\
& + \sum_{i \in S_G} \Big(\gamma_{on,i}\big(u_i(h|h) - u_i(h-1|h-1)\big) u_i(h|h) \\
& + \gamma_{off,i}\big(u_i(h-1|h-1) - u_i(h|h)\big)\big(1 - u_i(h|h)\big)\Big) \Delta t
\end{aligned} \tag{24}$$

s.t.: (1) - (23)

$$u_i(k+h|h)\underline{Q}_i \le Q_i(k+h|h) \le u_i(k+h|h)\overline{Q}_i, \quad i \in S_G \tag{25}$$

$$Q_i(k+h|h) = Q_i^D(k+h|h) + \textstyle\sum_{j\in S_{hT}} \delta_{i,j} Q_{i,j}^s(k+h|h), \quad i \in S_{hG} \tag{26}$$

$$Q_i(k+h|h) = Q_i^D(k+h|h) + \textstyle\sum_{j\in S_{cT}} \delta_{i,j} Q_{i,j}^s(k+h|h), \quad i \in S_{ac} \cup S_{ec} \tag{27}$$

$$0 \le Q_i^D(k+h|h) \le u_i(k+h|h)\overline{Q}_i, \quad i \in S_G \tag{28}$$

$$0 \le \sum_{j\in S_{hT}} \delta_{i,j} Q_{i,j}^s(k+h|h) \le u_i(k+h|h)\overline{Q}_i, \quad i \in S_{hG} \tag{29}$$

$$0 \le \sum_{j\in S_{cT}} \delta_{i,j} Q_{i,j}^s(k+h|h) \le u_i(k+h|h)\overline{Q}_i, \quad i \in S_{ac} \cup S_{ec} \tag{30}$$

$$\sum_{i\in S_{hG}} Q_{i,j}^s(k+h|h) = Q_{s,j}^{in}(k+h|h) - Q_j^{rs}(k+h|h), \;\; j \in S_{hT} \tag{31}$$

$$\sum_{i\in S_{ac}\cup S_{ec}} Q_{i,j}^s(k+h|h) = Q_{s,j}^{in}(k+h|h), \;\; j \in S_{cT} \tag{32}$$

$$\begin{aligned}\sum_{i\in S_{hG}} Q_i(k+h|h) \\ &= Q_{h,dem}(k+h|h) + Q_{h,loss}(k+h|h) \\ &+ \sum_{i\in S_{hT}} \Big(Q_{s,i}^{in}(k+h|h) - Q_i^{rs}(k+h|h) \\ &- Q_{s,i}^{out}(k+h|h)\Big) + \sum_{i\in S_{ac}} Q_i(k+h|h)\end{aligned} \tag{33}$$

$$\begin{aligned}\sum_{i\in S_{ac}\cup S_{ec}} Q_i(k+h|h) \\ &= Q_{c,dem}(k+h|h) + Q_{c,loss}(k+h|h) \\ &+ \sum_{i\in S_{cT}} \Big(Q_{s,i}^{in}(k+h|h) - Q_{s,i}^{out}(k+h|h)\Big)\end{aligned} \tag{34}$$

$$\begin{aligned}\underline{\tau}_{on,i}\big(u_i(k+h|h) - u_i(k+1+h|h)\big)u_i(k+h|h) \\ &\le \left(\sum_{n=0}^{k} u_i(n+h|h)\Delta t\right) u_i(n+h|h) \\ &+ \left(\sum_{n=\tau_{1,i}}^{h-1} u_i(n|n)\Delta t\right) u_i(n|n), \quad i \in S_G\end{aligned} \tag{35}$$

$$\begin{aligned}\underline{\tau}_{off,i}\big(u_i(k+1+h|h) - u_i(k+h|h)\big)\big(1-u_i(k+h|h)\big) \\ \le \left(\sum_{n=0}^{k} \big(1-u_i(n+h|h)\big)\Delta t\right)\big(1-u_i(n+h|h)\big) \\ + \left(\sum_{n=\tau_{2,i}}^{h-1} \big(1-u_i(n|n)\big)\Delta t\right)\big(1-u_i(n|n)\big), \quad i \in S_G\end{aligned} \tag{36}$$

