Digital twins for building performance optimization – definitions and benefits

<teaser>

Much faith is placed in digital twins as a tool for improvement of building performance. Yet the definition of the concept is vague. Can any digital model qualify as a twin? The paper presents a suggested level categorization scheme for building performance digital twins and discusses the potential utility of each type. Special emphasis is placed on the estimation of performance improvement potential for white box digital twins, i.e., IoT (Internet-of-Things)connected dynamic simulation models that are based on physical first principles.

Background and introduction

Our buildings take up a lot of space and energy by any measure. The total value of global real estate is roughly equal to all equities (shares), debt, and oil reserves combined[1]. From an environmental perspective, the construction industry itself and maintaining conditions in buildings use about 40% all traded energy and cause 30% of carbon emissions[2]. While it is difficult to precisely quantify the effectiveness of creating indoor comfort at minimal expense, year-on-year productivity of the actual construction process can be measured. The sad news is that it is continuously declining since decades and, despite high hopes in digitalization and other technology advancement, in most countries the situation has not improved in the last decade[3]. Unfortunately, the global energy use of the building sector seems to be following a similarly gloomy path, with fossil energy use steadily increasing by 0.7% yearly since 2010[4].

Construction and Non-Farm Labor Productivity Index (1964 = 100%)
US Department of Commerce Bureau of Labor Statistics

While the building industry's overall global trends leave much to be desired, there are several promising exceptions. For example, construction productivity in China has been increasing year-on-year by 6.7% during 1995-2015[5]. Individual buildings are constructed all over the world at

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[1] https://www.savills.com/impacts/market-trends/8-things-you-need-to-know-about-the-value-of-global-real-estate.html

[2] https://www.unep.org/explore-topics/resource-efficiency/what-we-do/cities/sustainable-buildings

[3] https://www.mckinsey.com/capabilities/operations/our-insights/reinventing-construction-through-a-productivity-revolution

[4] https://www.iea.org/reports/buildings

[5] https://www.mckinsey.com/capabilities/operations/our-insights/reinventing-construction-through-a-productivity-revolution

(all web references accessed on 2023-05-29) competitive costs that boast radically better-than-mainstream energy efficiency. Good solutions exist. The challenge is to make use of them.

The focus in this whitepaper will be on methods for the creation of a good indoor environment at minimal economic and environmental cost. In particular, we will discuss ways of improving the existing building stock. While the discussion of how to create new high-performance buildings is certainly interesting, only around 1% is added to the existing building stock each year in developed countries. The main issue for meeting the climate challenge is therefore to drastically cut energy use in the existing building stock. EQUAs experience from detailed investigation, monitoring, and modelling of existing buildings also suggests that a great majority of buildings underperform, mostly due to a combination of mistakes, oversights, and negligence. They can be improved by relatively simple means. The key is to find the right things to fix.

First, let us briefly review the available options for improving the performance of an existing building. The first thing that comes to mind is often physical improvements to the building itself, e.g., increasing insulation levels, replacing windows, or installing more efficient heating, ventilation and air conditioning (HVAC) equipment. Other things that can be done may be somewhat less obvious. First of all, one should make sure that the building actually works as well as it could, i.e., that there are no serious faults in already existing components and that they operate correctly. Once this is done, the option of installing a more sophisticated control system should be investigated. While this usually means the replacement of some physical components, the cost and effort of replacing control systems are usually significantly lower than other physical improvement measures. In summary, we need methods to find faults, improve controls, and provide advice on the most cost-effective physical improvements that can be done. This is where digital twins come in.

Multi-level categorization for building performance digital twins

The concept of having a digital replica of a physical system is intuitively attractive. Perhaps today even more so, when high hopes are placed in digitalization for solving many of the problems that fundamentally jeopardize our future.

Google Trends score for “digital twin”

When a concept becomes trendy, there is a tendency to stretch it in the interest of being heard. If almost any digital model can be called a digital twin, the term will quickly lose its attraction. The discussion will be less distinct and some of the genuinely attractive technical possibilities may get lost. Hence, we would like to introduce a multi-level categorization for building performance digital twins.

