# Modelica Models as Integral Part of the Building Design Process

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## Abstract

The design process of buildings and energy supply systems consists of several steps with increasing accuracy and decreasing fault tolerance. Because of a wide range of unknowns and increasing complexity, Modelica models are often an integral part of the first design steps. However, there are only rare updates and reuse of these models in later phases and/or during building use.

This paper emphasizes the potential of a continuous update and use of available Modelica models during all steps of building design processes. It therefore regards an example of a research greenhouse building for which the initially developed Modelica models were continuously updated and reused during the final phase of intensive scientific monitoring. Furthermore, general insights in latest scientific approaches indicate suitable steps of partly-automated continuous model updates during the whole building life span using BIM (Building Information Modeling).

*Keywords: Building Simulation, Monitoring, BIM Integration, Integral Design Processes*

## 1 Introduction

The building sector already represents one of the main fields of application of numeric simulation models. Especially, Modelica models therefore provide easy-to-use interfaces, a lively user community and a great variety of suitable toolsets and libraries. With its interdisciplinary physical modeling approach, Modelica enables engineers in many planning sections to analyze the cross-section behavior and influences of different system components, especially in the energy system with its HVAC and power supply units and a complex building control. Here, Modelica exploits its advantages in fast and accurate modeling of complex non-linear differential algebraic equation systems which are in this case caused by cross-domain system dependencies, volatile renewables availability and state-dependent storage behavior.

The design process of both newly constructed and retrofitted buildings follows an extensive, hierarchically-structured planning and implementation procedure which consists of three general phases and nine steps.

Figure 1: Steps of German building design process (Sommer, 2016)

It starts with a brief design description and variant analysis (c.f. P1 & P2 in Figure 1) which were followed by the development of all relevant planning documents and the permission process (c.f. P3 in Figure 1).

A second phase (c.f. P4 to P7 in Figure 1) adds detailed evaluations and design plans which are then the base of the final construction (c.f. P8 & P9 in Figure 1). In case of complex designs and/or new design approaches, a certified engineering entity (i.e. university, engineering office) uses the available measurement data in a final two to three year monitoring phase to evaluate resulting system efficiency and possible optimization measures. This monitoring phase is basically part of P9 but actually represents a separate design process step.

If engineers decide to use Modelica models during this design process, their implementation normally starts in phase P2 to get initial design feedbacks. These models are then continuously updated during phase P3 regarding the increasing level of detail and required accuracy of results. However, further updates are not usual. The models remain at the P3 level and will mostly no longer be a part of later evaluations.

This is obviously not efficient as these models include a high amount of the engineering knowledge which partly gets lost when they won't be refined and reused. A better design process would take the models as basis of design knowledge (c.f. BIM – Building Information Modeling) and would align them as an integral part of the overall planning process. Therefore, they can be the device-under-test (i.e. DuT) of the final building controller evaluation or something comparable describing the reference behavior during the final monitoring phase.

## 2 Building Example

Building and energy system models based on the Modelica modeling language and derived libraries are mostly necessary to solve complex design decisions, like storages and renewables dimensioning or optimal control strategies. An exemplary building design process which addresses all of these challenges regarding the construction of a new research greenhouse building in the city center of Leipzig, a major city in East Germany. As a center of biological research, scientists and students of the University of Leipzig will use it to identify and evaluate effects of global warming on indigenous vegetation, and to perform further research relevant experiments (e.g. Craven et. al. 2019).

The first planning phases began in 2014 with some basic discussions of the main goals as well as preliminary design developments, c.f. 3D sketch of later building within the surrounding public park (GEFOMA, 2014). The building owner decided in the early stages to highlight high energy efficiency and low carbon footprint as major design goals besides versatile research equipment and restrained park integration.

During the first design steps, several solutions were discussed to cope with these challenges. Greenhouse buildings are commercial buildings with significant requirements on cooling power. The cooling system design was therefore recognized as important at an early design stage. Variant analysis showed that a partly solar-powered cooling system might have the best chance to meet the challenging goal of +50% carbon dioxide emissions reduction. Existing funding regulations required a mathematical verification of these potentials.

Because of the system complexity and the non-standard greenhouse building type, suitable models became necessary. They should describe both the cross-linked interaction of building and planting as well as the energy supply system partly including renewable cooling, heating and power supply. Furthermore, these models had to provide a sufficiently accurate comparison of the planned energy efficient design approach and a comparable reference solution.

A number of different greenhouse building simulation platforms and solutions were available (e.g. Rodríguez et. al., 2002). Even specific Modelica libraries have been developed since then (e.g. Altes-Buch et. al., 2019). However, Modelica models based on SimulationX and the Green City library were chosen to handle these challenges. The customized models developed - including a brief discussion of results - were already described in Schwan et. al, 2015.

Figure 2: 3D digital mockup of the greenhouse building (GEFOMA, 2014)

All considerations and evaluations with the models of 2015 considered just the first design phase - including steps 1 to 3 in Figure 1. In a usual model-aided design process, the developed models would not be used or updated within the following design phases or even during the following building lifespan. However, this design process was different as the planned building included complex requirements on building use as well as sophisticated solutions of energy supply and building construction.

