Algorithmic optimisation of a building plant system

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Abstract. Using a practical example, the heat and cold storage volume of a building plant system is analyzed and optimized using tools integrated in the simulation software IDA ICE. In practice, the simulation models must be partially simplified for efficiency reasons. The level of detail of the storage tanks should be chosen in such a way that the temperature behavior of the simplification corresponds as closely as possible to the behavior of a non-simplified model. Hence, the required findings can be obtained from the simulation and optimizations can be carried out efficiently. The investigation showed that certain model simplifications are legitimate and that the optimization tools in IDA-ICE can be used reasonably for different tasks of an overall optimization.

1. Introduction
Gruner Roschi AG has the HVAC, electrical and plumbing planning mandate for a total renovation of two large service buildings with a net floor area of 40'000 m² in Zurich. The retrofitting began in summer 2019. Based on a detailed system energy simulation in the simulation tool IDA ICE, the heating and cooling systems were designed, and the district heating connection and cooling machine dimensioned. Based on this useful energy simulation, a model of the thermal-energetic system was constructed. All important components were mapped in IDA ICE to analyze their operation and interrelations in detail. The main components of the system are the chiller, the free cooling system, the recooling system, the district heating connection and the heat and cold storage tanks. Added to this are all consumers such as domestic hot water, air heaters and coolers as well as room heating and cooling. For the simulation, simplifications were made. The aim of the optimization reported in this paper is to optimally distribute the storage volume of 105 m³ to the heat and cold storage to reduce the electrical energy required for the chiller as much as possible. The total storage volume of 105 m³ is fixed, as there is no more space available.

Even today, although computer-aided dimensioning has long been possible, the design of thermal-energetic plants is still largely based on empirical values and static calculation methods. Simulations in general offer many advantages that previous working methods cannot. The dynamics of the elements within the system, their interplay and the processes acting on the system are ideally determined by a simulation. This enables the simulation engineer to show the planner which dynamics occur in the system and if necessary how to deal with them. The larger knowledge of a thermal-energetic system, which is generated through the simulation, can be used to optimally dimension system components, to test the effectiveness of innovative ideas or to determine the limits of the system. The optimization of thermal-energetic systems in buildings contributes to more energy-efficient buildings by identifying improvement potentials and taking them into account as early as the planning phase.
2. Methods
This chapter gives information about IDA ICE and shows the procedure for optimizing the storage volume.

IDA ICE is a simulation program of the Swedish software manufacturer EQUA. It is an innovative, detailed, dynamic and validated simulation program for the assessment of indoor climate and energy consumption of entire buildings [1].

Since IDA ICE version 4.8, four different analysis and optimization tools are available: Parametric runs, GenOpt, Sensitivity Analysis and Monte-Carlo. Parametric runs can be used to conduct parameter studies and GenOpt to optimize the system with selected parameters to specific targets. Sensitivity analysis can be used to investigate extreme values of selected parameters. With Monte-Carlo, the selected parameters can be randomly varied within the specified range. Parametric runs, GenOpt and Monte-Carlo combined with multiple linear regression analysis are used to optimize the storage volume.

2.1 Optimization with IDA ICE and GenOpt
IDA ICE communicates with the GenOpt optimization software via text files. Various optimization algorithms can be used in GenOpt [2]. Two suitable algorithms for optimizing problems in IDA ICE are Particle Swarm Optimization and Generalized Pattern Search (GPS) [3] [4]. The combination of these well-known optimization algorithms enables reliable and fast results. The optimization methodology can be used cost-efficiently even in the conflicting areas of a planning and engineering office. The use of algorithms for the automatic optimization of plant systems as an integrated step in a planning process has hardly been used so far. The goal of this approach besides optimizing the system is to detect problems possibly occurring during operation even before the start of construction. Finding the optimum for the investigated system used to require between 250 and 300 simulations in IDA ICE. This corresponds to a simulation time of approximately 24 hours with the investigated plant model and existing hardware. For use in an engineering office, faster optimization is desirable. However, for this study, the duration of the optimization is sufficiently short and was therefore not further improved. In the future, the optimization time can be shortened by using different algorithms or more powerful computers. Parametric runs and GenOpt are used to find the best parameter values for the system. To optimize the storage volumes in a short simulation time, various simplifications are made. These are explained in more detail in the chapter "Models in IDA ICE".