<<graphical presentation of the “DTLevels document>>

Black box and white box building performance simulation models

"Digitalization" has been a main driver of technology ever since the enabling transistor was invented at Bell Labs in 1947. On other hand, "artificial intelligence" has, after an early phase of popularity in the late eighties, truly started to deliver only relatively recently with striking results that anybody can assure themselves of by a session with ChatGPT. Like the human brain, artificial neural networks (ANN) have proven to be outstanding in recognizing, learning from, and reconstructing patterns. And meaningful patterns can be found in anything from digital images to natural language and time series (sequences of measurements). Measured power use from a building is an example of such a time series. In fact, "the ASHRAE great energy shootout[6]" was won by a team using ANN already in 1994. Since many building measurements are governed by predictable patterns in weather, time of day, day of week, week of year, etc., ANNs and similar technologies are great at forecasting future measurements based on already known signals. This, in turn, can be used to construct controllers that learn from observed building behavior how to achieve a desired outcome, typically maximum comfort at minimum cost.

A particular characteristic of ANNs and other machine learning methods is that they are completely free of prejudices; they have no a-priori theory about cause and effect, but blindly learn from past observations. This makes them quite easy to apply, you just show them the training data and ask them to predict what you are looking for. Such models that blindly predict output from input are often called black box models. An undesirable side effect of this is that they may also mistakenly identify relationships that do not exist, e.g., if two separate rooms are used with nearly identical patterns, influence from a completely unrelated room may be identified as having an effect in the room one is looking to control.

White box models, on the other hand, are generally based on fundamental laws of physics. They contain a lot of equations and parameters, and they take a great deal of effort to construct. Their main advantage is that they can explain how and why output depends on input. The model does not have to learn obvious things, like that the temperature goes up when heat enters a room, it already knows this. It is meaningful to look inside a white box model. The signals in there mean something.

While black box models are convenient to apply when a lot of measurement data is available, they are useless without it. Hence, in the design phase, one must resort to white box modelling.

As usual, things are not totally black or white. The two model types can and should happily coexist and be used for what they are good at. A white box model can, for example, never predict when somebody usually shows up at work and starts to use an office room. Black box models, on the other hand, know absolutely nothing about behavior outside of the measurement space that they have been trained at. If, for example, a borehole takes a decade to cool down to disastrous temperature levels, it will take decades of measurement data to learn this.

In practice, almost all white box models of buildings contain black box elements, such as a polynomial curve fit that predicts some device's behavior without a clue about the underlying physics. The coefficients of such a curve fit will then have to be computed separately, based on measurement data from the device. In a similar way, as we shall discuss next, it is often very meaningful to calibrate the parameters of a white box model to make it fit even better with actual measurements.

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[6] A contest organized by ASHRAE for predicting future building energy use from a given earlier pattern.

The IDA Building Tracker

A white-box model can be made to follow an actual building in two different ways: **parameter estimation** and **state estimation**. Parameter estimation means that the parameters (time-invariant inputs) of the model are calibrated to replicate the measured data as accurately as possible. This process is often done by hand, to improve the predictive capabilities of the model, but it can also be automated and carried out at regular intervals. When automatically applied, it can provide interesting diagnostic information. If, for example, the heat resistance of a wall, window, or heat exchanger start to drift away from the design value, interesting conclusions can be drawn. The fault may depend on an error in the model, the measurement or, in fact, in the actual building. State estimation, on the other hand, involves running a model under the same conditions as the physical twin in real time in parallel, and continuously forcing the model to replicate sensor signals. This is not a trivial operation for a model of a room that may have hundreds of variables, while perhaps only one or two physical measurements are available. However, if successful, the benefits are significant, and it allows access to hundreds of so-called **virtual sensors** in the room (all the additional variables of the white-box model).

This means that it is possible to reliably observe and control things that cannot easily be measured in real buildings, such as operative temperature or wall heat fluxes. Automated analysis of the forcing signals may reveal interesting insights, such as excessive opening of windows, malfunctioning blinds, simultaneous heating and cooling in rooms etc.

EQUA is currently developing parameter and state estimation functionality for its building simulation software IDA ICE, the **IDA Building Tracker**. So far, the focus has been state estimation, using air temperature measurements of several zones as inputs to estimate the state of the entire building. To compute how much forcing power is needed to adjust the digital twin so that it follows the real building, the differences between the measured air temperature and simulated air temperature for all measured zones are used. These differences are multiplied by an observer gain matrix that maps the measurements to relevant building state variables. How to best compute this gain matrix is ongoing research as of spring 2023.

The validation of the IDA Building Tracker is being done in collaboration with AEE INTEC, presently focusing on two buildings in Austria: The “Prüfbox”, a small-scale test facility equipped with high resolution measurements in Gleisdorf and a building in Villach operated by INFINEON Technologies Austria. In the newly built research and development building of INFINEON Austria, both real-time simulation and building tracking with adjustment signals are being tested in several selected office and meeting rooms. These rooms have been equipped with numerous sensors to measure flows and temperatures as well as detect window openings and the position of sun blinds. These measurements are used as inputs to the simulation (in real time and offline) and to validate the model. Fig. 1 <<figure numbering should be revised once document layout is finalized>> shows the physical and the digital twin of the observed building. Results for this object are not yet ready and will be presented in future publications.

