# Digital Twin for Heat Pump Systems - Description of a holistic approach consisting of numerical models and system platform

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**Abstract.** Numerical building simulation is a tool that has been used intensively for years to analyse systems engineering in buildings. In the past, the focus of the development work was increasingly on the creation of detailed partial models and the coupling to other simulation programs, which was called co-simulation in the professional world. The development work regarding the coupling of building and plant simulation programs with programs of the numerical flow simulation is to be mentioned here. Currently, the coupling to measurement technology is pushed more strongly, whereby the focus is seen on the parallel use of the numerical model to a real system. This development is called "digital twin" of components or subsystems in power engineering. The following article addresses this development and would like to describe the system concept of a digital twin using the example of a heat pump technology. Based on the characterization of a special use case, the digital twin will first be divided into the development phase, field test phase, and deployment phase of heat pumps. Different model accuracies of the digital twin are assigned to the individual phases. In a second step, the different models for the component's compressor, heat exchanger, expansion valve, and the necessary piping are described. The coupling to a building simulation program is also part of the article. Furthermore, an essential point is the interaction with a cloud platform, in which the comparison between measured values and values from the digital twin takes place. Here, the focus is on the data exchange formats and the additional analysis tools that were used in the system concept. The paper concludes with a demonstration of an example under laboratory conditions within the Combined Energy Lab (CEL) of the TU Dresden.

**Keywords.** Digital twin, heat pump systems, sector coupling, renewable energies, carbon footprint
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## 1. Introduction

The need for $CO_2$ reduction, especially in the building sector, leads to new system solutions. While in the past there was a transition from low-temperature gas technology to gas condensing technology and from low-temperature oil technology to oil condensing technology, development is currently focusing very strongly on heat pump technology and fuel cell technology. Fig. 1 shows the numbers of sold heat pumps in Germany during the last years. Within the heat pump technology, the air-to-water systems are in great demand, whereas the heat pump systems with ground coupling or groundwater coupling are less in focus.

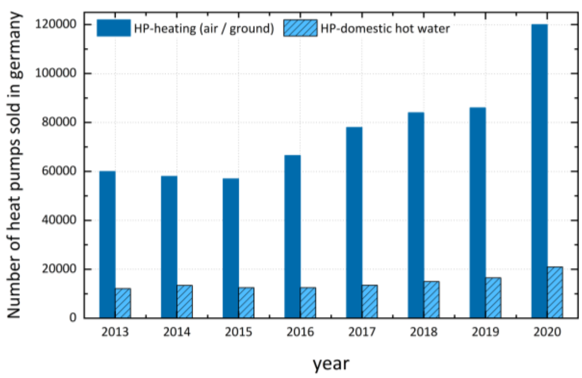


**Fig. 1 –** Number of sold heat pumps in Germany during the last years (air-to-water heat pumps / ground heat pumps and heat pumps for domestic hot water production) [1]