Nevertheless, the existing funding regulations demanded a long-term monitoring phase at the beginning of the use of the building. This monitoring phase includes both the evaluation of high-resolution measurement data of resulting system efficiency, as well as the proposal of

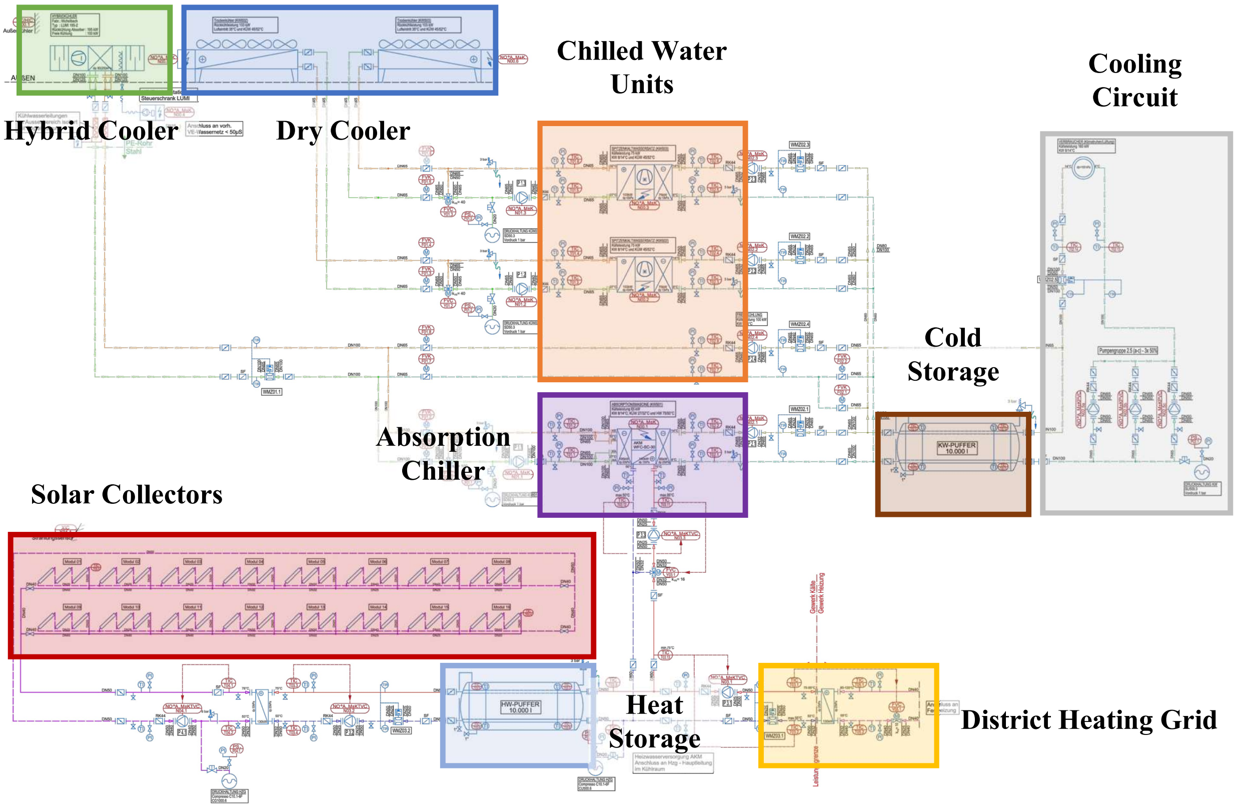


Figure 3: Cooling system concept at design step P2 (GEFOMA, 2014)

optimization measures. For both, the developed models are still necessary. On the one hand, the reference building model provides a source of comparison to evaluate the resulting carbon footprint savings. On the other hand, an updated model which is calibrated and enriched with available measurement data can provide further insight regarding alternative and optimized system solutions and control strategies. This is especially necessary if the monitoring indicates optimization potential which needs to be evaluated in detail regarding several suitable solutions prior to final real-world tests.

## 3 Continuous Model Refinement

To become an integral part of the building design process, Modelica models need to be refined continuously during the whole process as well as during the whole building life span in case of significant changes. This work effort considers on the one hand the model updates regarding increasing release versions of Modelica language and the simulation environment. The greenhouse building design process started in 2014 and ended in 2020 which included an update for Modelica from version 3.3 to 3.4 as well as several updates of SimulationX from version 3.6 to 4.1.

On the other hand, there are several evaluation steps of assumptions, accuracy tolerances and levels of detail between the different phases and design process steps. This often causes significant changes of the initially developed models depending on the design progress as well as the feedback to model requirements.

The first phase of the considered greenhouse building design process required Modelica models of both the energy supply system and the building including the crops. This was necessary to evaluate both savings potential from an improved building envelope and a better shading system as well as an increased environmental energy use via solar cooling. In later design phases, especially during the monitoring phase, the implemented cooling system model became more important. Monitoring data was then used to calibrate the model components and control, and to represent the building loads of cooling power consumption.

This paper focuses on the development steps and use of the cooling system model and neglects any simultaneous progress of building or heating system models. Therefore, Figure 3 shows the initial cooling system concept at design step P2 (c.f. Figure 1).

This concept described a bivalent cooling power supply by an absorption chiller and two peak-power chilled water units. The thermal compressor used solar heat from two types of solar collectors and heat from the local available district heating grid as a heat source to provide basic cooling power. A hybrid cooler is used as the recooler, which always ensures a recooling temperature of less than 27°C. It furthermore produces additional cooling power via free cooling in times of cold outdoor temperatures.