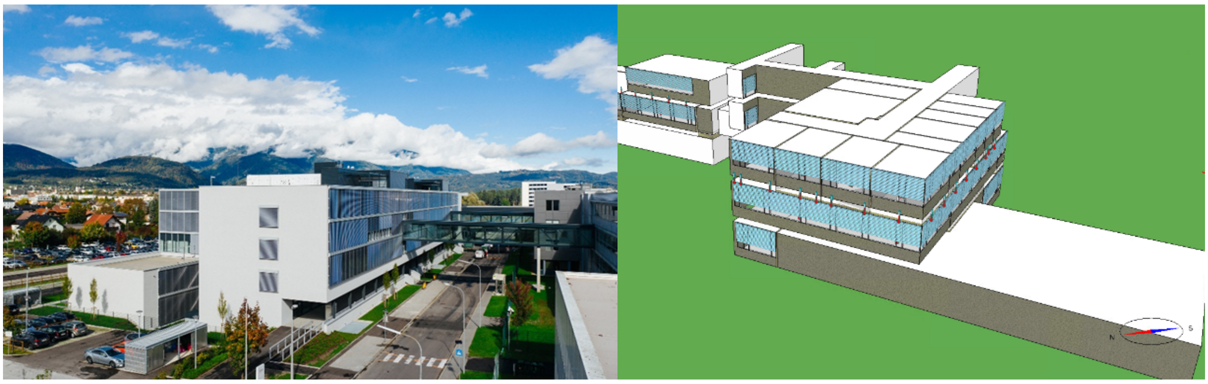

Fig. 1: Physical and digital twin of INFINEON office building (Source: INFINEON Technologies Austria & EQUA)

Fig. 2 shows measured (red) and simulated (blue) temperature for room 2 in the Prüfbox in Gleisdorf for about two months. The green line displays the difference. Within the presented period, different planned events took place, for example the radiator was turned on and off according to a given schedule, blinds were closed, and the mechanical air exchange rate varied. These events were replicated on the simulation model as closely as possible to try to match the measured values. Depending on the happenings, the gap between measurement and simulation alters. In Fig. 3, the IDA Building Tracker has used the error to apply forcing, which has reduced the simulation error significantly. In Fig. 4, the amount of applied forcing power is visualized as a function of time. Different events in the building will show specific signatures in these forcing terms, which will enable the identification of what is happening.

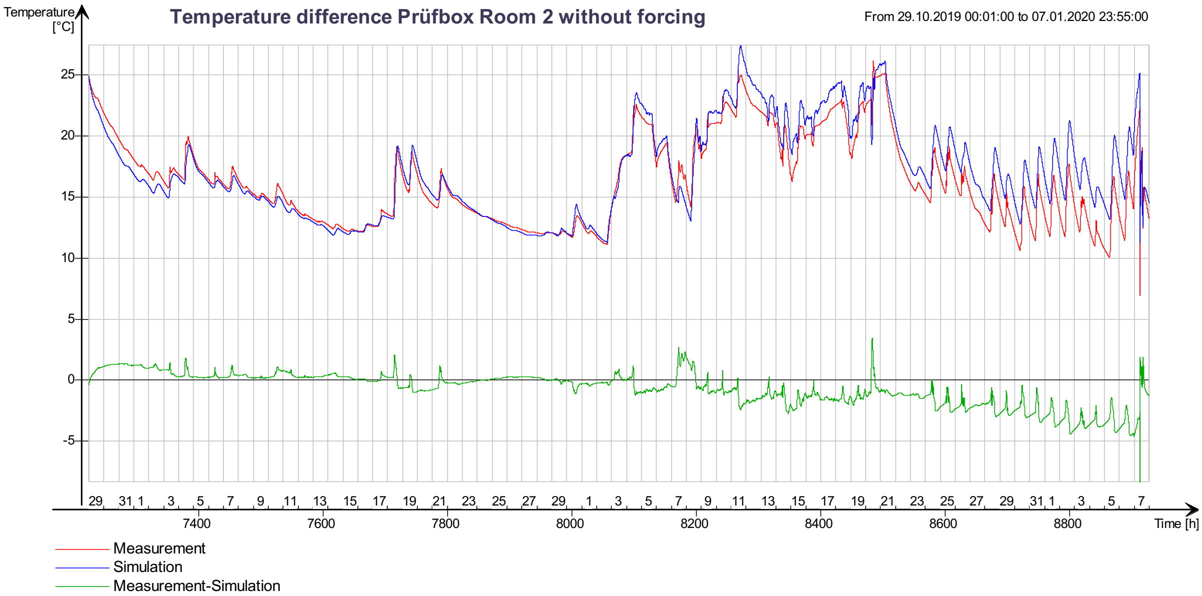

Fig. 2: Comparison of measured and simulated temperature without Building Tracker