$$\begin{aligned}r_{u,i}\Delta t \le \big(P_i(k+1+h|h) - P_i(k+h|h)\big)u_i(k+1+h|h)u_i(k+h|h) \\ \le r_{d,i}\Delta t, \quad i \in S_C\end{aligned} \tag{37}$$

$$\begin{aligned}r_{u,i}\Delta t \le \big(P_i(h|h) - P_i(h-1|h-1)\big)u_i(h|h)u_i(h-1|h-1) \le r_{d,i}\Delta t, \\ i \in S_C\end{aligned} \tag{38}$$

where $P_i = Q_i/\phi_i,\ i \in S_C$, and $\underline{\tau}_{on,i}/\Delta t$ and $\underline{\tau}_{off,i}/\Delta t$ are rounded down to $\tau_{1,i}$ and $\tau_{2,i}$, respectively.

Remark: If penalties for starting up and shutting down unit i are equal, i.e. $\gamma_{on,i} = \gamma_{off,i} = \gamma_i$, then the second and third terms in the objective function can be replaced with $\gamma_i\big(u_i(k+1+h|h) - u_i(k+h|h)\big)^2$.

The equality constraint (33) can be replaced with

$$\begin{aligned}Q_{h,dem}(k+h|h) + Q_{h,loss}(k+h|h) + \sum_{i\in S_{hT}} \big(Q_{s,i}^{in}(k+h|h) - Q_i^{rs}(k+h|h)\big) \\ - \sum_{i\in S_{hT}} \min\big(\hat{Q}_{s,i}^{out}(k+t|t), \overline{Q}_{s,i}^{out}\big) + \sum_{i\in S_{ac}} Q_i(k+h|h) \\ \le \sum_{i\in S_{hG}} Q_i(k+h|h) \\ \le Q_{h,dem}(k+h|h) + Q_{h,loss}(k+h|h) \\ + \sum_{i\in S_{hT}} \min\big(\hat{Q}_{s,i}^{in}(k+t|t), \overline{Q}_{s,i}^{in}\big) - \sum_{i\in S_{hT}} Q_{s,i}^{out}(k+h|h) \\ + \sum_{i\in S_{ac}} Q_i(k+h|h)\end{aligned} \tag{39}$$

where $\hat{Q}_{s,i}^{out}$ is thermal power of TES i inserted in DHCS where $Q_{s,i}(k+h|h) = \underline{Q}_{s,i}$, i.e. TES is fully discharged and $\hat{Q}_{s,i}^{in}$ is power inserted in TES i where $Q_{s,i}(k+h|h) = \overline{Q}_{s,i}$, i.e. TES is fully charged. Similarly, constraint (34) can be replaced with

$$\begin{aligned}Q_{c,dem}(k+h|h) + Q_{c,loss}(k+h|h) + \sum_{i\in S_{cT}} Q_{s,i}^{in}(k+h|h) \\ - \sum_{i\in S_{cT}} \min\big(\hat{Q}_{s,i}^{out}(k+t|t), \overline{Q}_{s,i}^{out}\big) \le \sum_{i\in S_{ac}\cup S_{ec}} Q_i(k+h|h) \\ \le Q_{c,dem}(k+h|h) + Q_{c,loss}(k+h|h) \\ + \sum_{i\in S_{cT}} \min\big(\hat{Q}_{s,i}^{in}(k+t|t), \overline{Q}_{s,i}^{in}\big) - \sum_{i\in S_{cT}} Q_{s,i}^{out}(k+h|h)\end{aligned} \tag{40}$$

In (17), the comfort bounds are relaxed to

$$\underline{T}_{z,i} - \epsilon_i(k+h|h) \leq T_{z,i}(k+h|h) \leq \overline{T}_{z,i} + \epsilon_i(k+h|h) \tag{41}$$

where $\epsilon_i(k) \geq 0$ can be random numbers, e.g. uniformly distributed random numbers.