2.2 Models in IDA ICE
For the simulation in IDA ICE the simplifications explained below are made. Two simplifications are examined in two steps to gain comparable results. The aim of these investigations is to find out which simplifications can be made in a simulation model to still obtain realistic results. The simplifications are shown graphically in Figure 1 using the example of the cold storage. The system has a cold and heat storage volume, both connected to the system parallel to the discharge. In reality, the total volume of these two storages consists of several individual tanks with water flowing in series. The total installed storage volume is 105 m³. In a first step, the influence of the connection type is investigated using the example of the cold storage tank. To reduce the modelling effort, the model should be as simple as possible, but nevertheless represent the real process.

![Figure 1. Simplifications in the models](image-url)
In the real system, the storage volumes have a bypass. Therefore, only the excess amount of water from the chiller, flows into the storage tank. In the simplified model, this bypass is neglected and only one storage tank is simulated. The flow of the chiller is connected directly to the storage tank, forcing the entire mass flow through the storage. This simplification means that more water flows into and out of the storage compared to the realistic connection. The investigation will show whether the simplified model conducts more or less energy to further storage layers than the detailed model. The focus of this investigation lies in the comparison of the energy flows. The second investigation aims to find out whether it is legitimate to represent a series circuit with only one single storage. The total storage volumes are connected to the system with a bypass as in the previous study and thus build on the previous study. The simplified model has only one tank, in which each storage layer represents a single storage tank in the series connection. It is to be shown whether the tanks in series behave differently than the layers of a single storage tank. The focus of this investigation lies on the storage temperatures. In both models thermal losses to the environment are neglected.

3. Results
This chapter summarizes the influences of the simplifications and the optimization results.

3.1 Storage connection
The effect of the connection type on the heat and cold storage is examined in more detail here using the example of cold storage. Figure 2 shows the mass flow into the storage tank in the model with the bypass as planned for the real system. Figure 3 shows the mass flow into the storage tank with the simplified piping without bypass. The mass flows in and out of the cold storage differ from each other due to the different connection types. In the simplified model, where the mass flow of the water always flows through the cold storage tank, the mass flow is up to four times greater than in the model with the detailed connection type. Table 1 shows the results of the simulations. The figures clearly show how the simplification of the storage connection affects the energy flows into and out of the cold storage. The pump control in the refrigeration and heating circuits is mainly responsible for the occurring effects. The pump control depends on the storage management and cooling machine. The pump control is very important for a realistic representation of the thermal-energetic system.

| Heat flow in cold storage | Heat flow out cold storage | vertical heat flow through cold storage |
|--------------------------|----------------------------|----------------------------------------|
| 194%                     | 194%                       | 92%                                    |

Table 1. Energy flows of the cold storage tank with simplified connection compared to the detailed type of connection.

Figure 2. Mass flow in cold storage with detailed connection type

Figure 3. Mass flow in cold storage with simplified connection type
Although the simplified connection means that almost twice as much cooling energy flows into and out of the cold storage, the cooling energy, which moves vertically through the storage layers, drops by 8%. The type of connection also causes the storage temperatures to deviate from each other. Especially in summer, when high mass flows are needed for cooling, different layer temperatures can be observed.