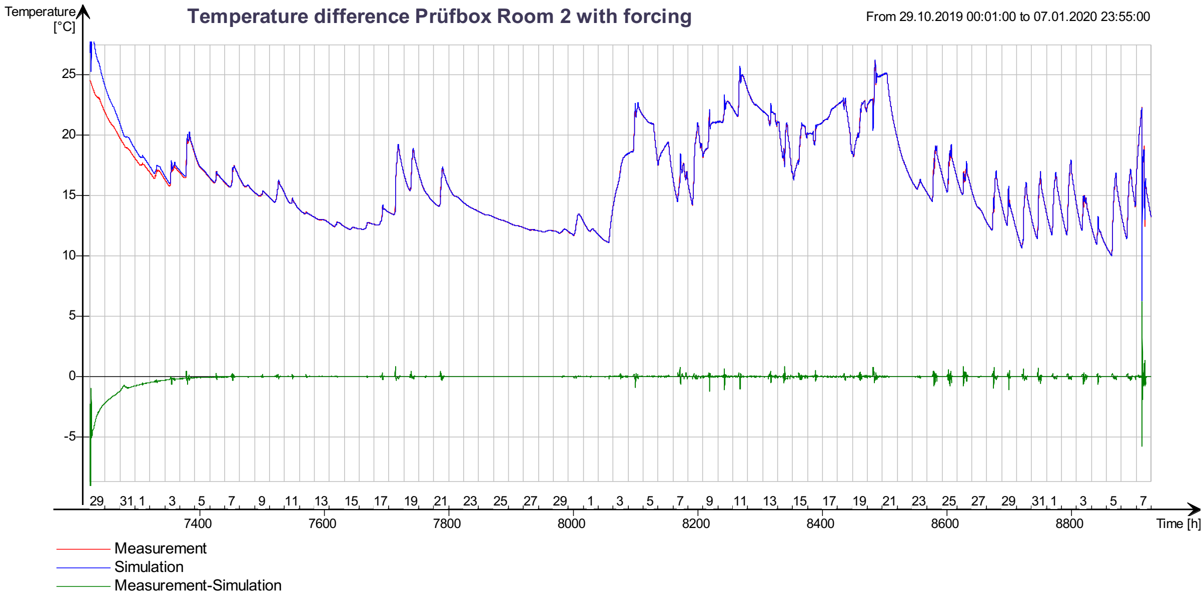

Fig. 3: Comparison of measured and simulated temperature with Building Tracker

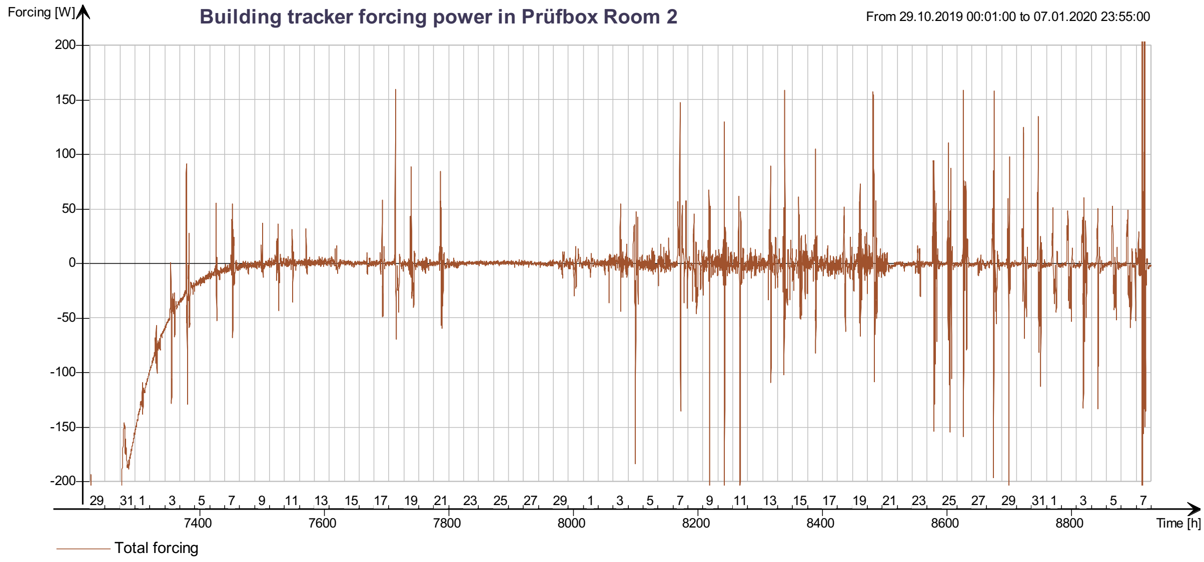

Fig. 4: Heat quantities supplied and removed in the model for the state adjustment

What about "the performance gap"?

In the academic discussion about building energy performance, there is a research direction about "the performance gap". This refers to the often remarkable discrepancy between as-designed and as-built building performance. It is not uncommon that a building in actual operation will use twice as much energy as it should. Some researchers even argue that more detailed simulation models are pointless since actual energy use seems to have little to do with computed values in the building permission process. Let us look a bit closer at the elements of this discrepancy.

The contributions to the performance gap can be broken down into:

1. **Models and parameters of the physical components of the building and its HVAC systems**. All white box models by necessity have simplifying assumptions. If these are inappropriate to the study at hand, results will obviously be more or less meaningless. Furthermore, physical parameters of components, such as U and g-values of windows, lambda-values of insulation, heat exchanger efficiencies, airtightness, etc. are obviously important. There is also a natural statistical spread in these values, that in addition may be influenced by quality of workmanship at the construction site and other factors that are hard to estimate.

   In this context, it should be noted that numerous experiments have been conducted for decades in lab conditions, near lab conditions, as well as in actual, but unoccupied, buildings that prove the reliability of recognized white box models. Computed results under carefully controlled circumstances often have a similar level of accuracy as the measurements themselves. There is nothing fundamentally wrong with the models used.

2. **Occupancy patterns in building**. This includes not only assumptions about occupant presence, but also about electricity usage, hot water usage etc. For modern, well insulated buildings, occupancy can have a huge relative impact on energy usage, as many parents to teenagers with wasteful showering habits can testify to. Several of these aspects are obviously nearly impossible to estimate with any accuracy at the design stage.

3. **Weather**. Input data about temperature, solar radiation, and wind will obviously have an impact on computed results.