If the optimization problem is not subject to buildings model and their temperature, then the flexibility can be considered as

$$\underline{Q}_{R,i} \leq Q_{R,i}(k+h|h) \leq \overline{Q}_{R,i}. \tag{42}$$

2.3.6 Approach to solving the optimization problem

The optimal energy management of the DHCS is a mixed-integer and nonlinear program. To solve this problem, an MPC can be employed. In MPC algorithms, at every time instant $\tau = h\Delta t$, an objective function is minimized, and the set of future control inputs at $t = \tau + k\Delta t, k = 0, 1, \ldots, N-1$ is calculated. Then, the first optimal value of the sequence is applied, and the horizon is displaced towards the future.

The DHCS optimal control presented in the previous section aims to minimize cost of energy production while considering the thermal energy storages, thermal inertia of buildings, and delay time in pipelines. This problem is solved at every time instant, and the optimal on/off state of thermal energy generation units and optimal power produced by them are obtained.

3 CONSIDERING DESIGN FLEXIBILITY

Design flexibility is determined during design time and planning time of a DHC system and thus, occurs and a longer time scale than the time scale at which the optimization of operation occurs. It needs to be further noted that the design and planning addresses future scenarios that might include the current DHC system or being a further development of it. Hence, the design will determine the boundary conditions and would need to be translated into the constraints and parameters of the optimization problem for the operation.

The design of the DHS will dimension production units, thermal storages, and pipe characteristics of the distribution system. Further, the thermal characteristics of buildings will also be affected by the design. These characteristics and dimensioning numbers will enter the optimization problem as constraints and parameters. Those will not only enable a more flexible operation but could at the same time impose fundamental limitations that cannot be circumvented and render performance limitations of the DHC system.

The constraints and parameters will now be related to the problem statement given in section 2.3.

3.1 Production units

There are currently two types of units considered: CHP plant or heating/cooling plant. While a CHP plant is a more complex units that is also determining for what end the energy is used, a heating or cooling plant will have a sole purpose.

Those boundary conditions will be characterized by the lower and upper bound of the energy that can be produced as $\underline{Q}_i$ and $\overline{Q}_i$ in (25) and (28), respectively. From a design perspective the upper bound will be given, but from an operational and plant design perspective a lower bound is usually imposed as there is a minimal production level for such a plant.

For the CHP plant there is also a ratio factor in place that determines the ratio ϕ between production of electricity and heat. From a design perspective, there might be a constraint available on that factor, but is not considered here.

3.2 Distribution

Usually, the distribution is characterized by dimensioning numbers relating to the pipes and the placement. These numbers are needed to build the correct system model for the operational optimisation and might not be known from the planning phase directly but will be determined during the design phase of the plant.

Note, the pipe dimension will impose a fundamental limitation on the flow characteristics and will limit the achievable performance for the distribution.

Along with the result described in D5.2 on the pipe wear it is possible to impose constraints on the allowed fluctuations in the pipes. Such a wear protection factor is chosen is introduced as $\underline{\Delta Q_p}$ and $\overline{\Delta Q}_p$ in (4). If this aspect is deemed neglectable, the constraint can be removed from the optimisation problem.

3.3 Buildings

From a design and planning perspective, the thermal storage capacity of the building mass is offering flexibility. In addition, the thermal comfort range of the residents over time is also an important factor in terms of flexibility, but it is not design or planning related.

The thermal capacity $C_{z,i}$ in (16) of the comfort zones[1] i need to be determined from a design and planning perspective in the future scenarios. Depending on the degree of aggregation in the design and planning, this parameter needs to be decomposed to the correct level of detail.

3.4 Thermal Energy Storages

A thermal energy storage can be both charged and discharged and the main limiting factor is the energy $\overline{Q}_s$ that can be stored, but there can be a lower limit as well denoted $\underline{Q_s}$. The constraint is given in (19) and will be determined at the design and planning stage.

Further, for the TES there might be constraints on the ability to charge or discharge during a certain timeframe which is determined by operational and plant design

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[1] Comfort zones should not be confused with the thermal comfort range of a resident. A comfort zones is a space in the building where a certain desired temperature set point is defined or set.

characteristics. Such constraints might be considered during the design and planning but could be unconstrained. These performance limitations are given by $\overline{Q}_s^{in}$ and $\overline{Q}_s^{out}$ in (20) and (21), respectively. Such constraints are directly affecting the ability to make use of available flexibility from an operational perspective.