3.2 Series connection and number of storages
The example of the heat storages illustrates how the series connection affects the temperature behaviour in the storage compared to the model with a single storage tank. In the cold storage a similar temperature behaviour can be observed, but the effect is less pronounced. The series connection only makes a small difference energetically. In the model with a single storage tank, 3.1% more heat was stored than in the comparable model with twelve storage tanks. This corresponds to an energy quantity of 4'000 kWh under the same conditions, which is only about 0.5% of the waste heat of the chiller. The temperatures in the storage tanks show a larger difference. Especially, when fewer storage layers are simulated, the layer temperatures from the simplified model diverge from those in the more detailed model. The higher the number of layers in the storages, the smaller the deviation becomes. Even with the same number of layers in the simplified model and in the detailed model, a small deviation between the two models is visible in the uppermost storage layer.

3.3 Optimization results
The following two graphs show how storage volumes affect the most influenced system components and variables in the system. The cold storage volume mainly influences the running time of the chiller in the lowest stage. The lowest stage is the most efficient and should therefore be in operation for as long as possible. With a smaller cold storage volume, the running time of the chiller in the lowest stage decreases and the average cooling performance increases (Figure 4).

Compared to the cold storage volume, the volume of the heat storage tank does not have a strong influence (Figure 5). The most influenced energy variable is the used waste heat from the chiller. It is higher for large heat storage volumes than for small ones. Since more of the total waste heat is stored in the heat storage, less waste heat must be removed through recooling. The total storage volume of 105 m³ is optimized with GenOpt, so that the electricity requirement for the chiller is minimal. In another optimization, recooling is minimized for comparison. Table 2 shows the optimum storage volumes and the lowest values for the power requirement of the chiller.

The ideal storage volume can vary depending on the selected target variable. As an example, the cooling energy of the chiller and the recooling energy are investigated here, since it was expected before the investigation that these two variables would be influenced by the storage volume distribution. The recooling energy proved to be unsuitable for defining the storage volume. For the minimization of the recooling energy, a larger heat storage volume was expected than that resulting from the optimization. As the investigation shows, the recooling energy is mainly dependent on the freecooling energy brought

![Figure 4. Influence of the cold storage volume on the running time and cooling performance of the chiller](image1)

![Figure 5. Influence of the hot water storage tank volume on the waste heat utilised](image2)
into the system, which optimally has a small cold storage volume, as it can be used more frequently by the control system. By minimizing the recooling energy, the freecooling energy is actually maximized and the heat storage volume is designed accordingly. Overall, the minimization of the recooling energy achieved the smaller improvement of both target functions. Designing the storage volume on the basis of the cooling energy of the chiller is the better choice in this study, as an overall better result was achieved.

| Table 2. Optimization results |
|------------------------------|
| **Volume [m³]** | **Energy [kWh]** |
| **Target size** | **Cold storage** | **Heat storage** | **Chiller cooling** | **Recooling** |
| Cooling energy chiller | 74/105 | 31/105 | 714'441 | 524'509 |
| Recooling energy | 52/105 | 53/105 | 719'013 | 525'927 |

4. Discussion

4.1 Connection type

Although the simplified connection type leads to almost double the amount of cooling energy passing through the lowest and uppermost layers of the cold storage, the energy through the intermediate layers drops by 8%. How much water and thus also cold or heat is led through a storage tank depends on the model, but in reality, also, on the charge and discharge of the storage. The storage serves as a compensation tank. If the supply of the chiller is higher than needed by the user, water is forced into the storage. In the opposite case, water is discharged from the storage tank. The difference between the two models is due to the different charging and discharging mass flows caused by the different connection types to the system and adapted pump control of the detailed model to execute it. The pumps of the chiller were transferred to a separate control circuit. They are now solely dependent on the cooling performance of the chiller, which is switched on if the cold storage is almost empty. This corresponds better to the system actually planned. For the sake of simplicity, the pumps in the simplified model were controlled in proportion to the cooling power consumed by the buildings. Variables of the control were not included in the optimization with GenOpt.

This also changes the charging and discharging of the storage tanks. Further investigations showed that the pump controls affected the difference even more than the connection type. Since the pump control also had to be adapted for the investigation of the connection type, it can be assumed that the differences between the two models are due to this.