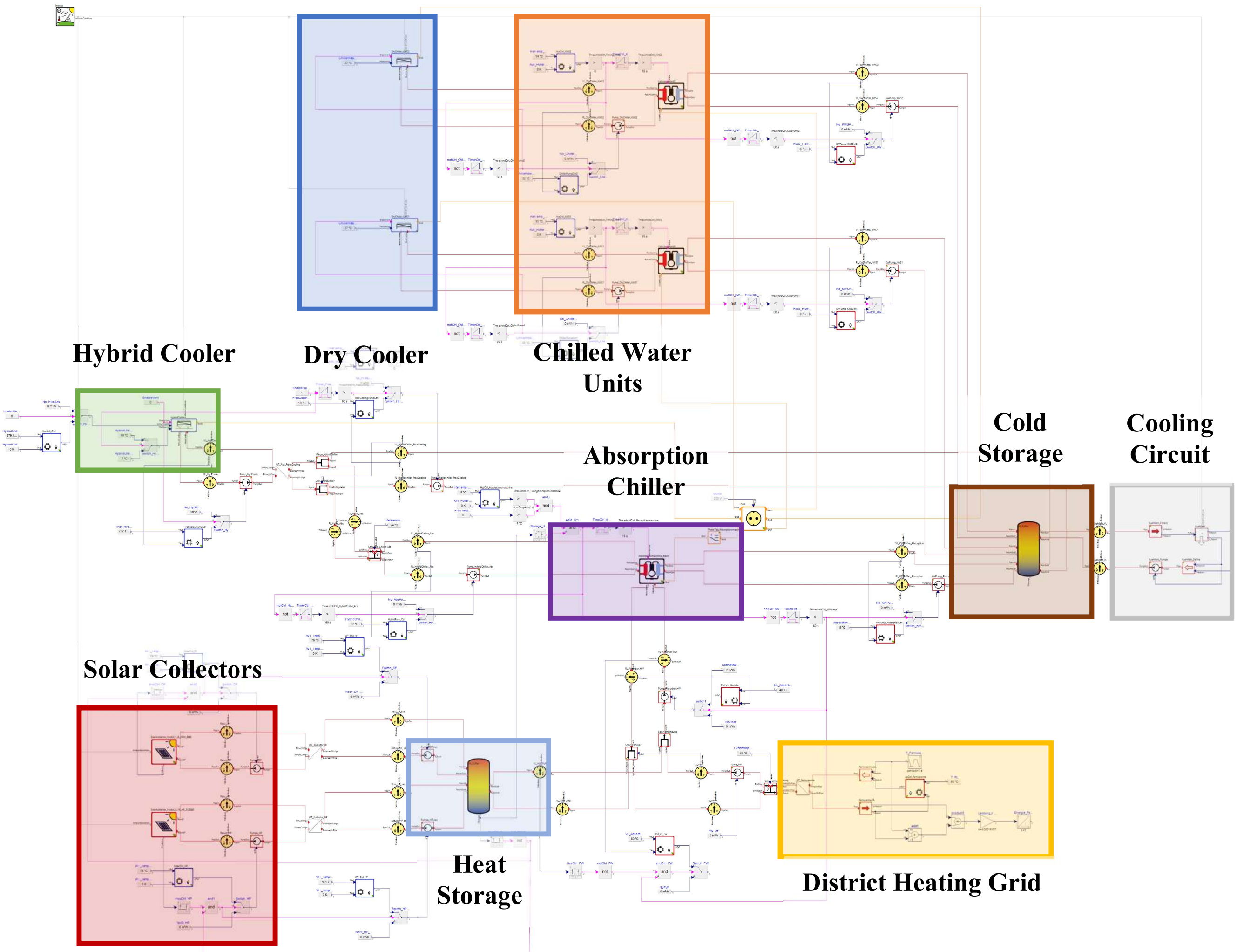


Figure 4: Simulation model at design step P2 (Schwan et. al., 2015)

This provides additional savings potential because greenhouse buildings continuously require high light intensity and thus cause significant cooling load even during winter and transit time periods.

Cooling power peaks should be buffered with the 10 m$^3$ cooling water tank and the chilled water units. Both tank systems were initially planned as single lying tanks underneath the laboratories. The chilled water units only use dry coolers as recoolers because of reduced requirements on recooling temperatures. These dry coolers use a water-glycol mixture as heating medium to avoid freezing outside the building shell. In contrast, the hybrid cooler was planned to use water with an electric trace heating system to avoid temperature drops at additional heat exchangers for free cooling.

All these constraints were then used to model an adequate mathematical and physical representation using the Modelica language and derived simulation libraries. Figure 4 shows this model which was based on the former Green Building library in SimulationX (c.f. Schwan et. al., 2015).

It almost shows a one-to-one representation of all relevant system and control components as well as their hydraulic and electric configuration and connections. The individual components, such as absorption chiller and chilled water units, used system parameters and operating characteristics which were derived from data sheets of typical system manufacturers but not from measurements. The simulated total system efficiency thus significantly depended on accuracy of this data, especially the EER characteristic of the chilled water units and the COP of the absorption chiller. The final P2 model evaluations showed a total carbon footprint saving potential for the cooling demands of about 51.06%, which is only about 1% higher than the design goal of 50%. This potential included both the savings of solar cooling and a better energetic standard of the building envelope, and a smart shading system.

The overall design process including final tests of building, planting area and energy supply system took over 6 years. Since the beginning, there have been an ongoing process of design updates with respect to system details and accuracy. The P2 model was always refined in