4. **Control settings**[7]. A separate group of inputs are setpoints and operation schedules of controllable devices. We include here both settings in the central Building Management System (BMS) and user-controllable settings such as self-acting radiator valves, and degree of openness of operable windows and doors (also interior doors).

Two additional elements that contribute to “the performance gap” are more related to human factors. First, the motivations of the modeler may have a significant impact. If the model is commissioned specifically to obtain some certification label or to pass building permission formalities, some modelers may systematically make estimations in favor of their client’s interest. Secondly, competence and experience vary greatly among modelers. Making accurate models is an art that it takes many years to master.

Incidentally, Sweden had for some years an outcome-based building permission process, i.e., buildings *became legal* only after two years operation, during which energy consumption data had to be monitored and reported as being below given thresholds. These years led to a tremendous development in quality of both models and modelers, and the “performance gap” was significantly reduced. After this period, buildings are sometimes sold with hard performance guarantees that are solely based on simulated values.

Since in any design-stage certification process input for items 2-4 must be based on some standardized regulations, direct comparison of computed to measured results is an extremely blunt instrument, especially for modern, energy efficient buildings. The building will rarely be used

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[7] Differences in actual control behavior vs. modelled control behavior can be significant depending on capabilities of the models used. Here, we include these discrepancies in the first item.

according to the assumptions made and the weather will certainly not agree with values used in simulation.

Normalization is a term that is used for methods for removing the impact of items 2-4 for the purpose of extracting intrinsic building behavior. Traditionally, normalization has focused on assumed vs. actual weather data (item 3 alone), especially temperature data, and most established methods are still devoted to this. However, for modern well-insulated, highly glazed buildings, occupancy patterns play an increasingly important role for energy use and ways of measuring or estimating occupant activities become a key element in meaningful performance comparisons. Furthermore, due to radically better glazing, and consequently increased glazing areas, solar radiation plays a much bigger role today, and normalization methods that exclusively focus on temperature data are becoming less and less relevant.