To optimize the storage volume, the simplified model is further used, but the pump control is transferred to the optimization model to get closer to the principle scheme of the planner.

4.2 Series connection

A single heat storage, which represents several heat storages in series, shows differences in temperature behavior compared to the detailed model with several tanks. The more layers the individual storage tank has, the smaller are the differences. Especially in the top layer differences between the two models can be identified. Even with the equivalent number of layers, differences are visible. Whether these differences are still relevant, for example, for a study of the efficiency of chillers, still needs to be examined. But for very sensitive investigations, it is advisable to model nine storages instead of just one with the equivalent number of layers. Since no relevant differences were observed for the energetic storage volume optimization, the optimization was done with the simplified model.

4.3 Optimization results

When dividing the total storage volume of 105 m³ into heat and cold storage tanks, a good overall result is achieved when the cold storage tank is 74 m³ and the heat storage tank is 31 m³ in size. With this the chiller operates most efficient. By minimizing the cooling energy, approx. 4.5 MWh less cooling energy is obtained from the chiller. The minimization of recooling resulted in a reduction of only approx. 1.5 MWh recooling energy. An additional benefit is less waste heat from the chiller, which means less recooling is required. The negative effect of the system needing more heat due to the smaller amount of
waste heat being available from the chiller did not occur. This is due to the relatively small storage tanks in relation to the size of the system. The heat storage is almost always saturated. A smaller amount of waste heat therefore has a direct impact on recooling. The results of minimizing the recooling energy show that the heat storage must be larger than the cold storage to reduce recooling. Nevertheless, this optimization resulted in a smaller improvement compared to the optimization of the chiller cooling energy. The amount of recooled heat was higher when the recooling energy was used as the target variable to minimize compared to when the chiller cooling energy was used as the target variable. This is due to their correlation in the system, since the amount of recooled heat mostly depends on how much freecooling energy can be brought into the system. GenOpt chose storage tanks that allow as much free cooling as possible, but neglected the cooling energy of the chiller, which also reduces recooling. This led to an optimization of the freecooling energy instead of the cooling energy which in the end produced worse results.

4.4 The target variable for optimizing

The choice of the best target variable for optimizing the storage volume proved to be difficult. Because only one target variable can be optimized with GenOpt, it must be chosen carefully and thoughtfully. Due to the relationships occurring in the system, a seemingly suitable target variable may give a less good optimization result than the choice of another, less suitable target variable. It is essential to check whether the best simulation results can be achieved with the target function used. To do this, several optimizations must be made and compared. The use of Monte-Carlo in combination with multiple linear regression analysis is well suited to check this without high simulation effort. Alternatively, a target variable can be created which contains all the values to be investigated and, if necessary, evaluates them. This was not done in the context of the present investigation. The present example shows, however, that such a target value could lead to the desired optimization faster and more effectively.

4.5 Conclusion

For purely energetic optimization, the type of connection and series connection can be simplified in the model. As the simulation results show, the stored heat or cold is mainly determined by the mass flows in the storage. These are mainly influenced by the control logic of the pumps in the system and should correspond as closely as possible to the control logic of the planner for realistic simulations. The type of connection and number of storage tanks only have a minor influence on the stored heat or cold compared to the control of the pumps. The temperature in the cold storage is influenced by the connection type especially in summer, when higher mass flows stream into the storage. The temperatures in many tanks with a series connection deviate from the temperatures of a single tank representing the same storage. The more layers the single storage tank has, the closer it is to the temperature behavior of the storage tanks in series connection. Even with the same number of layers, there are still temperature differences in the upper layers. For investigations in which the temperatures in the storage tanks are decisive, it is therefore recommended to use the detailed models. Algorithm-based optimization resulted in storage volumes in the expected range. This investigation showed that the optimization of a plant model cannot be carried out even with automated processes without adequate knowledge of the system. Depending on the nature and behavior of the system, limits must be set for the parameters used in the simulation. This work must still be entered manually before optimization and adjusted in several passes.

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