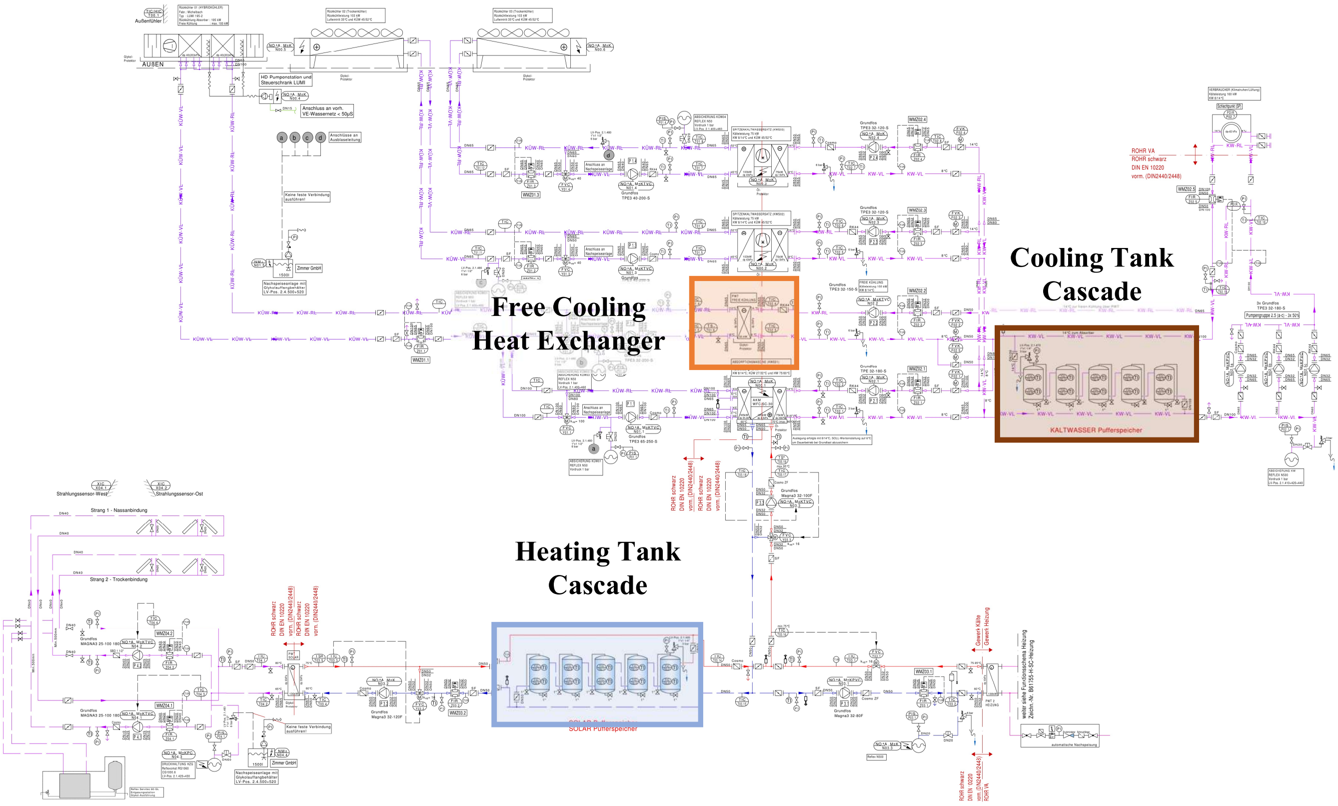


Figure 5: Cooling system concept at design step P9 (Zimmer, 2017)

order to be as up to date as possible and to be available for any design question.

Already in P3, the final design step, the building owner decided to change the hydraulic integration as well as the heating medium of the hybrid chiller for system safety reasons. An additional heat exchanger was therefore necessary which however caused an additional temperature drop and thus additional reductions of free cooling potential. Analyses of the updated model showed that this only slightly reduced the total carbon footprint saving potential to about 50.08%, still above the major design goal level.

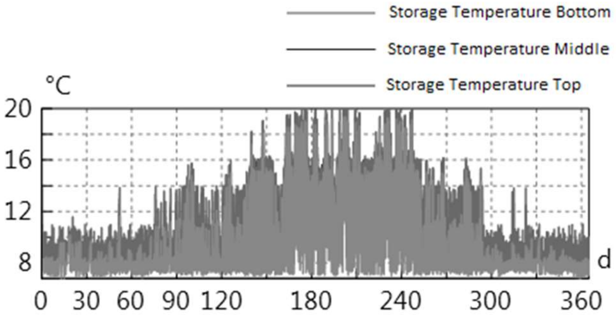


Figure 6: Simulated cold storage temperature with the P2 model (Schwan et. al., 2015)

Further evaluations during the design process at the P5 step showed that the lying heat and cooling storage tanks forced the mixture of the heating medium inside. Because of their configuration, they would be responsible for very low temperature spreads in both the cooling system as well as the heat supply circuit of the absorption chiller. This resulted in a significant increase of the required circulation pumps volume flow and thus necessary costs and auxiliary power consumption.

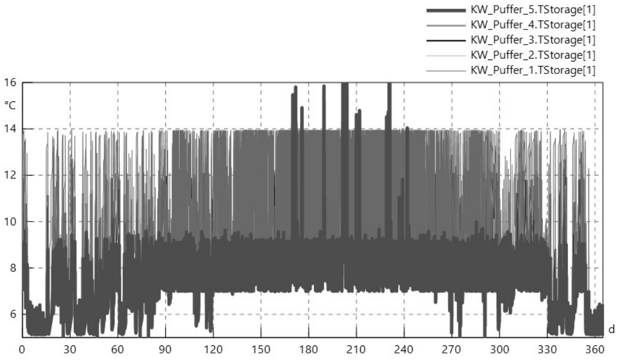


Figure 7: Simulated storage tank temperatures with updated P5 model

To avoid these short circuits, both storage systems have been changed to tank cascades with subsequent storage tanks of 1/5 of the original storage size, each within design step P5. With hydraulic connections between the top of the previous and the bottom of the next tank, the temperature difference between storage system input and output could be increased to a maximum level.