Fortunately, for digital twin usage of white box models, the blur introduced by items 2-4 can be largely avoided. This makes the concept radically more attractive. Occupancy activities can be directly measured or accurately estimated by indirect means, such as being correlated to measured electricity usage, hot water usage, and/or air quality. Weather data can be directly measured or obtained in near real time from meteorological services, and many control signals can be directly extracted from BMS signals and used as input for the model. User controllable settings represent both a problem and an opportunity. A problem because they are often difficult to measure directly. An opportunity, because they can usually be automatically deduced from other variables (and parameters) in the model and this can, in turn, provide valuable information for a building owner/operator about undesirable (or out of contract) occupant activities, such as excessive number of occupants, excessive window ventilation practices, misunderstanding of proper thermostat usage, tampering with building services equipment, etc.

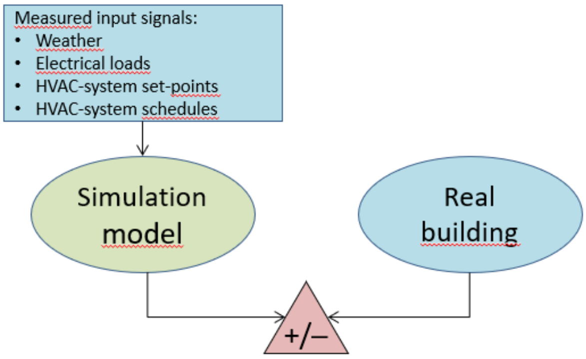

Figure xx. Feeding the white box simulation model with measured signals allows accurate comparison between as-designed and as-built behavior

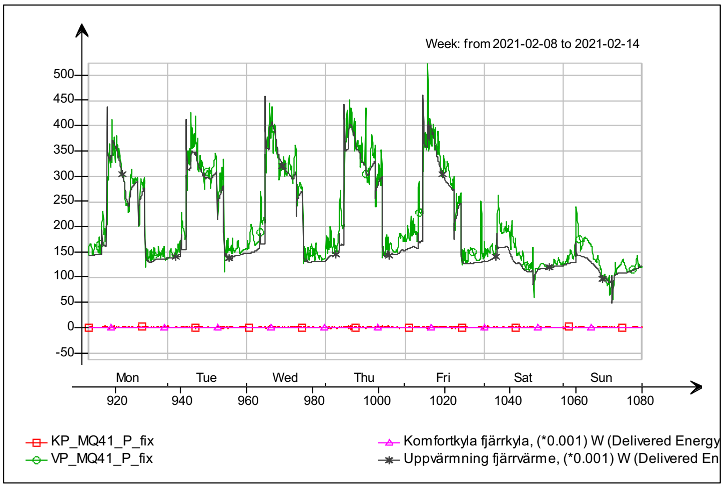

Figure xx. Measured (green) vs. simulated (black) district heating in kW for an un-tuned white box model of an occupied Swedish 22 000 m^2 office building. Yearly accuracy is within 2%.

Benefits and examples

Model based normalization

A white box digital twin not only enables accurate comparisons of energy usage data with as-designed as well as historical points of reference, but can by virtual sensing provide the same service also for indoor climate indicators such as PPD[8] or air quality. This way, changes in the systems (or settings) can be fairly evaluated also in terms of their actual impact on building utility (and consequent risk for tenant dissatisfaction). True optimization of cost vs. benefit can take place.

Virtual Sensing (VS)

A fundamental deliverable of the state and parameter tracking is the ability to measure things indirectly. A correctly tuned model, that is made to follow the building based on a few measurements - often key temperatures, energy supplies and system flows - will provide many additional “virtual sensors” that can be used for both monitoring and control purposes.

In the case of an IDA ICE model, several hundred signals are available per room at a time resolution of seconds. Some examples are surface temperatures, temperatures within walls and floors, operative temperatures, heat fluxes through walls and floors, air CO_2 and moisture levels, daylight levels and many, many more.

Furthermore, automated off-line parameter estimation (calibration) is done at regular intervals to tune the model to actual conditions. This can be done at hourly or less frequent intervals. This process typically leads to timeseries of fundamental room level building properties such as: envelope conduction, thermal mass, envelope leakage, solar aperture, moisture storage capacity, heating capacity etc. as well as key building level indicators such as heat recovery efficiency (unless already directly measured) or chiller performance parameters.

As we will discuss next, all these new signals in their raw form can be quite daunting. However, they will also be available for generation of tailored reports and dashboards for decision makers and maintenance staff with higher information value than present technologies allow.

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[8] Percentage of People Dissatisfied (PPD) is an ISO standardized measure of thermal indoor comfort that take all the most relevant factors into account, i.e., operative temperature, humidity, and local air velocity.