4 FEASIBILITY ASSESSMENT OF DESIGN FLEXIBILITY

Design flexibility is the result of an optimisation that is performed using the TIMES modelling approach to optimize energy systems on a city or regional scale over long term (years). The work is conducted within WP2 and results in a suggestion for a design of an energy system in terms of its components and their dimension. The approach does not use detailed models reflecting the operation and dynamic behaviour of the energy system, i.e. the DHC system. While the result is used for design and planning activities, it does not guarantee that the foreseen performance can be achieved or the foreseen flexibilities in the system can be exploited in real life.

The operational optimisation determines the short-term operation with respect to thermal but also hydraulic aspects of the DHC system. This is achieved using city-scale dynamic simulation models that reflect the real-life system or in case of a green-field the not-yet realized system. Nowadays, such a solution is also referred to as a digital twin. A review of the topic and experiences from city-scale simulation projects are summarized in Simonsson et. al. (2021).

The following prerequisites need to be available to perform the feasibility assessment of design flexibility:

- Dynamic simulation model reflecting the complete system capable of simulating the hydraulic and thermal aspects with a time granularity of at least one second.
- Realisation of the optimisation and control scheme for simulation
- Time series data reflecting different operational scenarios in terms of the exogenous inputs. Exogenous inputs are independent variables in the models that can be freely chosen. Those are usually consumer demands, ambient climate conditions, operational conditions, economic and environmental aspects.
- Simulation environment enabling the integration of the system model and the optimisation and control model with scenario-based exogenous time series data.
- Set of constraints and parameters translated from the design and planning activities which are needed in accordance with sections 2.3 and 3.
- Set of metrics that evaluates the performance of the DHC system using simulation data and comparing it with the foreseen performance from the design and planning stage.

The assessment can now be performed in the following way

1. The different operational scenarios are simulated, and the performance metrics are assessed.
2. During the simulation operational constraints of components in the DHC system should not be violated. Those constraints are the following only to mention some:
    a. Pump speed constraints
    b. Pressure and flow constraints in pipes
    c. Temperature constraints in boilers and storage tanks
    d. Volume constraints in storage tanks
3. If a violation occurs, it needs to be understood if the realized optimisation and control scheme it too aggressive and can be adapted to reduce violations or if these violations are acceptable. Acceptable means that the performance metrics from above a still fulfilled and components would remain unharmed.

If the assessment is successful, it is likely that the design and planning stage has achieved a design flexibility which can also be expected to be achieved in the real-life system.

5 NEXT STEPS

Now that a formal approach is established to integrate the design and planning activities with the operational optimization with respect to flexibility, there are some natural next steps.

To simplify the interaction with the design and planning the parameters for the constraints in the optimization problem can be collected in a list or database and then can be exchange between the activities. During the final months of WP1 this list or database will be established and then used jointly within WP4 and WP2.

The optimization problem will be further developed within T1.2 and then transferred to WP4 for realization and evaluated during the pilot studies. The work with the pilot cases in Mallorca and Berlin will also aid in understanding the limitations of the proposed methodology.

The methodology, when validated in the simulated case of the city in Luleå, will be reported as a key exploitable result. The methodology will comprise the statement of the optimization problem its solution as well as the assessment and quantification of the operational flexibility.