These design decisions could be technically supported

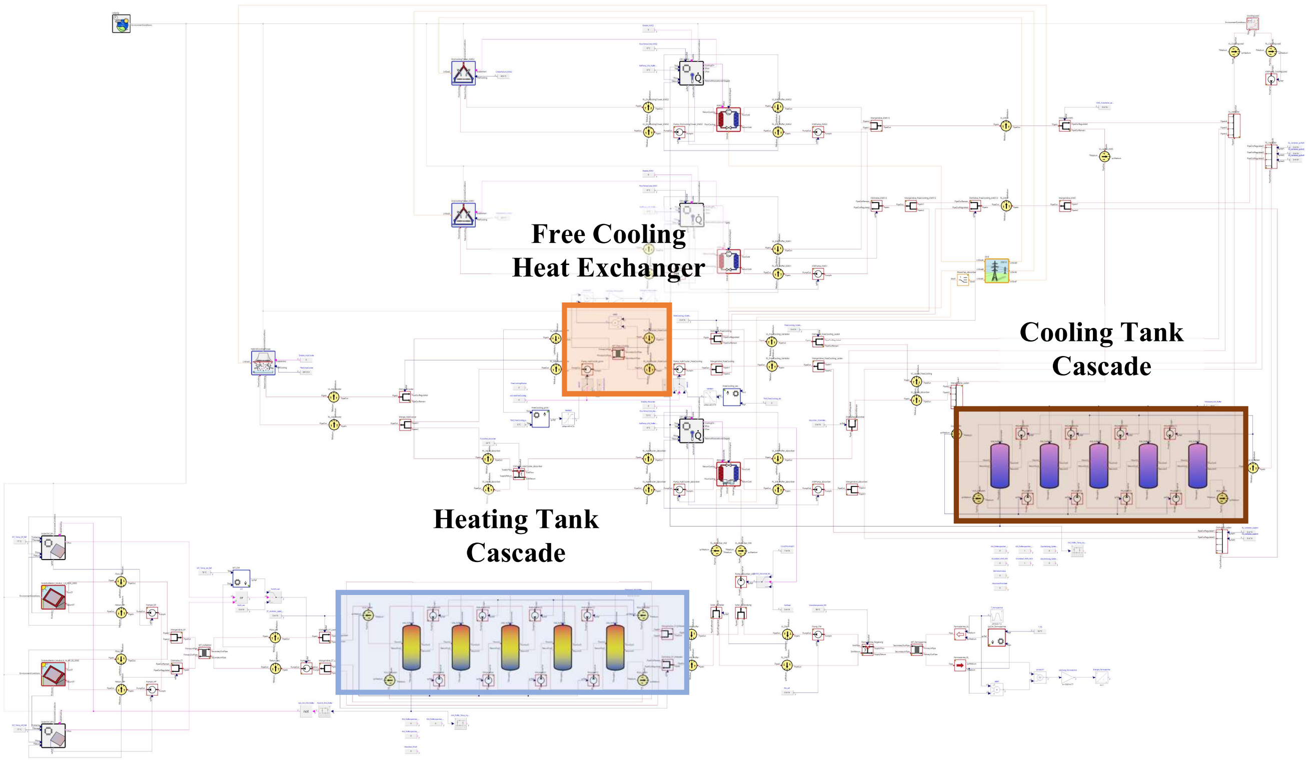


Figure 8: Simulation model at design step P9

and validated by the adapted simulation models. The results in Figure 7 in comparison to the former system behavior evaluated in Figure 6 show the effectiveness of these measures concerning the increase of storage temperature spread and cooling system temperature reduction.

Further model updates during the design progress mainly considered the level of detail of the implemented control strategies as well as further insights from the increasing availability of measurement data obtained from monitoring and surrounding conditions.

The original control strategy defined the absorption chiller as the basic cooling power source. If the solar heat in the storage tank(s) was too low, remaining heat was planned to be taken from the local district heating grid. The implemented Modelica models showed that during P2/P3 evaluations the solar collectors would provide only about 30% of the required heat demand for cooling. However, this was still efficient because of the expected performance characteristic of the chosen equipment.

First tests after the implementation showed significant influence of the heating system temperatures and temperature spreads on the total absorption chiller efficiency. This became another one of the unexpected issues, because the desired system efficiency required significantly higher heating system temperatures in both flow (85°C instead of 75°C) and return (80°C instead of 50°C). However, the return temperature of the district heating grid is limited to 55°C on the primary side.

|Thus, the originally planned system control is not possible. The cooling system simulation model was therefore updated according to latest analysis of system operation and control as well as measured system parameters. Further analyses compared alternative solutions which were necessary to still achieve the major design goal of 50% plus carbon footprint saving potential. Therefore, available measurement data from the monitoring as well as latest design documents were used to again update the model regarding the final P9 system status. This included updates of model components, parameters, and hydraulic connections and nevertheless integrated control algorithms (e.g. absorption chiller start-up procedure depending on heat tank temperatures). Furthermore, measurement time series of the total cooling power consumption partly replaced the previous simulated load curves.

## 4 Design Questions to the Models

One of the final measures in the P9 design step was the final adjustment of the system control after the construction of the building and energy system is finished. Especially, the absorption chiller operation in particular showed significant gaps between design phase and final implementation.

The main issue was the implemented heat supply circuit of the absorption chiller. It was designed to enable 50°C maximum return temperature with a 25K temperature spread because of district heating grid requirements. However, this caused significantly lower system efficiency as the absorption chiller required a lower temperature spread of about 5K at a higher temperature level to provide adequate efficiency ratios. Monitoring data of measured heat supply and recooling temperature as well as resulting cooling power were used to calibrate the corresponding model characteristics. Figure *9* shows some exemplary results of the calibration process.