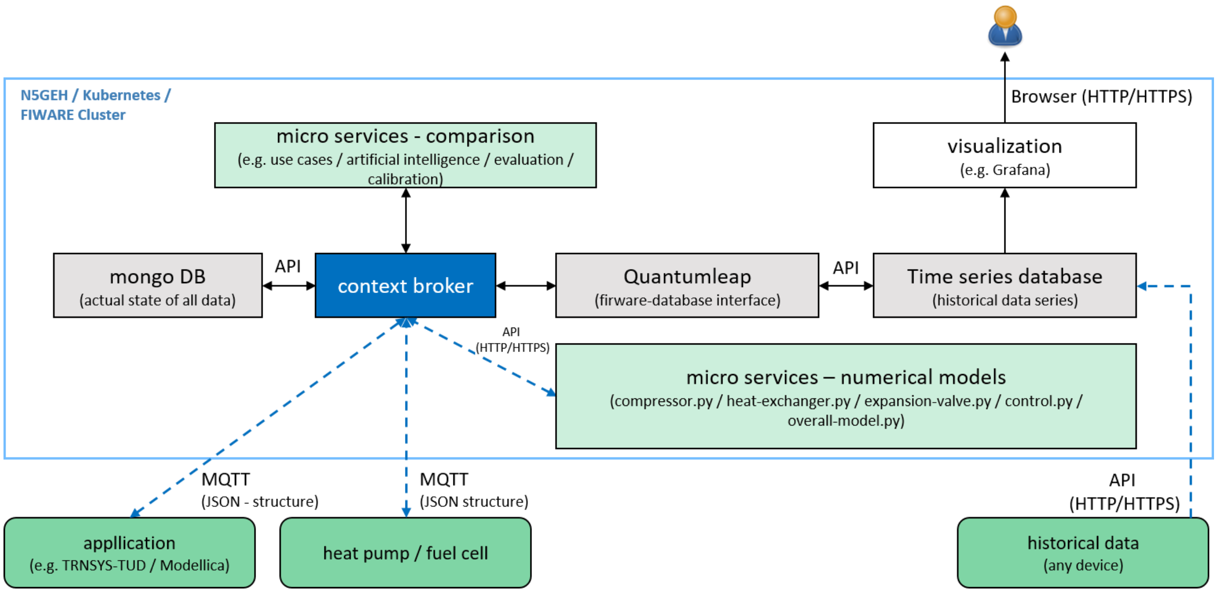


**Fig. 2 –** Digital twin for heat pump and fuel cell systems [2]

Heat pumps to produce hot water are also showing an increase in sales, but not as strong as air-to-water heat pumps. Heat pump technology is highly efficient, but also more dependent on external conditions than gas condensing technology. Against this background, it is advisable to carry out a comprehensive analysis of the thermal behaviour of the individual components of a heat pump during the development of new heat pump units. The following article will present a methodology for the analysis of heat pumps, which focuses on a digital twin.

## 2. Methodology of the digital twin

### *2.1 Fundamental consideration*

The literature contains a wide variety of explanations of digital twins. The concept is particularly well established in production engineering [2], [3], [4]. In energy technology, with a focus on heat pump technology, reference can be made to [5]. A digital twin can be defined as follows:

*"A digital twin is a digital representation of a tangible or intangible object from the real world in the digital world. Digital twins enable an overlapping exchange of data. They are more than just data and consist of models of the represented object and can also contain simulations, algorithms, and services that describe or influence the properties or behaviour of the re-presented object or process or offer services about it."*
Essential features for the digital twin are

- representation of reality utilizing numerical models,
- data analysis and comparison of numerical and real systems as well as
- service functions based on the selected data.

All these functionalities were combined in a digital twin for heat pump systems. Fig. 2 documents the developed structure, which is based on a cloud architecture.
With reference to Fig. 2, various applications within the cloud architecture make up the components of the digital twin. These components also utilize external services, such as Trnsys TUD [7] or Modellica [8]. Furthermore, the corresponding real devices are connected to these services and applications. The IoT framework FIWARE is used to collect and process all the necessary data coherently. FIWARE's approach to linked data and its support for extensive data models allows not only for a comprehensive set of data points regarding the current status of an entity but also for a uniform method to store all relevant metadata like relationships or geolocations. All data passes through the context broker, which manages metadata and subscriptions. Subscriptions define where specific data is processed (e.g., time-series data is passed on to the database) and which components should receive an update of this data. Additional data can also be queried on-demand, or a subscription can be configured to be triggered only when predefined conditions are met. The subscription-based data-forwarding facilitates a modular service architecture in which a service is receiving data as soon as it is available at the context broker and all components can be built upon a uniform API. External applications and entities are preferably

connected to the cluster through the MQTT [9] protocol which offers a similar data exchange mechanism and very good scalability.
Within the cloud structure, various database systems, the micro-services, and the central visualization processes were arranged. The Grafana [10] program was used for visualization. The microservice "comparison" and the microservice "numerical models" are the two main components of the digital twin. In the microservice "numerical models", all components of the heat pump were mapped numerically using the scripting language Phyton. This is described in detail in the following section. In the micro-service "comparison" the comparison between numerical data and real data measured on the device is realized. In addition, functionalities for clustering and data analysis are implemented in this microservice.

## *2.2 Micro-service "numerical models"*

For the development of the "numerical models" service, the initial focus was on the representation of an air-to-water heat pump. The implemented cooling circuit can be seen in Fig. 3. This consists of the air-refrigerant heat exchanger, the compressor, an intermediate heat exchanger, the refrigerant-water heat exchanger on the useful side, and the expansion valve.