Some examples of such high-level reporting that can be done are: PDH (Hours of people being thermally dissatisfied according to the PPD comfort measure), Cost and CO_2 impact of window ventilation during heating or cooling, Cost and CO_2 impact of actual building operation divided by ideal building operation (ideal control and all equipment working to specifications).

Fault Detection and Diagnosis (FDD)

Finding the faults in a building should always be the first thing to address. Today, faults go undetected for long periods of time. It is often unclear how the building or component *should* perform. There is no reference to compare to (other than building permission estimates, that are often dated and generally ridden by all the problems listed above.) The lack of relevant normalization methods makes the process of looking at final energy usage data - which is often the first indicator of something really going wrong – unreliable at best.

Another aspect of fault detection has to do with the cost of and access to relevant expertise. Although present BMS and monitoring systems may keep track of many relevant direct measurements, there will rarely be someone with sufficient understanding of the building to dig into this data on a regular basis, ask the right questions and figure out if something is wrong. Automated alarms will usually be available for major breakdowns and as reminders of needed maintenance, but only a small fraction of potential faults is typically covered by these. There will never be an alarm if somebody has forgotten to turn off a system that should not be running. Maintenance staff are expected to fix all things big and small in the building but may not always have the best understanding of the more complex technical systems. A famous quote in the industry is that “maintenance staff are not authorized to buy their own pens but may freely change setpoints that cost millions.”

If a white box digital twin is available, insightful but often quite abstract diagnostic signals can be automatically generated based on virtual sensing in combination with modern pattern recognition methods. Examples are normalized, dimensionless U-values instead of direct energy use data and event detection from forcing functions instead of looking at direct temperature measurements. These signals may not be of much use to maintenance staff that do not fully understand the systems to begin with. Instead, they should be used to enable remote monitoring by qualified experts. An expert that truly understands the model as well as the building (and its history) will be able to utilize the new diagnostic power fully and will be able to assist with perhaps hundreds of buildings and thereby become cost effective, despite a significantly higher salary.

Model Predictive Control (MPC)

When a control algorithm performs automatic what-if experiments and optimization with a model of the control object, one often speaks of Model Predictive Control. Such a control method is always based on predictions of important driving inputs. For buildings, these might be weather forecasts, day-ahead prices in the energy markets, ANN predictions of building occupancy etc. For MPC, copies of the digital twin are automatically simulated off-line by the control algorithm to find, e.g., optimal setpoint trajectories.

Let us look at some examples:

- A cheap and simple way of saving energy for poorly insulated buildings is to use night-set-back, i.e., to allow the building to cool to uncomfortable levels at night, when occupants are at home or asleep. However, it is not obvious when to turn the heat back on in the morning, so that the building is comfortable again in time for morning occupancy. The optimal start time can easily be computed by MPC.

- In a variation of the example above, the price of heating energy as a function of time is included in the optimization and an optimal setpoint trajectory is computed.
- In another similar example, a well-insulated building is instead overheated a bit at night, so that the building fabric is charged with cheap night-time heat.
- Analogous cases can be constructed for cooling. Furthermore, the price of cooling can often be zero during the night, when a building that is only used during the day can be cooled by simply leaving the fans running overnight.

Variants of these examples are already implemented in traditional BMS systems based on less sophisticated inputs of threshold parameters. However, with a digital twin they can be automated, and the needed inputs can be computed with much better accuracy and adapted to current conditions each day.

- For buildings with ground source heat pumps and the ability to re-charge the borehole with low-cost heat, it is not trivial to compute when it pays off to recharge the borehole. MPC can solve this.
- For buildings with PV systems and batteries, MPC can find the optimal times to buy, sell, and charge.

In summary, there are several opportunities for MPC in almost every building. With energy supply systems that are increasingly dependent on intermittent renewable energy, prices vary more dramatically over the day and year and these opportunities increase correspondingly. A similar pattern can be found as soon as local energy storage and production become available.

Manual what-if analysis

An obvious but important benefit of a white box digital twin is the fact that a tuned model of the building is always available for manual off-line studies. One can compute the life cycle assessment (LCA) and other consequences of various improvement packages. Experiments with changes to the control system can easily be done by replacing the recorded signals from the physical BMS with a new modelled control system. Options for the physical refurbishment of the building itself can be evaluated also from a performance point of view.

Estimates of potential savings

Since the EQUA digital twin solutions have yet to be deployed in whole buildings in real operation, it is too early to report on any actual results. However, some estimates can be made about the potential based on other sustained market offerings.