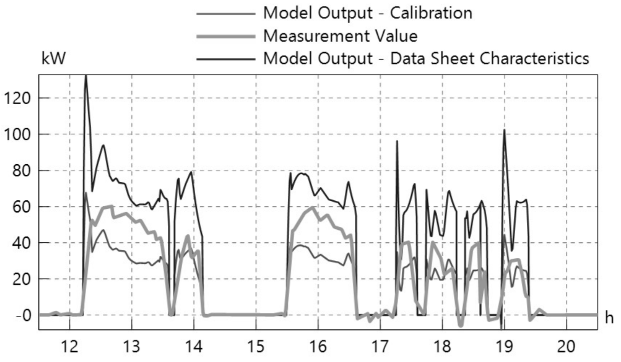


Figure 9: Comparison of measurement data and model results during the calibration process

Again, a carbon footprint saving potential of 50% of a comparable reference greenhouse building remained the major design goal. For this purpose, the engineers developed four technically-feasible solutions which might help to compensate the resulting efficiency reduction due to the changed boundary conditions.

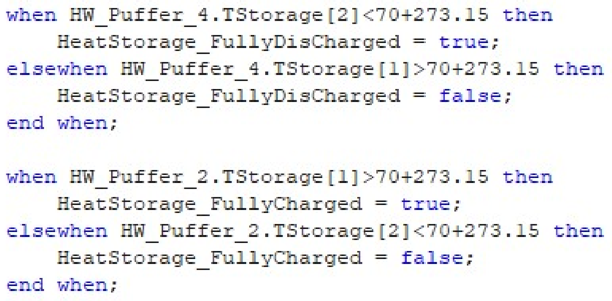
1. Replacement of absorption chiller with a machine with better efficiency ratio at the desired temperature level (i.e. 75°C)
2. Variable control of cooling power output depending on available solar heat storage tank temperatures (i.e. 60°C to 75°C)
3. Increase of heat supply temperature level (i.e. 85°C)
4. Bivalent heat supply from solar heat storage tanks and district heating grid

The first solution required significantly higher investment costs than the other ones because it considered the replacement of an already integrated system component- the complete absorption chiller including all peripheral components. In contrast, the second and third option would not need additional investments besides the engineering effort regarding the required controller adaption.

The last solution only represented an optional way to show the entire range of the technically-feasible approaches. However, it would violate the requirements of district heating gird because maximum return temperatures of 55°C would not be allowed.

To find the right solution regarding the major design goal, the continuously updated Modelica model of the cooling system is predetermined. It is precisely here that the strength of Modelica's approach of making models usable for the entire design period up to the building's use becomes apparent.

The required Modelica models must therefore represent the real-world conditions as accurately as possible to support those important design decisions. Intensive calibration work and structural redesign of the hydraulic model at the end of design phase P9 ensured this accuracy regarding the physical system behavior. However, effects of the control system are almost as important as the component parameters and model structure. Therefore, the complete technical description of the control system was implemented using all available terms of the Modelica language.



```
when HW_Puffer_4.TStorage[2]<70+273.15 then
    HeatStorage_FullyDisCharged = true;
elsewhen HW_Puffer_4.TStorage[1]>70+273.15 then
    HeatStorage_FullyDisCharged = false;
end when;

when HW_Puffer_2.TStorage[1]>70+273.15 then
    HeatStorage_FullyCharged = true;
elsewhen HW_Puffer_2.TStorage[2]<70+273.15 then
    HeatStorage_FullyCharged = false;
end when;
```

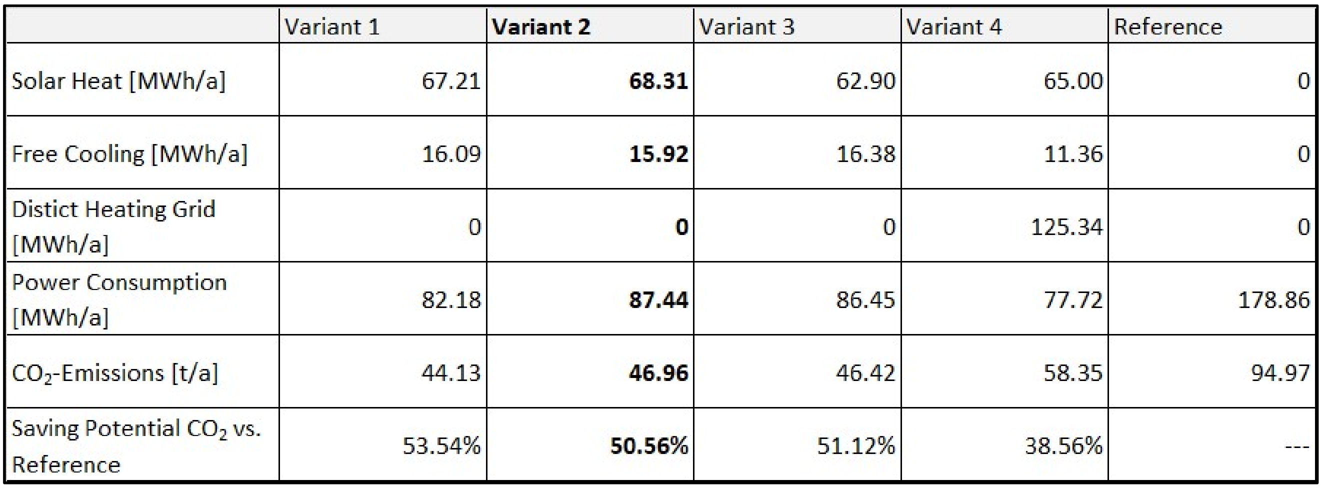
Figure 10: Section of the Modelica controller code of the storage temperature control

Figure *10* therefore shows a small exemplary section of the implemented controller code. It decides if the solar heat storage reached the level “fully-discharged” or “fully-charged” depending on simulated temperatures in different tanks and in different tank positions. This again shows the strength of Modelica models regarding the support of the whole building design process. Specific problems or even a complex system can be modeled in different levels of representation (i.e. structural and text view) and detail.