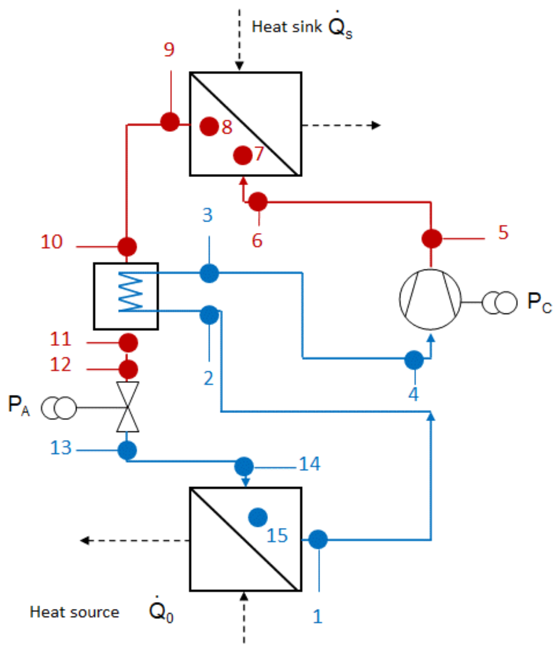


**Fig. 3 –** Refrigeration circuit of an air-to-water heat pump

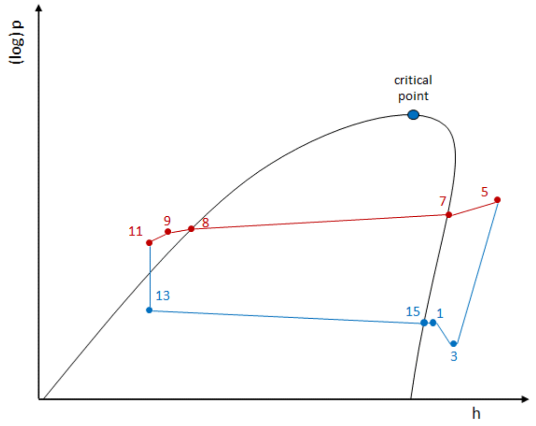


**Fig. 4 –** Process sequence in (log) p - h diagram

In the first step of modelling the internal heat exchanger was not considered. This means that the state points 2 and 3 as well as the state points 10 and 11 are omitted. The process sequence of the refrigeration cycle under these boundary conditions with temperature glide of the refrigerant and pressure losses can be seen in Fig. 4.
The numerical model of the heat pump should be able to be used in different phases of the product utilizing the digital twin. It is planned to use the digital twin

- in product development,
- in a field test phase
- as well as in the series product (and its use).

For the product development phase, very detailed models must be used to clarify construction details, for example. The time step sizes for the calculation are rather small here. It is advantageous to work with grey-box models [11] which are close to the high detailed white-box model approach (CTW). In the field test phase as well as in the real use phase of the product, simple models are required, since the number of data points is limited here, and the real-time capability of the models is important. It is advisable to use grey-box models which are close to the low detailed black-box model approach (CTB) for this purpose (see Fig. 5).
Figure 5 shows a classification of the digital twin with regard to the application area. The left diagram documents the requirements during the development phase of heat pumps. Very detailed models are needed here. The middle diagram documents the first field test phase of the prototype. Here rather robust models are needed. In the continuous operation of the devices, Black-Box models are required, which allow low computation times and allow a comparison to measurements.