Many companies are active in the area of improved controls. Although likely on the optimistic side, their claimed energy savings should have some bearing on reality since many of these offers have been successful on the market for several years. Typical claimed improvements for yearly heating energy use are in the range of 10-30%. One solution, EcoPilot, claims to have saved on average over all installed buildings 22% on heating, 28% on cooling, and 13% on facility electricity[9]. EcoPilot is a white box solution based on a simple thermal room model. There is no reason to assume that a full-fledged white box MPC solution based on IDA ICE should perform any worse.

Another significant savings potential lies in incentivizing occupants to cut down on energy use. Large studies have been made in buildings that have installed systems for individual billing of heating

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[9] https://www.ecopilot.com/about-ecopilot/how-it-works/

energy in multi-family apartment buildings[10]. Average usage of heating energy was reduced by 20% when tenants pay for their own heat compared to when the building heating bill was divided in proportion to floor area. A white box digital twin would allow such measurements to be done by virtual sensors without installation of measuring devices on each radiator.

As can be expected, there are very few formal reports on the benefits of fixing faulty buildings. In our own experience, we see a small number of buildings that basically work as they should and a larger group with a range of minor faults. There are also a few total disasters that are on the verge of ending up as court cases, at the other end of the spectrum. A general conclusion is that much can be won by having a method that minimizes the risk of long-term faulty operation.

It is not unreasonable to assume that a Level 4 white box digital twin can lead to combined savings in the range of 30-50% of heating cost. Naturally, the cost of heating varies depending on climate zone, building quality and usage. However, in warmer climates, buildings tend to be less well insulated and sealed and the actual difference in used heat is therefore smaller than first could be expected. As a reference, an average multi-family building in Sweden uses about 150 kWh/m^2 per year.

Cost of a real time white box digital twin

Setting up a white box digital twin entails two major separate activities. The cost of both can be estimated with some accuracy. First, one needs a sufficiently instrumented building and access to the relevant signals in the computer environment where the twin is operated. Second, an appropriate model of the building is needed.

The exact level of instrumentation that is needed or beneficial to the digital twin operation is still an open question. The central building systems should be sufficiently instrumented to be able to follow their main functions, i.e., temperature, moisture, and flow readings should be available with sufficient density. Key central power readings should be available, especially grid supply/export. It is good to be able to separate power for heating from domestic hot water. Local (zone/apartment) temperature readings are needed and for variable volume ventilation systems, local air flow. Local power readings are highly desirable for most applications.

For new construction of commercial buildings, the needed signals are normally available or can be added within marginal cost. Existing commercial buildings vary a great deal in level of instrumentation as well as in ease of signal access.

For new residential buildings in the Nordic countries, the needed level of instrumentation is often also available, while for existing residential buildings, only a small number of buildings will already be sufficiently instrumented. However, on the Nordic market companies such as EcoGuard successfully offer instrumentation for existing apartment buildings of the appropriate level of detail. Presently, the direct commercial benefit of this monitoring is to be able to charge individual apartment owners for used domestic hot water. Temperature measurements in individual apartments is done to allow landlords an overview of actual building temperatures. This information is useful background information in discussions with individual tenants about delivered indoor thermal comfort. The extra cost for using these signals for a potential white box digital twin should be marginal. So, apart from existing non-residential buildings, the cost of instrumentation should normally not be a significant obstacle.

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[10] Felsmann, Clemens – Schmidt, Juliane – Mróz, Tomasz. Effects of Consumption-Based Billing Depending on the Energy Qualities of Buildings in the EU, 2015

The other major cost, setting up the white box model, depends primarily on two factors, the complexity of the building itself and the availability of needed input parameters. For new construction in the Nordics, IDA ICE models will often already be available that can easily be adapted to digital twin usage. If there is no useful model, but the needed information is readily available, the modelling cost is about 1 EUR/m^2 for commercial buildings and about half of that for (normally less complex) residential buildings.

There will of course be other costs, for the initial set-up as well as for maintaining the digital twin, but overall, costs are reasonable with respect to potential benefits.

Present state of development and conclusions

Contrary to alternative approaches, white box digital twins have the potential of addressing all the areas that are critical for substantially improving building thermal efficiency, i.e., comfort vs. cost: fault detection, improved controls, individual tenant billing, as well as LCA optimization of general investment packages. Furthermore, they can deliver optimal energy trading in (prosumer) buildings with local energy generation and storage capabilities for heat and electricity.

As of spring 2023, a few fundamental research issues remain. In addition to these, several practical implementation problems must be addressed before more complete prototype installations can commence.

However, given the dignity of the climate challenge in combination with the potential for improvement of buildings, EQUA is committed to delivering useful white box digital twins.