The final evaluation of the four simulation model variants provides a conclusive result. Table *1* therefore shows some decision-making factors. The calculation of the total $CO_2$ emissions per year requires the evaluation of all energy flows, especially from fossil fuels or grid power, to the building. Therefore, power consumption from the electric grid and heat consumption from the district heating grid are the most important values. They will be multiplied with their individual $CO_2$ emission equivalent factors (i.e. power: 0.54kg/kWh, district heating: 0.15kg/kWh) to calculate the simulated total $CO_2$ emissions of each variant.

Furthermore, Table *1* also shows the generated local renewable energy amounts. This includes renewable cooling power via free cooling with the hybrid cooler and solar heat from the two types of solar collectors. As renewables, they are not part of the $CO_2$ emissions

Table 1: Simulation results of decision making factors regarding the analysis of variants



| | Variant 1 | **Variant 2** | Variant 3 | Variant 4 | Reference |
|---|---|---|---|---|---|
| Solar Heat [MWh/a] | 67.21 | **68.31** | 62.90 | 65.00 | 0 |
| Free Cooling [MWh/a] | 16.09 | **15.92** | 16.38 | 11.36 | 0 |
| Distict Heating Grid [MWh/a] | 0 | **0** | 0 | 125.34 | 0 |
| Power Consumption [MWh/a] | 82.18 | **87.44** | 86.45 | 77.72 | 178.86 |
| $CO_2$-Emissions [t/a] | 44.13 | **46.96** | 46.42 | 58.35 | 94.97 |
| Saving Potential $CO_2$ vs. Reference | 53.54% | **50.56%** | 51.12% | 38.56% | --- |

calculation (i.e. $CO_2$ factor is 0kg/kWh) but they are listed in Table *1* as well to enable a detailed discussion of different influencing factors.

The last column of Table *1* includes the corresponding values of a fictional reference greenhouse building with a lower energetic building standard and conventional cooling system with three independent chilled water units. The calculated $CO_2$ emissions of each variant are compared to this reference solution to evaluate the savings potential.

In contrast to the results of the first design phase, a bivalent heat supply to the absorption chiller via solar heat collectors and district heating grid (i.e. variant 4) doesn't meet the major design goal anymore. The total $CO_2$ savings potential decrease below 40%. The measurements showed that the deciding temperature level of the absorption chiller results from average temperature between flow and return (i.e. 75/50°C => 62.5°C) which is much lower than the estimated temperature level during the design phases P2/P3 (i.e. 75°C). The lower the heat supply temperatures, the lower the absorption chiller performance which results significantly higher district heating consumption and higher $CO_2$ emissions. Furthermore, this control variant also significantly reduces the free cooling potential because the cooling tank temperature mostly remains on a low level because of the infinite availability of district heating.

Variants 1 to 3 all meet the major design goal of 50% $CO_2$ saving potential. The higher heat supply temperature level (i.e. 85°C) of variant 3 results in a higher cooling power output of the absorption chiller which reduces the operation time of the peak-power units. However, this higher temperature level causes a lower solar collector efficiency which is compensated by the better performance characteristic of the absorption machine.

A new machine with a better performance characteristic (i.e. variant 1 – 75°C) enables both a higher cooling power consumption and higher solar collector efficiency. However, this variant requires significantly higher investment costs.

Variant 2 requires the lowest investment costs as it needs only minor changes of the control strategy, and as such it is preferred over variant 1. Variant 3 is more expensive as well because the system of internal volume flows (i.e. pumps and piping) must be converted to other dimensions. The presented use of Modelica models provided a conclusive design recommendation of variant 1 even at a very late step of the design process.

## 5 Process Integration

This paper presents the use of Modelica models as an integral part of the complete design process. However, complex commercial buildings in particular still require a high level of manual effort for model updating and process synchronization.

However, there are already ongoing processes and scientific research, i.e. German FMI4BIM project, which works on solutions which partly link simulation models and derivatives (i.e. FMUs) to typical digital data platforms used within building design processes (i.e. BIM – Building Information Modeling). This approach already shows a lot of application scenarios (c.f. Eckstädt et. al., 2020).

Building Information Modeling (BIM) is a core concept of Industry 4.0 mainly used by the construction industry as a consistent approach of data management during the whole design and construction process (c.f. Doan et. al., 2019). It was once designed to provide a database of building construction data, parameters and configurations but is now extending to additional engineering domains of the building sector, especially HVAC systems and building control.