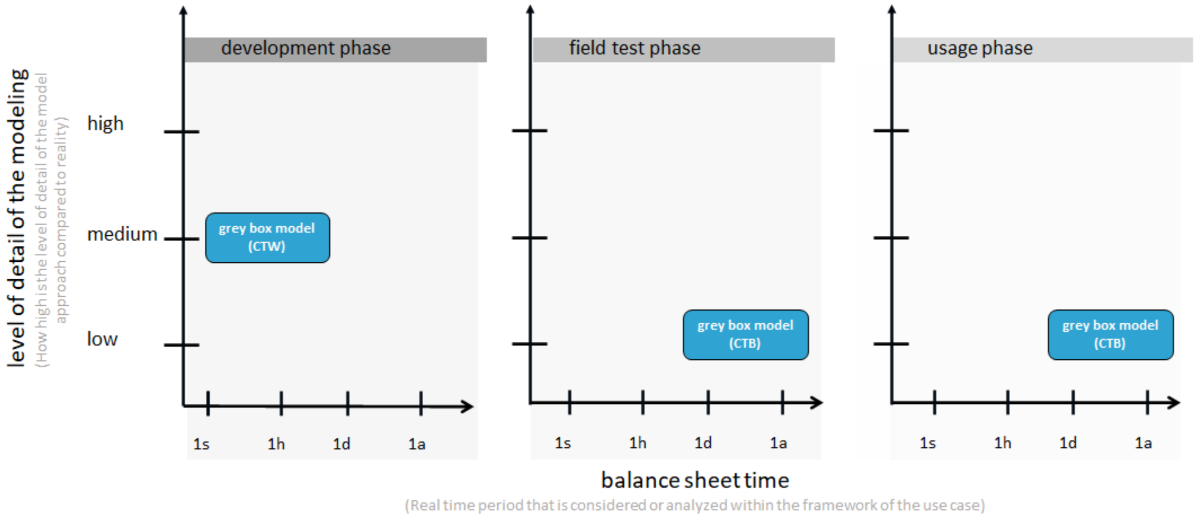


**Fig. 5 –** Numerical models – level of detail depends on development and usage phase

Figure 5 shows a classification of the digital twin with regard to the application area. The left diagram documents the requirements during the development phase of heat pumps. Very detailed models are needed here. The middle diagram documents the first field test phase of the prototype. Here rather robust models are needed. In the continuous operation of the devices, Black-Box models are required, which allow low computation times and allow a comparison to measurements.

As a result, the digital twin must contain a variety of models that can be flexibly combined depending on the usage requirements. In this case, at least one grey-box model (CTW) and one model (CTB) were created for each component of the heat pump (heat exchanger, compressor, expansion valve). Fig. 6 shows the possible combinations.

| component | model 1 | model 2 | model 3 |
|---|---|---|---|
| heat exchanger | X | O | ... |
| compressor | X | O | ... |
| expansion valve | X | O | ... |

X grey-box model (CTW – close to White-Box Model)

O grey-box model (CTB – close to Black-Box Model)

**Fig. 6 –** Heat pump subcomponents and their combination

Not all models can be described in detail here. For this reason, only the heat exchanger calculation and the overall model will be presented below as an overview.

The interconnection of the subcomponents in the overall cycle process for the simulation is illustrated in Fig. 7. In the iterative algorithm, the condenser model calculates the refrigerant mass flow rate in dependence on the pressure values determined by the other subcomponents.

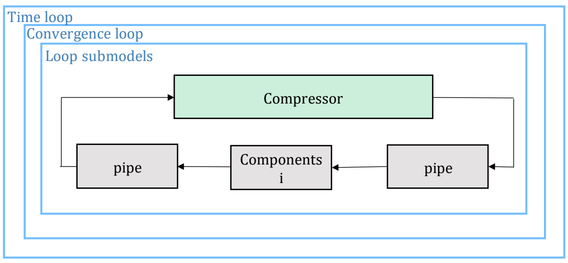


**Fig. 7 –** Simulation loops of the cycle process

As a simplified alternative to the detailed simulation of the heat exchanger with a cell model, a model based on the operating characteristics was implemented as follows. According to Fig. 8, the heat exchanger is therefore divided into 3 parts. For the condenser, the sub-processes a) cooling-superheating, b) condensing, c) sub-cooling are considered. The three different areas in the heat exchanger are required for the exact mapping of the heat transfer processes on the condenser side. On the evaporator side, only one subdivision into two areas is necessary.