ABBREVIATIONS

Abbreviation	Explanation
ADR	Automated demand response
CHP	Combined heat and power
DC	District cooling
DH	District heating
DHC	District heating and cooling
DHCS	District heating and cooling system
DHS	District heating system
DR	Demand response
MPC	Model predictive control
RC	Thermal resistance and thermal capacitance
TES	Thermal energy storage

NOMENCLATURE

Symbol	Unit	Description
$\underline{a}$ / $\overline{a}$	unit of a	minimum/maximum values of each parameter a
$C_{z,i}$	kJ/°C	thermal capacity of zone i
$d_{p,j}$	m	diameter of pipe j
h	h	time instant
K_{delay}	-	thermal delay coefficient of the pipelines
L_j	m	length of pipe j
$m_{p,j}$	kg/s	mass flow rate in pipe j
N	-	prediction horizon
N_{zm}	-	the number of buildings in substation m
P_i	kW	electricity power produced by CHP unit i
$P_{pu,i}$	Pa	pressure supplied by pump i
$\Delta P_{p,j}$	Pa	pressure loss in pipe j
$Q_{c,dem}/Q_{h,dem}$	kW	total demanded thermal power on cooling/heating side of DHCS
$Q_{c,loss}$	kW	total thermal power loss on cooling side of DHCS
$Q_{h,loss}$	kW	total heat loss including heat loss on heating side of DHCS and in absorption chillers
Q_i	kW	thermal power produced by energy generation unit i
Q_i^D	kW	thermal power inserted in DHCS by unit i
$Q_{i,j}^s$	kW	thermal power inserted in TES j by unit i
Q_j^{rs}	kW	heat inserted in TES j by other heat sources, e.g. data centers
$Q_{p,j}^{in}$ / $Q_{p,j}^{out}$	kW	thermal power at the inlet/ outlet of pipe j
$Q_{R,i}$	kW	thermal power required by aggregated buildings i
$Q_{rad,i}$	kW	solar irradiation for aggregated buildings i
$Q_{s0,i}$	kW	thermal power of TES $\boldsymbol{i}$ at which its loss is zero
$Q_{s,i}$	kW	thermal power of TES $\boldsymbol{i}$
$Q_{s,i}^{in}$	kW	thermal power inserted in TES $\boldsymbol{i}$
$Q_{s,i}^{out}$	kW	thermal power of TES $\boldsymbol{i}$ inserted in the DHCS

Symbol	Unit	Description
$r_{u,i}$ / $r_{d,i}$	kW/h	ramp up / down rate of the CHP unit i
S_{ac}	-	set of absorption chillers
S_C	-	set of CHPs
S_{cT}	-	set of cold storages
S_{ec}	-	set of electric chillers
S_G	-	set of thermal energy generation units
S_{hG}	-	set of heat generation units including CHPs and boilers
S_{hT}	-	set of heat storages
$S_{p,l}^{s,n}/S_{p,l}^{e,n}$	-	set of pipes starting/ending at node l
S_{ps} / S_{pr}	-	set of supply/return pipelines
$S_{ps,i}$ / $S_{pr,i}$	-	set of supply/return pipes connected to heat exchanger i
S_{pu}	-	set of pumps
T_a	°C	ambient temperature
T_w	°C	vector of walls temperatures
$T_{z,i}$	°C	indoor temperature of zone i
$t_{delay,j}$	s	transmission delay time in pipe j
Δt	h	Sampling time
u_i	-	on/off state of unit i
v_j	m/s	velocity of medium in this pipe
α_i	EUR/kWh	cost of heat production by heat generation unit i
β	EUR/kWh	electricity price
$\beta_{c,i}$	EUR/kWh	cost of thermal energy production by electric chiller i
$\gamma_{on,i}$/ $\gamma_{off,i}$	EUR/h	penalties for starting up/shutting down unit i
$\delta_{i,j}$	-	binary parameter that is 1 if unit i is connected to the TES j and is 0 otherwise,
$\eta_{he,i}$	-	efficiency of heat exchanger i
$\eta_{in,i}$ / $\eta_{out,i}$	-	charging / discharging loss factor of TES $\boldsymbol{i}$
$\lambda_{s,i}$	-	loss factor of TES $\boldsymbol{i}$
$\mu_{loss,j}$	1/m	thermal power loss coefficient of pipe j
$\mu_{p,j}$	1/(mkg)	pressure loss coefficient of pipe j
ρ	kg/s	medium density
$\underline{\tau}_{on,i}$/ $\underline{\tau}_{off,i}$	h	minimum duration of time for which unit i must be kept on/ off
ϕ_i	-	heat to power ratio of CHP unit i

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