Therefore, BIM is predestinated to serve as an

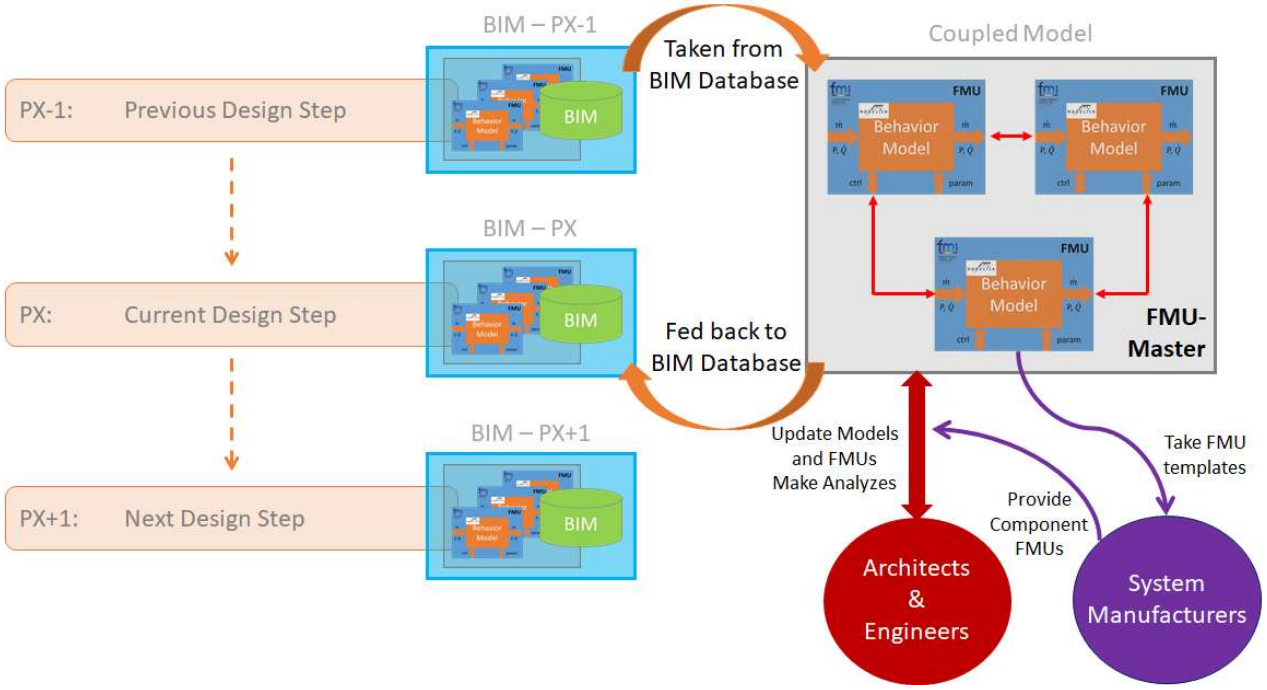


Figure 11: Basic approach of Modelica model (FMU) integration in BIM-based building design process

independent model database during the whole building design process and the following building lifespan. To increase interoperability and tool-independency, Modelica models should therefore be converted to FMUs as it is proposed by the FMI4BIM consortium.

Therefore, BIM is predestinated to serve as an independent model database during the whole building design process and the following building lifespan. To increase interoperability and tool-independency, Modelica models should therefore be converted to FMUs as it is proposed by the FMI4BIM consortium.

Figure *11* describes the basic approach of a BIM-based building design process. All architectural data is stored in the BIM database. Architects and engineers use these data with each design step and refine the collected data and information in the BIM model regarding the increasing design knowledge and accuracy. Additional links to suitable building and HVAC system FMUs (or coupled FMU models) can extend this process to enable a full integration of Modelica models.

The share of BIM-based building construction projects is constantly increasing worldwide (c.f. Liu et. al., 2021). Typical CAD tools began to integrate ifc-files (i.e. BIM file format) export and import. BIM has become an important issue in the field of building engineering. There are even toolchains that already exist that automatically generate and parameterize Modelica models with BIM data (c.f. Nytsch-Geusen et. al., 2019). All these tools and methods contribute to a more consistent building design process and facility management.

Basically, the approach in Figure *11* extends the existing BIM-based process with suitable links to models represented by FMUs or FMUs libraries. Therefore, the assigned model environment is updated with new parameters and information during each design step. Then, engineers and architects use the models for individual analysis, e.g. energetic evaluation of different HVAC system variants. The most preferred solution is then fed back to the BIM environment as base for the next design steps.

The model design, interfaces and FMU integration will be defined by a standard or standard extension. This will allow system manufacturers to provide individual component FMUs of their products based on the developed standard templates. This will contribute to both security of intellectual property as well as integration of expert knowledge.

## 6 Conclusion

The presented example building design process of the new research greenhouse building of the University of Leipzig shows the versatility of Modelica models regarding upcoming design questions. Currently, Modelica models are often used as base of decision-making in the first design phase until step P3, the final design. However, there is rarely any use of these models after this phase.

The different design steps and phases have different requirements regarding accuracy and level of detail. The use of these models in subsequent design phases needs continuous refinement and a consistent data base.

Therefore, BIM seems to be the means of choice as it already represents a digital mockup of the continuously refined building construction during all design phases. Ongoing research activities focus on the integration of different toolsets and databases, like BIM, GIS and Modelica models. Open-source frameworks are thus available to use BIM data in Modelica models (c.f. Wetter, et.al., 2019).

Another research activity, i.e. FMI4BIM, currently analyses approaches of a full BIM process integration of Modelica models. Thus, a project specific BIM model should be linked to the Modelica models which are represented here by FMUs to provide a tool-independent model exchange standard. One major outcome of the presented exemplary greenhouse building construction process considers the total process length corresponding to the desired BIM workflow. Design and construction of complex buildings can easily take several years. If Modelica models (or derived FMUs) should be linked to different process steps, a well-suited version management is necessary. This doesn't only consider the model's level of detail and accuracy, but also the version of current Modelica language and Functional Mockup Interface release, and the used simulation environment which is also important. This is a particular challenge when backward compatibility needs to be ensured.

Models can help identify optimal solutions of specific design questions during all design steps via variant analysis and parameter study. In case of a continuous model refinement process, models can also serve as virtual devices-under-test for the building control development. This requires a significantly automated process including controller design until the phase where controller code is exported to specific targets (i.e. PLCs, DDCs, etc.). Further research activities, such as ARCHE, have special emphasis on this topic. This includes the consistent decoupling of controller code and physical model. Therefore, the Modelica Synchronous library provides suitable approaches which describe boundaries between clocked and continuous-time partitions of a model (c.f. Elmquist et. al., 2012).

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