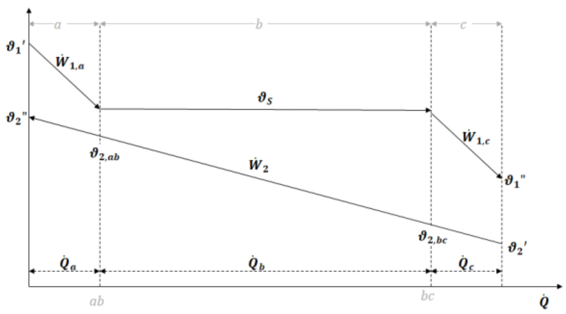

**Fig. 8 –** Temperature curves with trisection of the heat exchanger with condensation according to [12].

Here, the known design total heat transfer surface *(UA)$_{des}$* is divided among the 3 different parts. Initially, the distribution is not known, so with a known boiling temperature, a solution must be determined by iteration. Knowing the outlet temperature of the refrigerant determined in the iteration, the unknown temperatures can be calculated from energy balances (see equations (1) to (3)).

$$\vartheta_{2,bc} = \vartheta_2{'} + \frac{\dot{W}_{1,c}}{\dot{W}_{2,c}} \cdot \left(\vartheta_S - \vartheta_1{''}\right) \tag{1}$$

$$\vartheta_{2,ab} = \vartheta_{2,bc} + \frac{\dot{m}_1 \cdot \left(h_{1,ab} - h_{1,bc}\right)}{\dot{W}_{2,b}} \tag{2}$$

$$\vartheta_2{''} = \vartheta_{2,ab} + \frac{\dot{W}_{1,a}}{\dot{W}_{2,a}} \cdot \left(\vartheta_1{'} - \vartheta_S\right) \tag{3}$$

with $\dot{W}_{1,i} = \dot{m}_1 \cdot c_{1,i}$ , $\dot{W}_{2,i} = \dot{m}_1 \cdot c_{2,i}$ , $R_{2,i} = \frac{\dot{W}_{2,i}}{\dot{W}_{1,i}}$

*Index i = a, b, c*

With the temperatures according to equations (4) – (6), the dimensionless temperature changes (temperature effectiveness) P and from this the number of transfer units NTU are calculated.

$$P_{2,a} = \frac{\vartheta_2{''} - \vartheta_{2,ab}}{\vartheta_1{'} - \vartheta_{2,ab}} \tag{4}$$

$$P_{2,b} = \frac{\vartheta_{2,ab} - \vartheta_{2,bc}}{\vartheta_S - \vartheta_{2,bc}} \tag{5}$$

$$P_{2,c} = \frac{\vartheta_{2,bc} - \vartheta_2{'}}{\vartheta_S - \vartheta_2{'}} \tag{6}$$

$$NTU_{2,i} = \frac{1}{1 - R_{2,i}} \cdot \ln\left(\frac{1 - R_{2,i} \cdot P_{2,i}}{1 - P_{2,i}}\right) \tag{7}$$

From the sum of the NTU values, the total heat transfer area *(UA)$_{calc}$* can be calculated (see equation 8). With these results, a new outlet temperature of the refrigerant $\vartheta_1{''}$ is determined by the iteration algorithm until the deviation between *(UA)$_{calc}$* and *(UA)$_{des}$* is below a present value.

$$(UA)_{calc} = \sum\left(NTU_{2,i} \cdot \dot{W}_{2,i}\right) \tag{8}$$

# 3. Validation of the digital twin

Different procedures are available for validating the models within the digital twin. In the first step, measurement data from companies can be used. This data can be transferred into the cloud system via the "historical data" interface. The second possibility is the targeted measurement in the Combined Energy Lab of the TU Dresden [13]. The Combined Energy Lab consists of three main test facilities that are coupled together. Test facility 1 is the outdoor climate room which is used for testing heat pumps. Test facility 2 is the indoor climate room used for heat transfer tests and indoor air quality / thermal comfort issues. To ensure the reaction of the building and to be able to test realistically, an energy park is necessary. Fig. 9 (CAD view) and Fig. 10 (real implementation) show the different experimental setups.

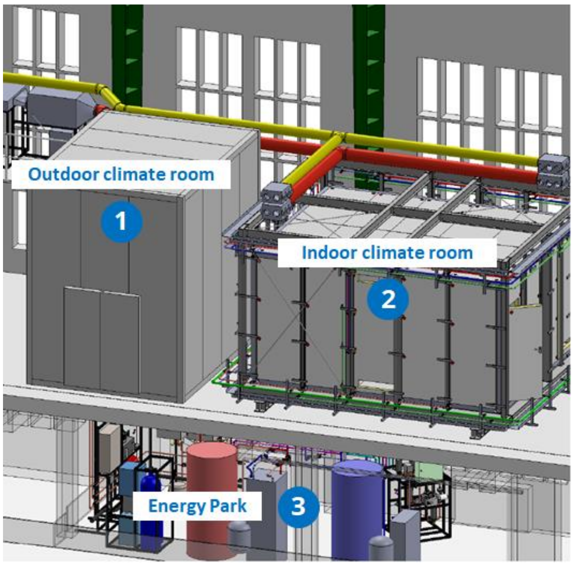


**Fig. 9 –** Overview about the Combined Energy Lab 2.0

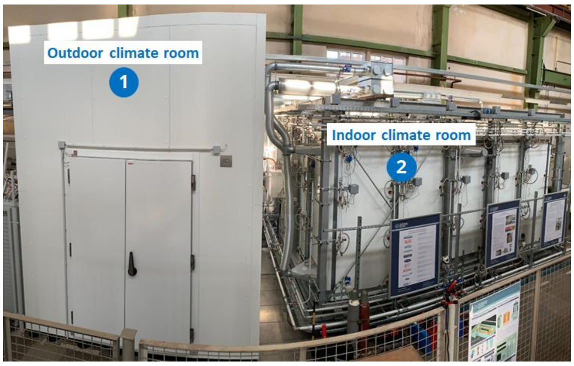


**Fig. 10 –** Photography of the Combined Energy Lab

Within test environment 3, a low-voltage emulator is also integrated, with which it is possible to vary the characteristics of the electrical distribution network.

With the Combined Energy Lab 2.0, it is possible to analyse complex energy supply structures. However, since the test time is limited to real-time, a type day procedure was developed with which an annual test can be reduced to for example four representative type days. These type days are used to validate the digital twin. Details are documented in [13][1].

# 4. Conclusion

This paper presents the methodology of a digital twin for heat pumps. The main component of the digital twin is a cloud structure which, in addition to the numerical representation of the refrigeration cycle including the control system, also includes a comparison of the numerical data with field test data. The exchange can be adapted to the granularity of the task. The main component of the digital twin is the numerical model, which was implemented in Phyton. It consists of some grey-box models (CTW, CTB) for each component, which can be combined in any way. The strong structure of the presented numerical model is to be understood as a positive system property since it is possible to generate digital twins or digital system twins for other heat and cold generation systems very quickly.
However, concerning the development of numerical models, it must be noted that there are some limitations in the Python scripting language. Especially the overall convergence for the calculation of the refrigeration cycle is difficult and should be completely revised for future development.

# 5. Acknowledgement

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# 6. Symbols and abbreviations

| | | |
|---|---|---|
| | specific enthalpy | J/kg |
| c | specific heat of fluid | J/(kg K) |
| | mass flow rate | kg/s |
| *NTU* | number of transfer units | - |
| $\dot{Q}_S$ | heat transfer rate (building) | W |
| | pressure | Pa |
| $\dot{Q}_0$ | heat transfer rate (air, water, ground) | W |
| $P$ | temperature effectiveness | - |
| $P_C$ | electric power (compressor) | W |
| $P_a$ | electric power (auxiliary energy) | W |
| $R$ | heat capacity ratio | - |
| $(UA)_{calc}$ | calculated product of overall heat transfer coefficient and total heat transfer area | W/K |
| $(UA)_{des}$ | product of overall heat transfer coefficient and total heat transfer area (designed) | W/K |
| $\dot{W}$ | flow stream heat capacity rate | W/K |
| $x$ | dimensionless temperature change | - |
| $\vartheta_1'$ | inlet temperature | °C |
| $\vartheta_1''$ | outlet temperature | °C |
| $\vartheta_2'$ | inlet temperature | °C |
| $\vartheta_2''$ | outlet temperature | °C |

| | |
|---|---|
| 1…x | points of calculation |
| 1 | refrigerant side |
| 2 | heat sink - side |
| a, b, c | index of the calculation (sections) |

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## Data Statement

The datasets generated and analysed during the current study are not available because patent protection law votes are currently being carried out but the authors will make every reasonable effort to publish them in near future